University of Alberta

Interactive and Dynamic Integrated Module for Mobile Cranes Supporting System Design

by

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This thesis is dedicated with love and respect to my parents and

to my beloved wife

ABSTRACT

Analyzing and designing a crane supporting system can be a time-consuming process. In particular, the dynamic nature of mobile crane operations entails a variety of reaction values for truck and crawler cranes. This research presents an algorithm which is designed to assist practitioners in evaluating the elements required in order to calculate the reaction forces and in designing the supporting system for both types of mobile cranes—truck cranes on outriggers and crawler cranes on tracks. The developed algorithm integrates a reaction influence chart, which accounts for the dynamic relationship between the reaction of the outriggers or pressure of the crawler tracks and the boom's horizontal swinging angles and vertical angles. The proposed algorithm has been developed into a computer system, which has been integrated with a previously developed crane selection system and two crane databases. The system has proven to be effective in reducing the time and costs associated with the preparation of lift studies. Two case examples are described in order to demonstrate the use of the presented algorithm.

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There have been a great number of exceptional people who contributed to my research.

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Axis of Rotation - the vertical axis around which the crane superstructure rotates (see Figure 1).

Base / Carrier - the traveling base or carrier upon which the rotating superstructure is mounted: may be a car, truck, crawlers, or wheel platforms (see Figure 1).

Boom - a member hinged to the front of the rotating superstructure with the outer end supported by ropes leading to a gantry or A-frame which is used to support the hoisting tackle (see Figure 1).

Boom Angle - the angle between the longitudinal centerline of the boom and the horizontal centerline. The boom longitude centerline is a straight line between the boom foot pin (heel pin) centerline and the boom point sheave pin centerline (see Figure 1).

Counterweight - a weight used to supplement the weight of the machine in providing stability for the lifting of working loads (see Figure 1).

Jib - an extension attached to the boom point in order to provide added boom length for lifting specific loads. The jib may be in line with the boom, or may be offset to various angles (see Figure 1).

Load (Working Load) - the external load applied to the crane, including the weight of load-attaching equipment such as load blocks, shackles, and slings (see Figure 1).

Outriggers - extendible or fixed metal arms, attached to the mounting base, which rest on supports at the outer ends (see Figure 1).

Superstructure - the rotating upper frame structure of the machine and the operating machinery mounted thereupon (see Figure 1).

Swing - the rotation of the superstructure to facilitate the movement of loads in a horizontal direction about the axis of rotation. This can also be defined as the machinery involved in providing rotation of the superstructure.

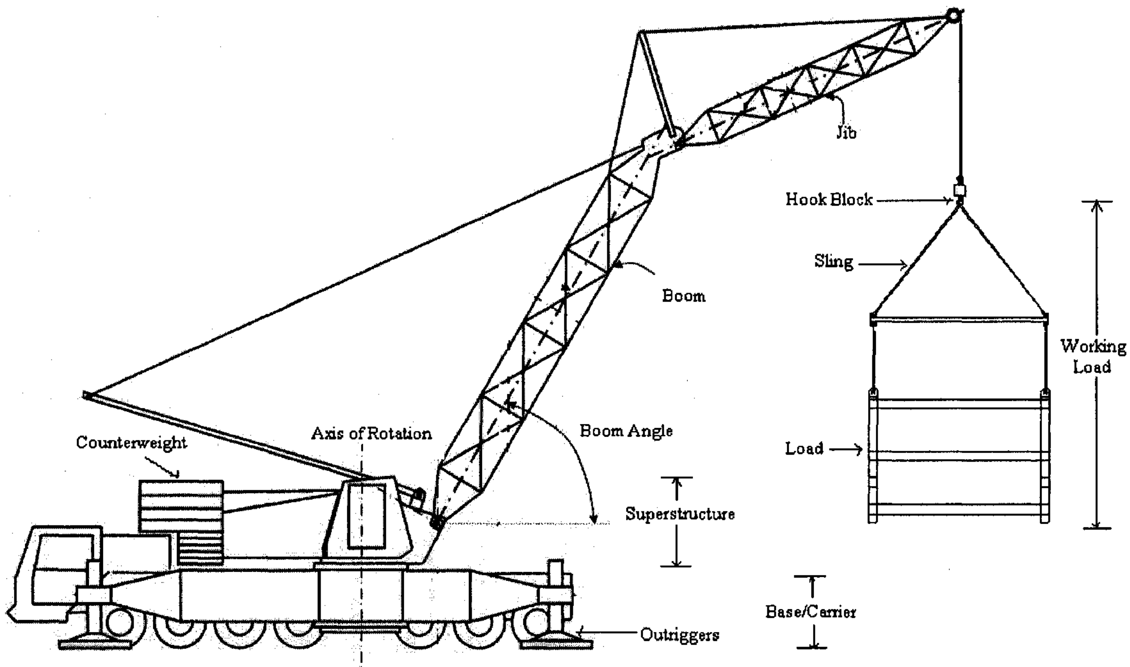

Figure 1. Mobile Crane Configuration

CHAPTER 1: INTRODUCTION

1.1 Research Motivation

Cranes are involved in many different tasks, and are one of the most heavily used and shared resources on construction sites (Liu 1995). An efficient crane operation can have a significant positive impact on the overall scheduling, cost, and safety of a construction project. According to a website tracking and documenting crane accidents (www.craneaccidents.com), 347 accidents occurred worldwide in 2007 alone, and already 119 accidents have been reported in 2008 so far (as of April 28, 2008). Braam (2002) has noted that a significant share of crane accidents have been caused by instability during crane operations. Instability accidents for mobile cranes have generally resulted either in the crane tipping or the load falling off the hook or slings. More broadly, the cause has been improper design, lack of a proper crane support system, or a faulty decision to carry a load which exceeds the lifting capacity of the crane. As such, it has become increasingly necessary to build a system which can design the supporting system for mobile cranes as well as check the operations against tipping failure and capacity constraints.

