Interactive and Dynamic Integrated Module for Mobile Cranes Supporting System Design

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Abstract: Analyzing and designing a crane supporting system can be time-consuming process. In particular, the dynamic nature of mobile crane operations entails a variety of reaction values for truck and crawler cranes. The platform of a mobile crane can either be set on outriggers—denoted as a truck crane, or on a crawler tracks—denoted as a crawler crane. Designing of a mobile crane supporting system depends on the lifting configuration, type of crane and the type of materials to be used under the crane outriggers or crawler tracks. This paper presents an automated system which is designed to assist practitioners in calculating the mobile crane's support reactions and in designing the supporting system. This system is developed such that it can generate a 2D reaction influence chart which shows the reactions for each outrigger at varying horizontal swing angles and vertical boom angles to the ground. Most of the geometric configurations needed to perform the support design are not ordinarily given in crane manufacturer's manual and to address this deficiency, this newly developed system has been integrated with a previously developed crane database which contains information on widely used mobile cranes for construction along with a crane selection system. A case example is described in order to demonstrate the use and effectiveness of the presented system in automating crane lift analysis.

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Introduction

A common link among most mobile crane accidents is human-related factors, such as poor design or improper crane selection (www.craneaccidents.com). The use of mobile cranes has represented over 84% of fatalities in the use of cranes (Beavers et al. 2006). In the United States, the construction industry accounts for 19.4% of work place fatalities and 12.3% of occupational injuries and illnesses, in spite of the fact that construction workers represent only 4.8% of the U.S. work force (Abudayyeh et al. 2003). This fact is critical considering that cranes maintain a central role in building projects, and mobile cranes in particular have dominated the North American market (Shapira et al. 2007).

Current research in the domain of construction cranes focuses primarily on developing tools to assist practitioners in the crane selection process (Al-Hussein 1999; Zhang et al. 1999; Warszawski 1990). Al-Hussein et al. (2005) developed an optimization algorithm for the selection and location of mobile cranes on construction sites. Furthermore, Sawhney and Mund (2002) developed a prototype-integrated crane selection tool, IntelliCranes, based on adaptive probabilistic neural network principles. This tool assists in both crane type and crane model selection. A fuzzy logic approach to selecting the best crane type in a construction project from selected crane types has also been established by Hanna and Lotfallah (1999). Furthermore, Al-Hussein et al. (2000) developed a database that is designed to house information related to cranes, their lifting configuration geometries, and their lifting capacities based on the information provided by manufacturers in the crane lifting capacity charts. Computer modules for planning heavy and critical lifts have also been made available using integer programming and optimization techniques (Lin and Haas 1996). Other modules involving 3D graphics and simulation for crane selection have been developed and are referred to by Hornaday et al. (1993) and Dharwadkar et al. (1994). Many researchers have developed approaches to assist practitioners in site layout optimization and automated path planning of mobile cranes (Tantisevi and Akinci 2008; Ali et al. 2005; Sivakumar et al. 2003; Reddy and Varghese 2002). Unfortunately, these models fail to emphasize factors related to crane supporting system design. In practice, mobile cranes become highly unstable as a result of rapid penetration of the outriggers into the ground (Tamate et al. 2005).

Crane support design is commonly carried out by the crane rental company, general contractors, or a third party, either manually or using rules of thumb. craniMAX GmbH (2009), however, developed a system named CRANE MANAGER V3.0 that calculates the crane support reactions for the static position of a mobile crane (http://www.cranimax.com). This system includes features such as 3D animation capabilities; but, does not assist in the design for support system. In addition, CRANE MANGER

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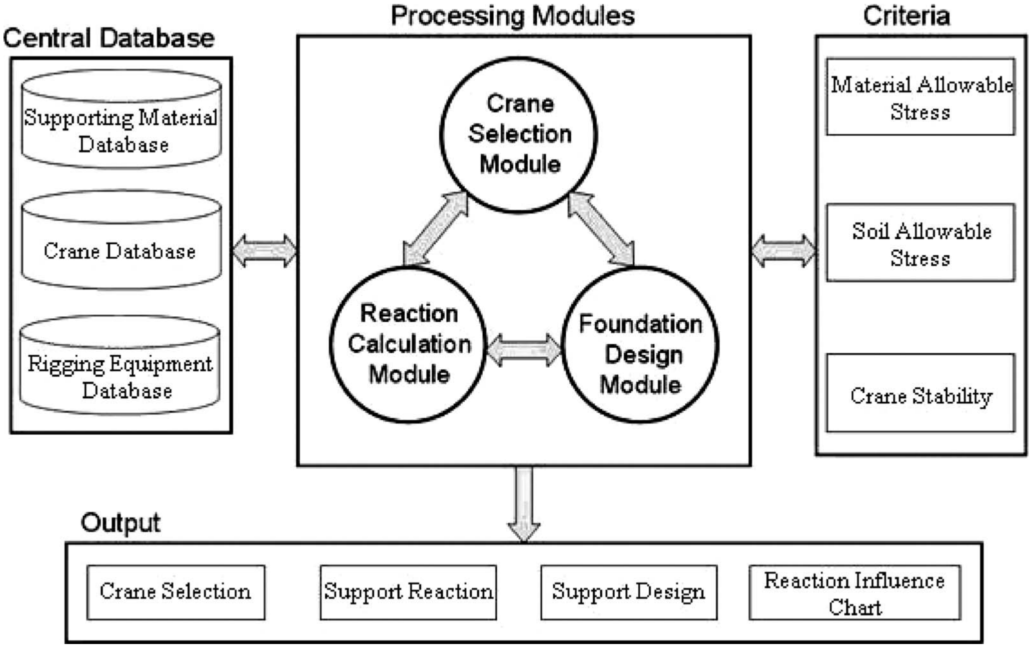