The process of analyzing and designing crane supporting systems for mobile cranes is a highly critical and time consuming process, due to the dynamic movement and the variation involved in the weight and geometric configuration of these cranes. Either poor design or improper crane selection will contribute to most of the crane accidents on construction sites, which contribute to over 84% of all worksite fatalities resulting from the improper use of cranes (Beavers et al. 2006). This implies that a successful crane operation requires pre-planning, including the arrangement of adequate crane support and risk-control measures with respect to crane stability.

Stability is one of the most important safety issues related to the use of mobile cranes. Dynamic loading related to crane motion and load are the key factors associated with the failure to maintain stability. The dynamic nature of mobile crane operations entails a variety of outrigger reaction values for truck cranes and track pressure values for crawler cranes; crane supporting reaction or pressure is a function of the lifting configuration, crane geometry, and the crane component's weight; in most situations, such information is not readily available, a condition which has an enormous impact on both safety and economy.

This research presents a newly developed automated system designed to aid practitioners in the process of preparing lift studies and designs for a mobile crane supporting system. The methodology has been built based upon the principles of limit state structural design in order to calculate the outrigger's reaction values for truck cranes as well as to calculate the values and display the shape of the reactions for crawler cranes. The developed methodology has been incorporated into a computer system, utilizing an algorithm developed previously for crane selection (see Al-Hussein 2005); this algorithm has been designed to assist practitioners in the selection of optimum cranes for construction sites. The developed methodology has also been integrated with the "D-Crane" (see Al-Hussein et al. 2000) and "Crane 2007" (developed by PCL), both of which are designed to house such information as the geometrics, weight, and lifting capacity of commercially available cranes. In addition, a reaction influence chart has been produced to show the dynamic relationship between a truck crane's outrigger reaction or a crawler crane's track pressure and the boom's horizontal swinging angles and vertical boom angles to the ground. The integrated system has been developed using MS-Visual Basic™. The unit of the developed system is metric; however, user can use imperial unit as the system has self contained unit changes.

1.2 Research Objectives

This research aims at developing computational methods and an algorithm to design a crane supporting system. The main objective of this research is summarized below:

- To build a computer program prototype in order to define the major element required to calculate the reaction forces for a mobile crane by means of a generalized formula and the establishment of a methodology which retrieves those elements from an existing database to design the crane supporting system.

- To select an optimum crane from the list of technically feasible cranes considering the capacity of the crane along with the operation configuration of the lifts.

- To allow engineers or construction managers to circumvent potential accidents and to help in reducing the time and cost associated with the design of lift studies for heavy and critical lifts on construction sites.

1.3 Research Methodology

The platform of a mobile crane can either be set on outriggers—denoted here as a truck crane, or on a crawler track—denoted here as a crawler crane. For the truck crane, a set of interactive forms has been developed to facilitate user friendly data entry for the user. The required input data has been divided into three categories: crane geometry, weight of crane components, and lifting load. The proposed methodology output is divided into two categories—outrigger reaction and support design—for both timber and steel plate. The program is developed such that it can generate a reaction influence chart which shows the reactions for each outrigger at varying horizontal swing angles and vertical boom angles to the ground. For the crawler crane, the main objective is to calculate the reaction under each track for loading configuration or calculate the pressure influence chart at varying horizontal swing angles and vertical boom angles to the ground, and then to design the supporting system accordingly. Although this research considers dynamic loading condition, but all the equations used to calculate the support reaction and design the support system are queasy static The research has been carried out using two databases, "D-Crane", which has been described elsewhere (Al-Hussein et al. 2000), and "Crane 2007", developed by PCL Industrial Constructors Inc.

1.4 Thesis Organization

The thesis is organized into six chapters; chapters 2-6 are outlined below:

Chapter 2 (Literature Review) includes a summary of the previous research related to lift planning and selection of cranes for construction. The application of simulation, database management, and 3D animation for mobile crane planning in the construction field are described in this chapter. The state of the art on mobile crane dynamic loading and stability are also discussed. Finally, this chapter summarizes the current practice as well as the factors to be considered in crane support design. **Chapter 3** (Proposed Methodology) presents the proposed methodology for crane supporting design and reaction calculations. The chapter first introduces the geometric information required for truck cranes and crawler cranes; the methodology to retrieve the data from the databases and input it into this system is presented in this section, followed by a description of the methods used in this research to calculate the reactions and design the support system. **Chapter 4** (Design Process) describes the development of the reaction calculation module, influence chart, and foundation design module. It explains the interrelationship between the proposed system and the databases used within this system. The chapter also describes the safety considerations to be taken into account in the design of this system. **Chapter 5** (System Performance) describes the performance of the newly developed crane support design system. Two case examples are described in this chapter in order to demonstrate the use of the presented algorithm practically using the "D-Crane" database and the "Crane 2007" database. This chapter also validates the performance of the algorithms and the developed system. **Chapter 6** (Conclusion and Recommendations) summarizes this work and outlines research contributions and some limitations. The chapter also lists several research directions which merit further investigation to broaden the application of this research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a summary of the previous research related to lift planning in the construction industry in the following areas: 1. Crane Selection Process; 2. Crane Database Management System; 3. 3D Animation; and 4. Crane Dynamics. This chapter also focuses on the various types of mobile cranes and their geometric configurations. Finally, it summarizes the current practice and the factors to be considered in the crane support design process.

2.2 Review of applications used in lifting study

Cranes maintain a central role in building projects, and mobile cranes in particular have dominated the North American market (Shapira et al. 2007). In the United States, the construction industry accounts for 19.4% of workplace fatalities and 12.3% of occupational injuries and illnesses, in spite of the fact that construction personnel represent only 4.8% of the U.S. workforce (Abudayyeh et al. 2003). Furthermore, generating workspaces that encapsulate spaces occupied by mobile cranes operations could serve to minimize delays associated with spatial conflicts and to reduce potential hazards on construction sites (Tantisevi and Akinci 2007). At present, planning for mobile crane operations is mostly performed intuitively and informally (Shapira and Glascock 1996). Knowledge-based expert systems have been used in construction for several years, although primarily for the purposes of equipment selection and site layout optimization (Lim et al. 2005, Chung 1999, Avseev et al. 1994, Alkass et al. 1993, Moselhi and Ghazal 1992, Alkass and Aronion 1990, Alkass and Harris 1988, Christian et al. 1987, Bernel 1986) and scheduling of construction activities (Shaked and Warszawski 1992, Alshawi and Jagger 1991, Moselhi and Nicholas 1990). Today, however, lift planning and crane selection are receiving considerable attention from practitioners and academics who wish to ensure safety and economy within the workplace.

2.2.1 Crane Selection Process Application in Construction

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), for instance, developed an optimization algorithm for the selection and location of mobile cranes on construction sites. Sawhney and Mund (2002) developed a prototype integrated crane selection tool, IntelliCranes, based on adaptive probabilistic neural networks, which assists in both crane type and crane model selection. Kamat and Martinez (2001) demonstrated that process-based simulation could be used to analyze crane operations by modeling the dynamic movement of cranes as well as the interaction between the crane and the lifted material during a given operation. A fuzzy logic approach to selecting the best crane type for a construction task from a list of selected crane types has also been established by Hanna and Lotfallah (1999).

2.2.2 Crane Database Management System

Relational database management systems (DBMSs) are widely used to model data using a simple table-type structure without having to predefine the inter-data-relations. Al-Hussein et al. (2000) developed a database designed to house information related to cranes, their geometric lifting configuration specifications, and their lifting capacities based on the information provided by manufacturers in 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).

2.2.3 Application of 3D Animation of Crane Operation in Construction

Where jobsites are tightly congested, using a series of 2D or 3D drawings helps engineers to select and plan for mobile cranes. A basic 4D Computer Aided Design (CAD) simulation model allows users to visualize the expected evolution of building structures during a given period of construction based on the schedule of activities. In specific, these drawings show where cranes are expected to be located at different periods of time during the construction process (Akinci et al. 2003). 3D visualization is helpful in the verification and validation of crane operations (Al-Hussein et al. 2006). Kamat and Martinez (2004) developed VITASCOPE for the purpose of generating and displaying 3D animations of the motion of pieces of equipment during construction based on a simulation model. Other modules involving 3D graphics and simulation for crane selection have been developed and referred to by Hornaday et al. (1993) and Dharwadkar et al. (1994). Sivakumar et al. (2003), finally, developed an approach for coordinating motions of multiple cooperative cranes during material lifting operations based on a robot path planning algorithm.

2.2.4 Research on Crane Dynamic Stability and Loading

The dynamic stability of a truck crane can be compromised for specified geometrical and load conditions (Sochacki 2007). Jerman (2006) proposed a mathematical model for investigating the dynamic loading of a slewing crane, and obtained the dynamic forces which act on the crane's steel structure during load transport. Not only do the structures of the crane and external loads determine the dynamic behavior of mobile cranes, but the body motion and drive system of the crane are also responsible for dynamic stability (Sun and Kleeberger 2003). Moreover, in order to reduce the dynamic effect on crane operation, the swing operation must be effectively controlled. In this regard, Klosinski (2005) developed a mathematical model of mobile crane operations in order to ensure minimization of crane swings. Also, Maczynski and Wojciech (2003) developed an optimization algorithm of drive functions for mobile crane slewing.

2.3 Current practice for crane support design

In practice, mobile cranes may become unstable as a result of rapid penetration of the outriggers into the ground (Tamate et al. 2005); accordingly, design of the crane support system has typically been carried out manually except in the case of the system developed by CRANIMAX®, which includes features such as 3D animation capability (http://www.cranimax.com). Chin et al. (2001) have demonstrated the causes of crane instability during payload motion, and have developed a mathematical algorithm for equilibrium and dynamic solutions of crane motion.

Crane support design is commonly carried out by the rental company or the general contractors or the third party; they use rules of thumb to calculate outrigger reaction and support design; including:

(Maximum Outrigger Load = Maximum Crane Capacity) for outrigger reaction and

(Minimum Pad Area = Maximum Crane Capacity (tons) / Allowable Soil Bearing Capacity) to calculate support size.

The maximum reaction of an outrigger cannot be greater than the crane's capacity; however, it is not economical to design support for a maximum reaction that may not act in all situations. It thus becomes important to calculate the exact reaction in each outrigger when the crane is in motion. Some geo-technical engineers use the traditional soil bearing capacity calculation for building foundation to design the crane mat. However, the duration of loading for a crane is relatively short and the allowable settlements for cranes are higher than building foundation (Liu 2005).

CHAPTER 3: PROPOSED METHODOLOGY

3.1 Introduction

The proposed methodology will be employed to analyze and design the supporting system for truck cranes and crawler cranes. The procedure for calculating the reactions and designing the support system will also be discussed in this chapter. There are three major 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 support system.

3.2 Type of Mobile Crane

The types of mobile cranes available vary due to the different types of booms (telescoping or lattice) and undercarriages (on wheeled or crawler-tracked) used. The basic types of mobile cranes are: Boom Truck, Carry Deck, Crawler, Mobile Conventional, Mobile Hydraulic, Rough Terrain, Sky Horse, Tower Crawler, Transi-Lift, and Traveling Ringer.