Fig. 1. Main system components

has not any option to calculate the reactions for 360° swings of a crane with changes in boom angle and loaded/unloaded condition. This paper presents a newly developed automated system designed to aid practitioners in the process of preparing lift studies and designs for the mobile crane supporting system. The methodology has been built based upon the principles of limit state structural design to calculate the outrigger's reaction values for truck cranes as well as to calculate the values and display the shape of the pressure for crawler cranes. The developed methodology has been incorporated into a computer system, using an algorithm developed previously for crane selection [see Al-Hussein et al. (2005)]. This algorithm has been designed to assist practitioners in the optimal selection of cranes for construction sites. The developed automated system has also been integrated with the crane database [see Al-Hussein et al. (2000)], which is designed to house such information as the geometrics, weight, and lifting capacity of commercially available cranes. The integrated system has been developed using MS-Visual Basic in order to ensure a user-friendly interface and to control the data integrity.

Proposed Crane Supporting System Architecture

As shown in Fig. 1, the proposed system is comprised of the following four components: (1) processing modules; (2) central database; (3) design criteria; and (4) system output. The focus of this paper will be on the processing modules, which include crane selection, reaction calculation, and foundation design.

The crane selection module assists in selecting a crane which can be obtained in three different ways: by (1) manually selecting a crane; (2) selecting from the crane database; or (3) using crane selection module. The crane database, "D-Crane," which has been described elsewhere (Al-Hussein et al. 2000), has been employed here in order to retrieve the geometric information for the selected crane. Also "Selectomatic" software, which has been described by Al-Hussein et al. (2001), is used here to select the optimum crane based on the given lifting configurations for supporting system design. The reaction calculation module assists in determining the reaction under the crane's outriggers in the case of the truck crane and the pressure under the tracks in the case of the crawler crane. The foundation design module assists in designing the support foundation using either steel plates or timber. The design characteristic of timber is retrieved from the supporting material database.

The design process is based upon the following criteria: (1) material allowable stress for the material selected for the supporting system design; (2) soil allowable stress; and (3) crane stability against tipping failure. The reaction calculation module evaluates the crane stability against tipping by highlighting the reaction with negative values (i.e., tipping would occur). The design output includes the following four components: (1) crane selection, either optimum or feasible based on user's selected design mode; (2) support reaction, which is determined by calculating the values of the outrigger reaction for the truck crane, as well as the shapes and values of the track pressure for the crawler crane; (3) the proposed design for the supporting system (steel plate or timber); and (4) the reaction influence chart, which accounts for the relationship between outrigger reaction or track pressure and boom horizontal swinging angle to allow to rotate the boom horizontally, as well as vertically. This paper focuses on the process used to automate the crane supporting system's design, including the foundation design module and the reaction calculations module.

Crane Supporting System Design Process

In the design of the crane support the developed computer system presents four different options as shown in Fig. 2: (1) truck crane; (2) crawler crane; (3) crane database mode; and (4) crane selection mode. For the first two options user has the opportunity to input manually the crane geometric information and lifting configuration for a truck crane and a crawler crane respectively. The last two options represent the links to D-Crane database (Al-Hussein et al. 2000) and the Selectomatic software (Al-Hussein et al. 2001) to retrieve the crane geometric information for a se-

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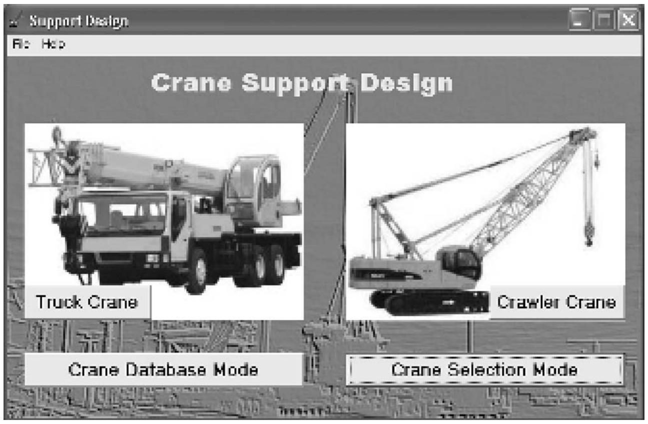