To simplify the reaction calculation process, in this research mobile cranes have been classified into two categories: truck crane and crawler crane. A crane is called a truck crane if the rotating superstructure of the mobile crane is mounted on a wheelbase (rubber) or outrigger base, and when the superstructure of the crane is mounted on a crawler carrier it is referred to as a crawler crane (see Figure 3.1).

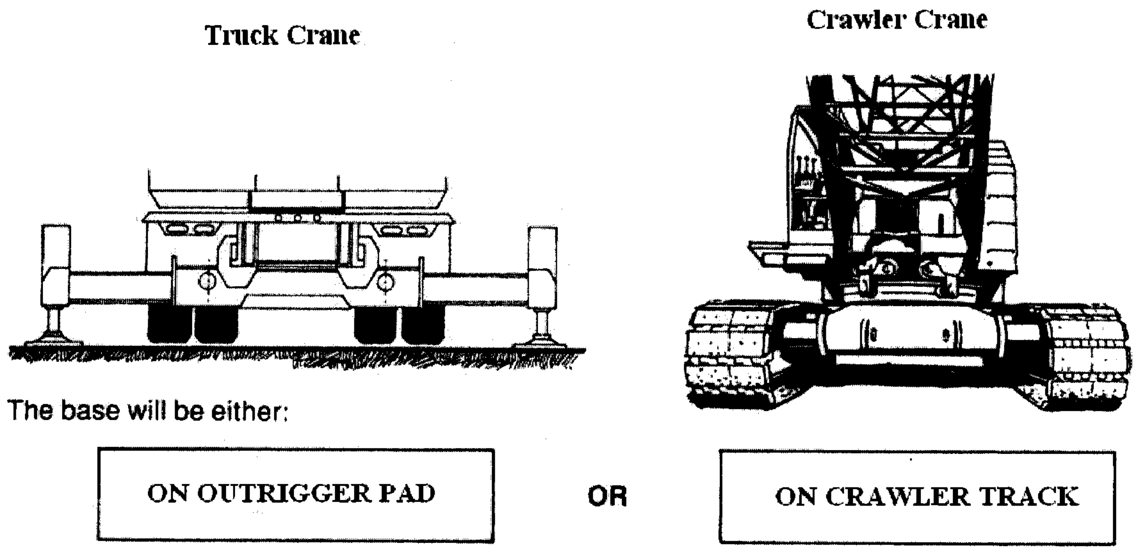

Figure 3.1 Crane on Outriggers (Truck Crane) or on Tracks (Crawler Crane)

3.3 Geometric Configuration

The geometric configurations needed to perform the calculations are not ordinarily given in the crane manufacturer's literature. Crane owners, users, or installation designers can, however, request needed data from the crane manufacturer. Unfortunately, manufacturers supply information about their cranes in inconsistent and paper-based formats. To address this deficiency, researchers have developed a database to replace and store the existing paper-based crane load charts and geometric information in a standardized computer-based format. In this research, the "D-Crane" and "Crane 2007" databases have been used to store information about crane geometry. Based on the type of crane under study, the geometric configuration module interacts with the crane database to retrieve the information. For the truck crane, the variables used in the analysis process are listed in Table 3.1 and are shown in Figures 3.2 and 3.3.

Table 3.1 Truck Crane Parameters

Type	Notation	Description
Constant Parameter	t	Distance between Boom pin and center of rotation.
	x_o	Distance between outrigger centerline and axis of rotation.
	d_t	Distance between outriggers in the transverse direction.
	d_l	Distance between outriggers in the longitudinal direction.
	θ	Boom angle to the ground
	W_r	Weight of the suspended hoist ropes, hook block and Slings.
	W_b, W_j	Weight of the boom & weight of the jib
	L_b and θ_b	Position of boom center of gravity (CG)
	J_j and μ_j	Position of jib CG
	L	Boom length
	W_{u1}, d_{u1}	Upper-structure weight & CG distance to center of rotation
	W_{u2}, d_{u2}	Counterweight weight & CG distance to center of rotation
	W_c, d_c	Carrier weight & CG distance to center of rotation
	W_m, d_m	Machine weight & CG distance to center of rotation
	W_a	Additional weight
	V	Total weight of the crane and the lifting load
User defined parameter	α	Boom horizontal swinging angle
	W	Weight of the lifted load
	R	Lifting radius
Calculated parameter	P_{fb}	Reaction of front outrigger on the boom side
	P_{fc}	Reaction of front outrigger on the counteract weight side
	P_{rb}	Reaction of rear outrigger on the boom side
	P_{rc}	Reaction of rear outrigger on the counteract weight side

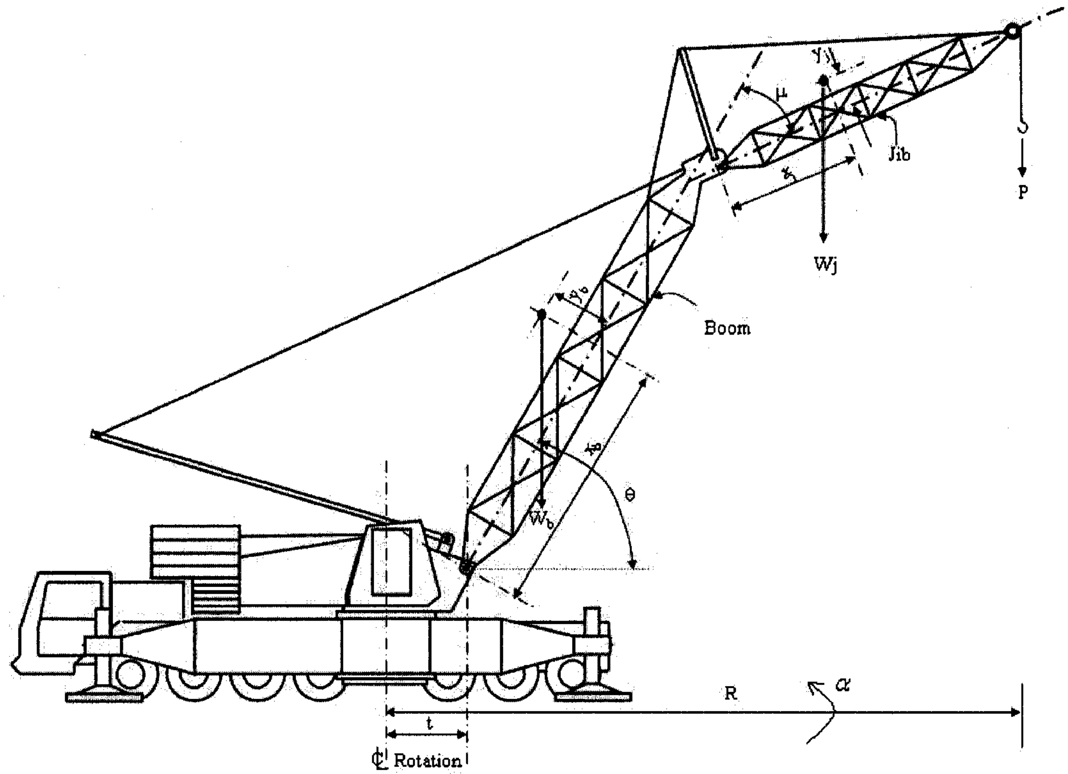

Figure 3.2 Truck Crane Parameters used in Reaction Calculation

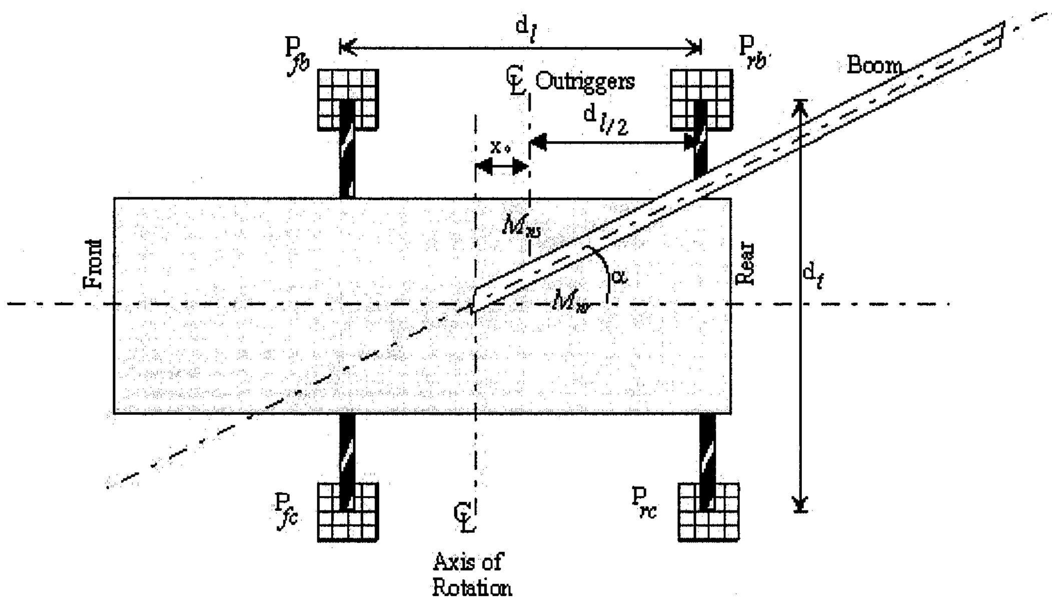

Figure 3.3 Plan view of a truck crane

For the crawler crane, the variables used in the analysis process are listed in Table 3.2 and are shown in Figures 3.4 and 3.5.

Table 3.2 Crawler Crane Parameters

Type	Notation	Description
Constant Parameter	t	Distance between Boom pin and center of rotation.
	x_o	Distance between outrigger centerline and axis of rotation.
	d_t	Distance between tracks in the transverse direction.
	d_l	Crawler bearing length.
	θ	Boom angle to the ground
	W_r	Weight of the suspended hoist ropes, hook block and Slings.
	W_b, W_j	Weight of the boom & weight of the jib
	L_b and θ_b	Position of boom center of gravity (CG)
	J_j and μ_j	Position of jib CG
	L	Boom length
	W_{u1}, d_{u1}	Upper-structure weight & CG distance to center of rotation
	W_{u2}, d_{u2}	Counterweight weight & CG distance to center of rotation
	W_c, d_c	Carrier weight & CG distance to center of rotation
	V	Total weight of the crane and the lifting load
User defined parameter	α	Boom horizontal swinging angle
	W	Weight of the lifted load
	R	Lifting radius
Calculated parameter	P_{max1}	Front track pressure on boom side
	P_{min1}	Rear track pressure on boom side
	P_{max2}	Front track pressure on counterweight side
	P_{min2}	Rear track pressure on counterweight side