Fig. 2. Crane supporting system design modes

lected crane or an optimum crane respectively. There are three steps in this methodology which must be followed in order to achieve the final results: the geometric configuration of the crane, the reaction calculation, and the design of the supporting system. The variables used in the analysis process are shown in Fig. 3 and most of these variables are not ordinarily given in the crane manufacturer's literature. Some of the variables are also not available in the D-Crane database. Therefore, mathematical algorithms have been developed to calculate the values for those missing variables.

Once the crane configuration has been added, the user can design the required support for either a single position or multiple positions of the boom. For a single position, the reactions have been calculated for a specific boom angle and horizontal angle and for a specific load. For multiple positions, the reactions have been calculated for loaded and unloaded scenarios for changing boom angles (θ) and swing angles (α) (see Fig. 3). For the truck crane, each outrigger shares the total vertical load of the crane. Thus the reactions for the four outriggers, two fronts P_{fb}, P_{fc} and two rears P_{rb}, P_{rc}, are preliminary calculated satisfying Eq. (1)

$$P_{fb} = P_{fc} = P_{rb} = P_{rc} = \frac{W_{\text{crane}} + W_{\text{load}} + W_{\text{add}}}{4} \tag{1}$$

where W_{crane}=total weight of the crane, which is calculated satisfying Eq. (2) and W_{load} and W_{add}=weights of lifted load and additional load, respectively. For the unloaded condition, $W_{\text{load}}=0$

$$W_{\text{crane}} = W_b + W_j + W_{cr} + W_{cw} \tag{2}$$

where W_b, W_j, W_{cr}, and W_{cw}=weight of the boom, jib (if attached), carrier, and counterweight, respectively.

In D-Crane database the values of W_b, W_j, and W_{cr} variables are not given. In order to calculate these variables Eqs. (3)–(5) has been developed

$$W_b = L^* w_b \tag{3}$$

$$W_j = L_j^* w_j \tag{4}$$

$$W_{cr} = W_{\text{crane}} - W_b - W_j - W_{cw} \tag{5}$$

where L, L_j=lengths of the boom and jib, respectively, and w_b and w_j=unit weights per length of the boom and jib, respectively. To simplify the process default values for these variables are given. The user has the option to edit these variables.

Since transverse and longitudinal moments due to the eccentricity of the loads affect the outrigger reactions value (Shapiro et al. 1999), the four outrigger reactions can be calculated satisfying Eqs. (6)–(9)