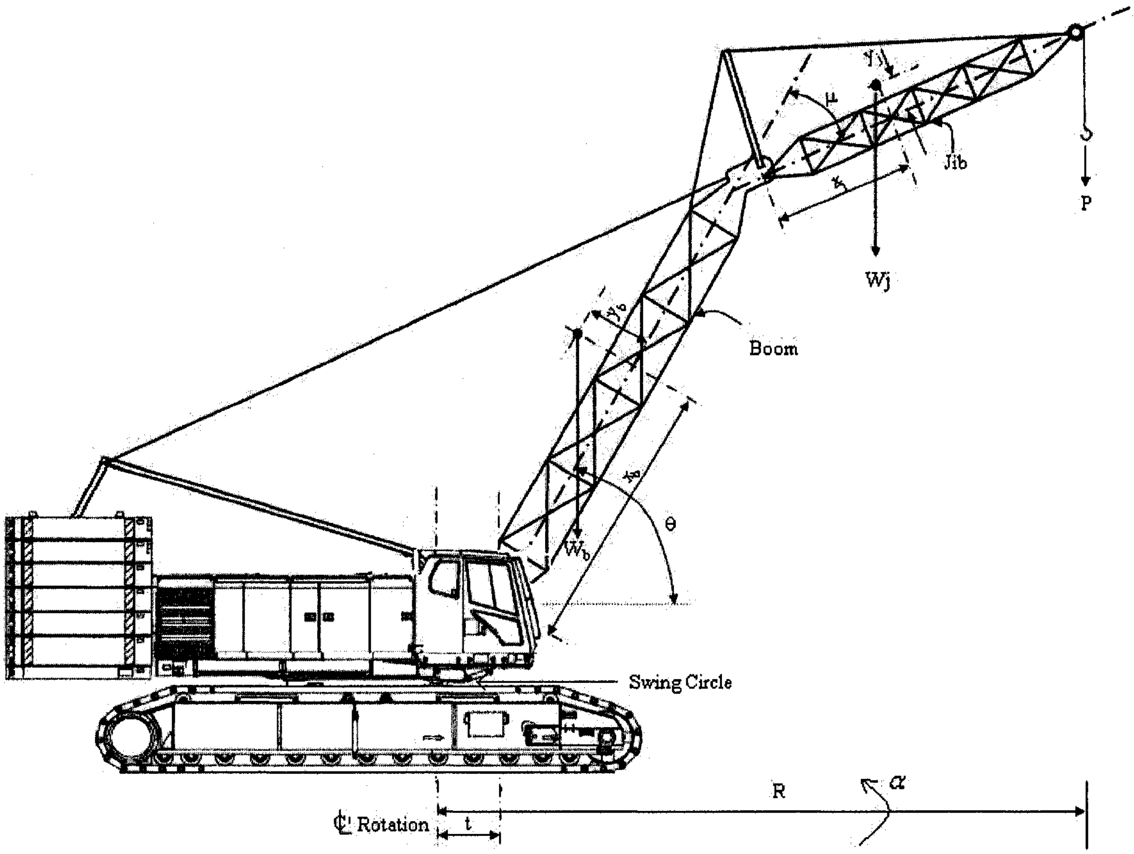

Figure 3.4 Crawler Crane Parameters used in Reaction Calculation

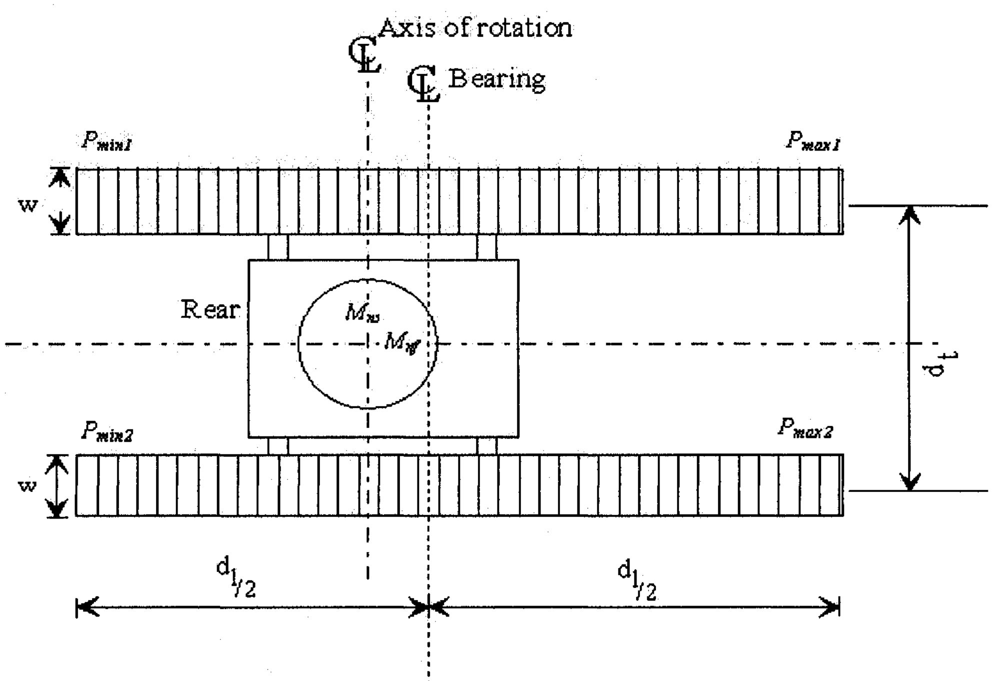

Figure 3.5 Plan View of Crawler Crane

Geometric information from D-Crane Database: Al-Hussein et al. (2000) developed the "D-Crane" database using Microsoft® Access in order to replace the existing paper-based load charts and information for cranes and accessories supplied by crane manufacturers with a more efficient standardized computer format. This database has also been incorporated into a computer system, the "Selectomatic" module, utilizing an algorithm developed for crane selection (see Al-Hussein 2005). The algorithm was initially designed to assist practitioners in the optimum selection of cranes for construction sites. The geometric information which is needed for the proposed methodology and may be retrieved from the "D-Crane" database includes: (1) Type of Crane; (2) Crane manufacturer name and model no.; (3) Distance between boom pin and center of rotation; (4) Distance between outriggers or tracks in the transverse direction; (5) Distance between outriggers in the longitudinal direction or Crawler bearing length; (6) Boom angle to the ground; (7) Weight of the suspended hoist ropes, hook block, and slings; (8) Boom length; (9) Jib offset; (10) Jib Length; (11) Counterweight; (12) Boom horizontal swing angle; (13) Weight of the lifted load; and (14) Lifting radius. At present, boom weight, jib weight, structure weight, carrier weight and center of gravity locations, and pad and track widths—all of which are required variables in the calculation of reactions to support design—are unavailable in the D-Crane database.