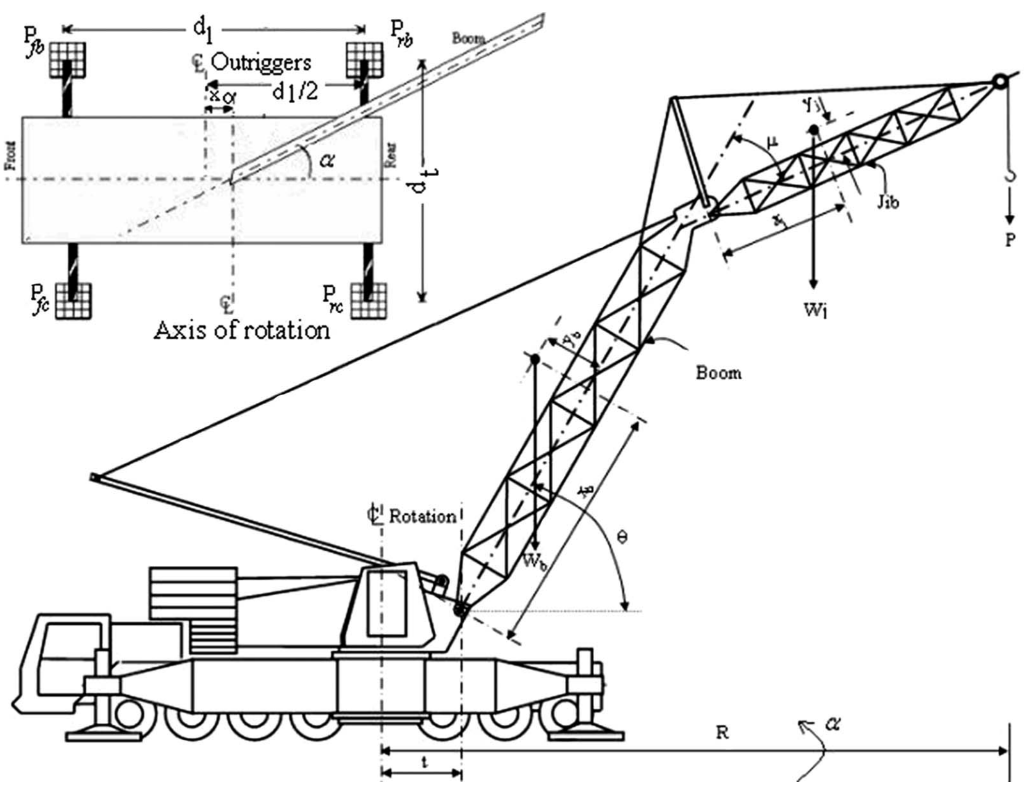

Fig. 3. Parameters used in reaction calculation

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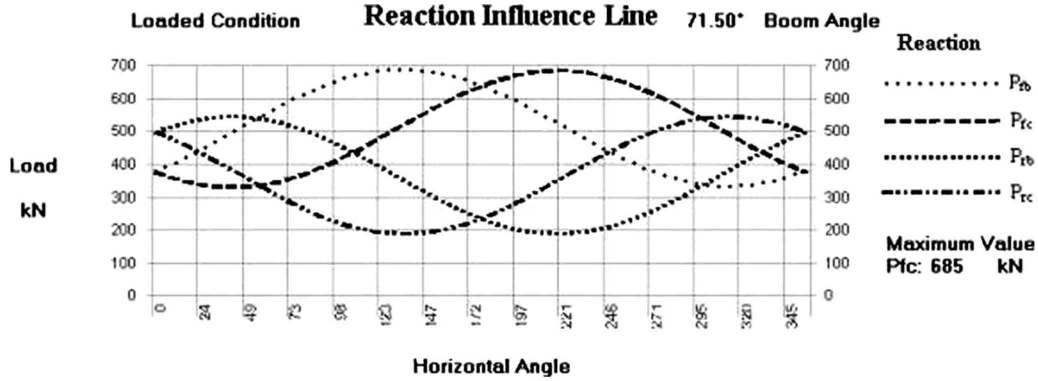

Fig. 4. Reaction influence chart for a specified boom angle and loaded condition

$$P_{fb} = \frac{W_{\text{crane}} + W_{\text{load}} + W_{\text{add}}}{4} + \frac{1}{2}\left(\frac{M_u \sin\alpha}{d_t} - \frac{M_u \cos\alpha - W_m x_o - W_{cr} d_{cr}}{d_l}\right) \tag{6}$$

$$P_{fc} = \frac{W_{\text{crane}} + W_{\text{load}} + W_{\text{add}}}{4} - \frac{1}{2}\left(\frac{M_u \sin\alpha}{d_t} + \frac{M_u \cos\alpha - W_m x_o - W_{cr} d_{cr}}{d_l}\right) \tag{7}$$

$$P_{rb} = \frac{W_{\text{crane}} + W_{\text{load}} + W_{\text{add}}}{4} + \frac{1}{2}\left(\frac{M_u \sin\alpha}{d_t} + \frac{M_u \cos\alpha - W_m x_o - W_{cr} d_{cr}}{d_l}\right) \tag{8}$$

$$P_{rc} = \frac{W_{\text{crane}} + W_{\text{load}} + W_{\text{add}}}{4} - \frac{1}{2}\left(\frac{M_u \sin\alpha}{d_t} - \frac{M_u \cos\alpha - W_m x_o - W_{cr} d_{cr}}{d_l}\right) \tag{9}$$

where d_t=distance between outriggers in the transverse direction; d_l=distance between outriggers in the longitudinal direction; x_0 =distance between the outrigger centerline and the center of rotation; d_{cr}=distance between carrier CG to the center of rotation; and M_u, W_m=ultimate moment and the total movable vertical load, respectively, and are calculated satisfying Eqs. (10) and (11)

$$M_u = W_b[t + L_b \cos(\theta + \theta_b)] + W_j[t + L\cos\theta + J_j \cos(\theta - \mu + \mu_j)] + (W_{\text{load}} + W_{\text{add}})R - W_{cw} d_{cw} \tag{10}$$

$$W_m = W_{\text{crane}} - W_{cr} + W_{\text{load}} + W_{\text{add}} \tag{11}$$

where t=distance between the boom pin and the center of rotation; L_b and θ_b denote the position of the boom's center of gravity (CG); J_j and μ_j denote the position of the jib's CG; μ=angle between the boom and the jib, and R=lifting radius.

The proposed system use default values for some of these variables, like $L_b = L/2$, $\theta_b = 0$, $J_j = L_j/2$, and $\mu_j = 0$. However, the user has the option to edit these variables.