Geometric information from "Crane 2007" Database: The "Crane 2007" database has been developed by PCL Industrial Constructors Inc., a company based in Edmonton, Alberta. They have stored the geometric specifications, load information, and other data supplied by the manufacturer for 195 different cranes into this database using Microsoft® Access. The data needed for the proposed methodology and retrieved from "Crane 2007" include: (1) Type of crane; (2) Crane manufacturer name and model no.; (3) Distance between boom pin and center of rotation; (4) Distance between outrigger centerline and axis of rotation; (5) Distance between outriggers or tracks in the transverse direction; (6) Distance between outriggers in the longitudinal direction or crawler bearing length; (7) Outrigger pad or crawler track width; (8) Machine weight (total); (9) Distance of machine CG to axis of rotation; (10) Additional load; (11) Lift from main / jib / fly; (12) Lift quadrants; (13) Boom length; (14) Jib length; (15) Lifting radius; (16) Boom angle; (17) Jib offset; (18) Capacity; and (19) Weight of the lifted load. The reaction calculation module has been developed in such a way that no additional data about crane geometry is required in utilizing the "Crane 2007" database.

3.4 Reaction Calculation

Once the crane configuration has been added, the outrigger reaction can be calculated for the truck cranes and the track pressure for crawler cranes can dually be calculated. Furthermore, calculations can be made either at a single position or at multiple positions along the boom. For a single position, the reactions have been calculated for a specific boom angle and horizontal angle as well as 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 Figure 3.2 and 3.4). Reaction calculations can also be changed based on the data in the "D-Crane" and "Crane 2007" databases. Here, eight possible scenarios are defined based on the nature of the given lift and the geometric configuration as shown in Table 3.3.

Table 3.3: Reaction Calculation Scenarios

Scenario	Lifting Condition		
	Crane Type	Position	Database
1	Truck	Single	"D-Crane"
2	Truck	Multiple	"D-Crane"
3	Crawler	Single	"D-Crane"
4	Crawler	Multiple	"D-Crane"
5	Truck	Single	"Crane 2007"
6	Truck	Multiple	"Crane 2007"
7	Crawler	Single	"Crane 2007"
8	Crawler	Multiple	"Crane 2007"

Scenario 1: For the truck crane, the reactions for the four outriggers—two at the front, P_{fb}, P_{fc}, and two at the rear, P_{rb}, $P_{rc,}$ (see Figure 3.3)—are calculated satisfying Equations (1) to (4) (Shapiro et al.1991):

$$P_{fb} = \frac{V}{4} + \frac{1}{2}\left(\frac{M_{ns}}{d_t} - \frac{M_{nr}}{d_l}\right) \quad (1)$$

$$P_{fc} = \frac{V}{4} - \frac{1}{2}\left(\frac{M_{ns}}{d_t} + \frac{M_{nr}}{d_l}\right) \quad (2)$$

$$P_{rb} = \frac{V}{4} + \frac{1}{2}\left(\frac{M_{ns}}{d_t} + \frac{M_{nr}}{d_l}\right) \quad (3)$$

$$P_{rc} = \frac{V}{4} - \frac{1}{2}\left(\frac{M_{ns}}{d_t} - \frac{M_{nr}}{d_l}\right) \quad (4)$$

where V is the total vertical load, which is calculated satisfying Equation (5):

$$V = W_b + W_j + W + W_r + W_{u1} + W_{u2} + \mathrm{W}_c \quad (5)$$

The outrigger reaction values are a function of the respective weights of the lift and crane components and their moments around the center of rotation of the crane. These moments are divided into two categories according to the horizontal and vertical movements of the boom—one acting around the crane's sides M_{ns} and the other acting on the crane rear or front M_{nr} (see Figure 3.3). These moments are calculated satisfying Equations (6) and (7):

$$M_{ns} = M_u \sin \alpha \tag{6}$$
$$M_{nr} = M_u \cos \alpha - V_u x_o - W_c d_c \tag{7}$$

where M_u is the ultimate moment and V_u is the total movable vertical load, both of which can be calculated satisfying Equations (8) and (9):

$$M_u = W_b[t + L_b \cos(\theta + \theta_b)] + W_j[t + L\cos\theta + J_j \cos(\theta - \mu + \mu_j)] + (W + W_r)\mathrm{R} - \mathrm{W_{u1}d_{u1}} - \mathrm{W_{u2}d_{u2}} \tag{8}$$

$$V_u = W_b + W_j + W + W_r + W_{u1} + W_{u2} \tag{9}$$

Scenario 2: In the case of multiple positions, the reactions have been calculated for loaded and unloaded scenarios and for changing boom angles (θ) and swing angles (α) (see Figure 3.2). For changing swing angles (α) with a constant boom angle (θ), the reaction can be calculated using all of Equations (1) to (9). The crane can swing between 0° and 360°, and for each swing angle there will be four outrigger reaction values. For the changing boom angle to the ground (θ), sets of outrigger reaction values can be calculated satisfying Equations (1) to (9) for swing angles (α) between 0° and 360°. Cranes operating on a construction site are involved in lifting objects from the pick location and swinging them to their final destination; 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. In terms of loaded and unloaded conditions, only the weight of the lifted load changes. In the case of the unloaded condition, there is no load to be lifted, and in this case (W = 0).