Cranes operating on a construction site are involved in lifting objects from the pick location and swinging them to their final location. After having placed the load, the boom may swing unloaded to another location. In other words, the swinging operation can occur in either a loaded or an unloaded condition. Outrigger reaction values change in proportion to changes in the boom's horizontal swinging angle (α) used in Eqs. (6)–(9) and boom (vertical) angle (θ) used in Eq. (10). With regard to loaded and unloaded conditions, only the weight of a lifted load changes in the Eqs. (6)–(11). An influence reaction chart for a 360° swing has been integrated into the system in order to illustrate the variability in the outrigger's reaction with respect to the change of α for each boom angle to ground θ and for either loaded or unloaded condition (see Fig. 4). The influence reaction chart will change with either a change in boom angles (horizontal and vertical) or a change between loaded/unloaded condition. In addition to being displayed in the chart, this information is also shown in a tabulated format which the user can view using a standard spreadsheet. The maximum values from that table are highlighted as shown in Fig. 5. The user can view the load distribution in each outrigger (see Fig. 6) for any swinging angle by selecting any of the swing angles listed in the table shown in Fig. 5, since both the table and Fig. 6 are interactively linked.

In the case of the crawler crane, the pressure under the track is more complex due to the extended contact area of the tracks with the ground. According to Shapiro et al. (1999), in this case the various forces should be presented based on the shape of their pressure, which will vary from trapezoidal to triangular (see Fig. 7). Due to the vertical load and moments around the center of rotation, pressure under the tracks can be divided into three categories. ν, f_e, and f_s represent pressure due to vertical load, front or rear moment, and side moment, respectively, and can be calculated satisfying Eqs. (12)–(14)

$$\nu = \frac{W_{\text{crane}} + W_{\text{load}} + W_{\text{add}}}{2wd_l} \tag{12}$$

$$f_e = \frac{3(M_u \cos\alpha - W_m x_o - W_{cr} d_{cr})}{w(d_l)^2} \tag{13}$$

$$f_s = \frac{M_u \sin\alpha}{wd_l d_t} \tag{14}$$

where w=width of the crawler track (see Fig. 7).

If $v + f_s > f_e$, then the pressure diagram is *trapezoidal*. The pressure for the track on the boom side (P_{fb}, P_{rb}) and counterweight side (P_{fc}, P_{rc}) as shown in Fig. 7 can be calculated using Eqs. (15)–(18)

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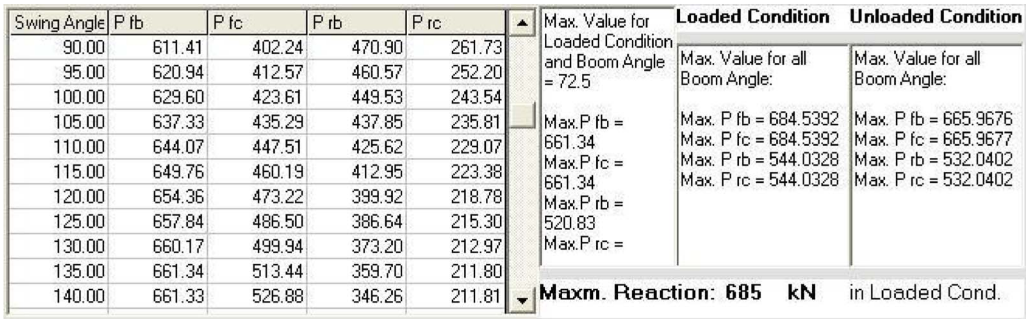

Swing Angle	P fb	P fc	P rb	P rc
90.00	611.41	402.24	470.90	261.73
95.00	620.94	412.57	460.57	252.20
100.00	629.60	423.61	449.53	243.54
105.00	637.33	435.29	437.85	235.81
110.00	644.07	447.51	425.62	229.07
115.00	649.76	460.19	412.95	223.38
120.00	654.36	473.22	399.92	218.78
125.00	657.84	486.50	386.64	215.30
130.00	660.17	499.94	373.20	212.97
135.00	661.34	513.44	359.70	211.80
140.00	661.33	526.88	346.26	211.81

Max. Value for Loaded Condition and Boom Angle = 72.5

Max.P fb = 661.34
Max.P fc = 661.34
Max.P rb = 520.83
Max.P rc =

Loaded Condition	Unloaded Condition
Max. Value for all Boom Angle:	Max. Value for all Boom Angle:
Max. P fb = 684.5392	Max. P fb = 665.9676
Max. P fc = 684.5392	Max. P fc = 665.9677
Max. P rb = 544.0328	Max. P rb = 532.0402
Max. P rc = 544.0328	Max. P rc = 532.0402

Maxm. Reaction: 685 kN in Loaded Cond.

Fig. 5. Reaction value sheet

$$p_{fb} = v + f_s + f_e \tag{15}$$

$$p_{rb} = v + f_s - f_e \tag{16}$$

$$p_{fc} = v - f_s + f_e \tag{17}$$

$$p_{rc} = v - f_s - f_e \tag{18}$$

If $v + f_s < f_e$, then the pressure diagram in the triangular form over length l will appear as shown in Fig. 7, and the side can be calculated satisfying Eq. (19)

$$l = 1.5 d_l - \frac{3(M_u \cos \alpha - W_m x_o - W_{cr} d_{cr})}{V} \tag{19}$$

The pressure for the track on the load side (P_{fb}) and counterweight side (P_{fc}) can be calculated satisfying Eqs. (20) and (21)

$$p_{fb} = \frac{V + 2(M_u \sin \alpha / d_t)}{wl} \tag{20}$$

$$p_{fc} = \frac{V - 2(M_u \sin \alpha / d_t)}{wl} \tag{21}$$

For crawler cranes, the track pressures have also been calculated for both loaded and unloaded lifts, and for changing horizontal swing angles and vertical boom angles. These pressures are presented in a similar influence chart and table as shown in Figs. 4 and 5, respectively. The user can view the pressure distribution in each crawler track for any horizontal swinging angle by simply selecting and clicking on any of the swinging angles in the table as shown in Fig. 5. Unsafe rotation is highlighted in this table when any track pressure value becomes negative.

A variety of materials (timber, steel, gravel) can be used to distribute the mass of the mobile crane and the suspended load to the ground. Once the outrigger reactions or track pressures have been calculated and the soil bearing capacity has been determined from the geotechnical soil report, the design of support can be performed. The final step here involves the design of a supporting system using design forces or pressure in conjunction with allowable stress, which can be accomplished using either timber or steel plates. Lengths of timber with rectangular cross sections are the most common mechanism used here. For heavier lifts, steel plates are often used under the outriggers of the truck crane. The design is performed based on the maximum values of forces or pressure in the previous step.

In the case of a timber design, the user is prompted to select a timber type and section dimensions and to enter the soil bearing capacity (see Fig. 8). This design module is incorporated with a built-in supporting material database. This database stores the allowable stresses for 12 different types of timber. Also properties i.e., area, moment of inertia, have been stored in this database for more than a hundred different timber sizes. Once the user has selected the material type and its sectional dimensions, the design is carried out and the results are divided into two types: geometry and stress. The geometric output will be different for a truck crane than for a crawler crane. For a truck crane the output includes: (1) the quantity of timber to be used in each layer; (2) the length of timber required; (3) timber mat width; and (4) the number of layers. For the crawler crane the geometry output includes (1) the quantity of timber to be used in forming a mat; (2) the length of mat required; (3) mat width; (4) the total number of mats in each layer; and (5) the number of layers required where a mat is a group of timbers, usually four 305 × 305 mm (12 × 12 in.) lengths bolted together to form a unit. The stress output includes: (1) bending stress and (2) shear stress, both displayed in the model adjacent to the allowable bending stress and shear stress. Both stresses are compared with the allowable stress for the selected type of timber, and the result is highlighted if the discrepancy is such that the design is determined to be unsafe. In the case of a failure, the user is prompted with a message indicating unsafe stress, such that the user has the option to increase the timber size, select another timber type, or reinforce the soil.

The steel plate design is limited to the truck crane scenario. In this case, the user is prompted to enter the allowable bending stress of the steel along with the soil bearing capacity. Once these values have been entered, the design is carried out and the results are displayed, including (1) plate dimension; (2) plate thickness; and (3) number of plate layers. At the end of the design the user can view and print all the design results along with the operational inputs and the name of the crane.

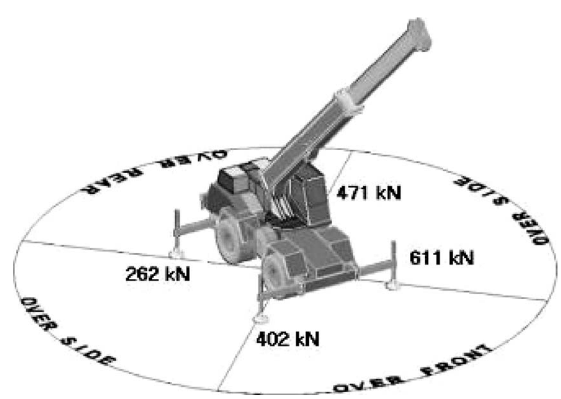

Fig. 6. Load distribution in each outrigger

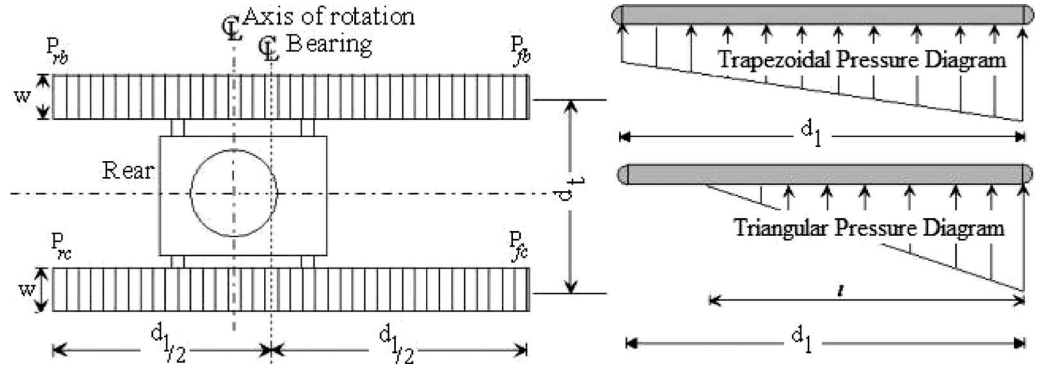

Fig. 7. Crawler crane variables and pressure diagrams

Case Example

The case considered involves the construction of a modular building in Edmonton, AB, Canada. The operations include taking the slings and rigging from the east side of the facility, swinging them to the north side in order to pickup the module (with an obstruction of 3 m in height and 12 m in depth), and swinging it to the south in order to place the load with an obstruction of 3-m height and 8-m depth (see Fig. 9). Due to the size of the object, eight lifting points are required. In the case example, this resulted in multiple levels of rigging equipment. The weight of the slings and rigging is 16,000 kg and the height is 23 m. The module weight is 45,000 kg, and the maximum height allowed in placing this load is 8 m. The solution requires selecting an appropriate crane and a suitable design for the supporting system for these lifts.

Step 1

This step is carried out in order to select an appropriate crane to perform these lifts with the geometric and lifting configuration inputs. In this case, one crane must be selected with a constant boom length and counterweight which can perform all lifts with their varying vertical boom angles and horizontal swing angles. Selecting the crane selection design mode (see Fig. 2) and performing these configurations in Selectomatic Software (Al-Hussein et al. 2001), a list of all technically feasible cranes can be generated. Manitowoc M250 has been selected as the crawler crane and Demag TC2000 has been selected as the truck crane in order to perform these lifts.

Step 2

The purpose of this step is to calculate either the reactions in the outrigger pad or the pressure in the crawler track. The crane must swing to Location B to pick the load and place it at Location C as shown in Fig. 9, while at the same time changing both boom angles (horizontal and vertical). In such a case, the design must be carried out for multiple positions, accounting for both loaded and unloaded conditions. The horizontal swing angle ranges from $-90°$ to $+90°$. The vertical boom angle must also be changed due to varying obstruction depths; the value of the vertical boom angle to ground is determined to be 58.47° when initiating the lift of the module and 55.82° when placing it. The output maximum reaction for all these swing and boom angles in either loaded or unloaded condition is 1,183 KN (Fig. 10). In the case of the crawler crane, Manitowoc M250, output maximum pressure for all these swing and boom angles in either loaded or unloaded condition is 350 KPa.

Step 3

In this step, the support design is carried out based on the maximum reactions, which were determined in the previous step. For the Demag TC2000, two types of designs can be carried out. In the case of the timber design, selecting the Northern (SS) timber type and the 305×305 mm (12×12 in.) timber size and enter-

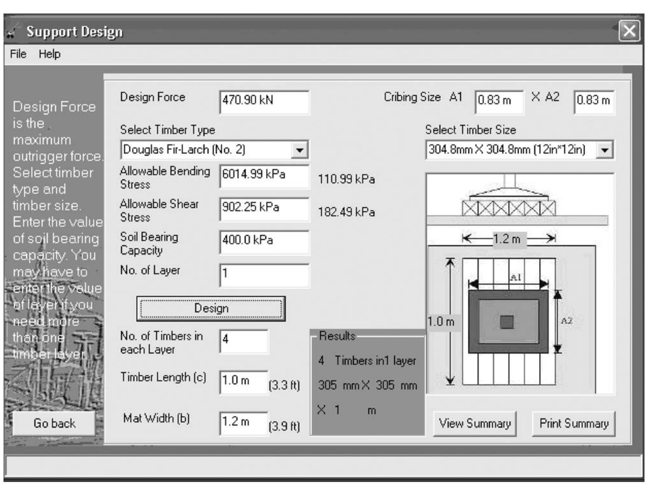

Fig. 8. Support design module for truck crane

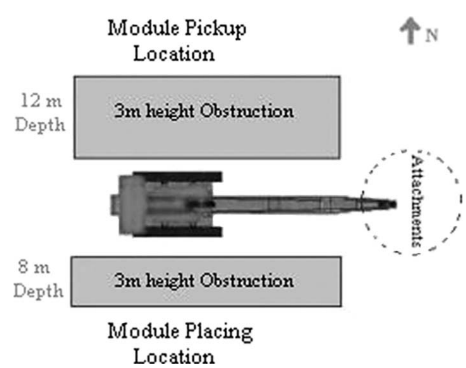

Fig. 9. Plan view of crane operation

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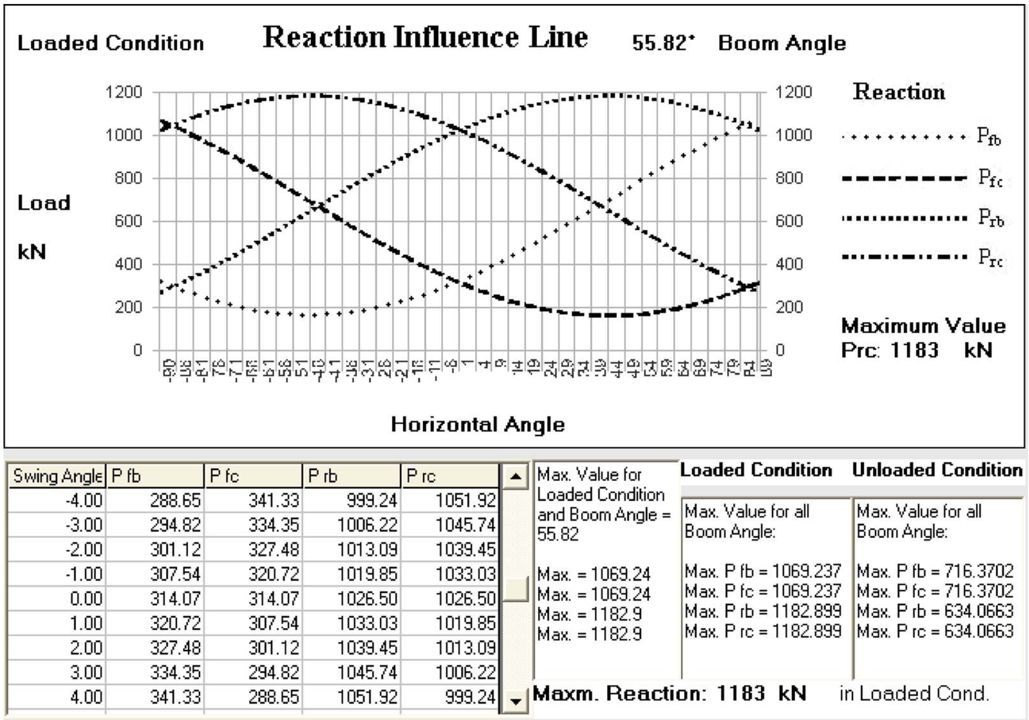

Swing Angle	P fb	P fc	P rb	P rc
-4.00	288.65	341.33	999.24	1051.92
-3.00	294.82	334.35	1006.22	1045.74
-2.00	301.12	327.48	1013.09	1039.45
-1.00	307.54	320.72	1019.85	1033.03
0.00	314.07	314.07	1026.50	1026.50
1.00	320.72	307.54	1033.03	1019.85
2.00	327.48	301.12	1039.45	1013.09
3.00	334.35	294.82	1045.74	1006.22
4.00	341.33	288.65	1051.92	999.24

Fig. 10. Reaction influence chart and table for Demag TC2000

Table 1. Crane Support Design Results

Crane type	Timber support						Steel plate support	
	Timber size (mm)	Timber or mat length (m)	Mat width (m)	Number of layer	Number of timber or mat/layer	Number of timber forming a mat	Plate dimension (m)	Plate thickness (mm)
Demag TC2000	305×305	2.0	1.5	2	5	—	1.8	30
Manitowoc M250	305×305	9.0	1.17	1	8	4	—	—

ing the soil bearing capacity (400 kPa) generated from the soil test report, the results given by the supporting system are as shown in Table 1. In the case of the steel plate design, the allowable bending stress of steel was chosen as 186 MPa. Entering the soil bearing capacity, the outputs are as shown in Table 1. For the Manitowoc M250, only the timber support design is carried out. Selecting the Northern (SS) timber type and the 305 ×305 mm (12×12 in.) timber size and entering the soil bearing capacity, the results given by the supporting system are as shown in Table 1.

Conclusions

This paper has presented an automated system for the analysis and design of crane supporting systems. The primary focus has been on the methodology used to support planners in executing lift studies for mobile cranes. The developed automated system provides its users with additional graphics in the form of 2D influence reaction charts supporting the visualization of the forces being exerted upon the outriggers or crawler tracks for the planned lift, from start to completion. Again the reaction influence chart is much more comprehensible to contractors or crane operators than the manufacture's provided crane load chart to control the direction of crane swing and changing boom positions for a particular crane operation. The developed supporting system integrates a previously developed set of selection modules as well as a crane database. This system also ensures the safety operation of a mobile crane by providing the actual support reaction and adequate support system during dynamic movement of crane. The system has been developed, using MS-Visual Basic, to control the data integrity as well as to provide a user-friendly interface. The system has proven to be effective in helping to circumvent potential accidents and in reducing the time and cost associated with the design of lift studies for heavy and critical lifts on construction sites.

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