Scenario 3: In the case of the crawler crane, the pressure under the tracks is more complex due to the extended contact area of the tracks with the ground. The various forces, in such a case, are presented based on the shape of their pressure diagram, which will vary from trapezoidal to triangular based on the given horizontal swing angle (α) (see Figure 3.4).

The moment of the boom with or without jib about the axis of rotation is calculated satisfying Equation (10):

$$M_{bj} = W_b[t + L_b \cos(\theta + \theta_b)] + W_j[t + L\cos\theta + J_j \cos(\theta - \mu + \mu_j)] \tag{10}$$

The ultimate moment about the axis of rotation above the swing circle (see Figure 3.4) of the crane is calculated satisfying Equation (11):

$$M_u = M_{bj} + (W + W_r)R - W_{u1}d_{u1} - W_{u2}d_{u2} \tag{11}$$

The ultimate vertical load (V_u) above the swing circle (see Figure 3.4) of the crane is calculated satisfying Equation (12):

$$V_u = W_b + W_j + W + W_r + W_{u1} + W_{u2} \tag{12}$$

As such, the total vertical load can be calculated satisfying Equation (13):

$$V = V_u + W_c \tag{13}$$

The moments around the center of rotation can be divided into two categories: M_{nf}, which is the moment applied at the center of the bearing, and M_{ns}, which is the moment portion acting over the side of the crane (see Figure 3.5). These values can be calculated satisfying Equations (14) and (15):

$$M_{nf} = M_u \cos\alpha - V_u x_o - W_c d_c \tag{14}$$

$$M_{ns} = M_u \sin\alpha \tag{15}$$

Due to the vertical load and moments around the center of rotation shown in Figure 3.5, pressure under the tracks can be divided into three categories. v, f_e, and f_s represent pressure due to vertical load, front or rear moment, and side moment, respectively, and can be calculated satisfying Equations (16), (17), and (18):

$$v = \frac{V}{2wd_t} \tag{16}$$

$$f_e = \frac{3M_{nf}}{w(d_t)^2} \tag{17}$$

$$f_s = \frac{M_{ns}}{wd_t d_t} \tag{18}$$

According to Shapiro et al. (1991), the track pressure diagram will assume either a trapezoidal or a triangular shape as shown in Figures 3.6 and 3.7. If $v + f_s > f_e$, then the pressure diagram is *trapezoidal* (see Figure 3.6).

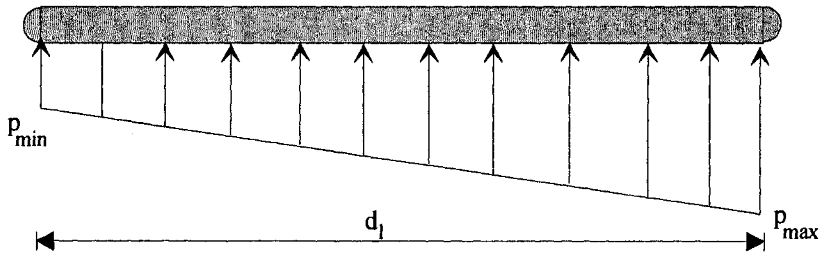

Figure 3.6 Trapezoidal Pressure Diagram under Crawler Track

The pressure for the track on the boom (load) side can be calculated satisfying Equations (19) and (20):

$$p_{\max 1} = v + f_s + f_e \quad (19)$$
$$p_{\min 1} = v + f_s - f_e \quad (20)$$

The pressure for the track on the counterweight side can be calculated satisfying Equations (21) and (22):

$$p_{\max 2} = v - f_s + f_e \quad (21)$$
$$p_{\min 2} = v - f_s - f_e \quad (22)$$

If $v + f_s < f_e$, then the pressure diagram in the triangular form over length l will appear as shown in Figure 3.7, and the side can be calculated satisfying Equation (23):

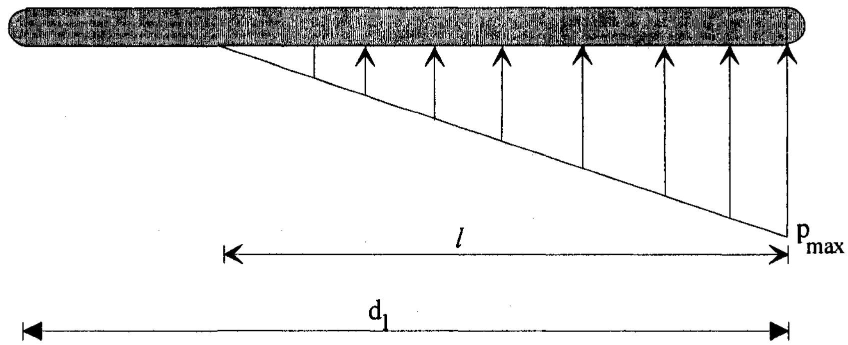

Figure 3.7 Triangular Pressure Diagram under Crawler Track

$$l = 1.5d_l - \frac{3M_{nf}}{V} \quad (23)$$

The pressure for the track on the load side (P_{max1}) (see Figure 3.5) can be calculated satisfying Equation (24):

$$p_{\max 1} = \frac{V + 2\left(M_{ns}/d_t\right)}{wl} \quad (24)$$

The pressure for the track on the counterweight side (P_{max2}) (see Figure 3.5) can be calculated satisfying Equation (25):

$$p_{\max 2} = \frac{V - 2\left(M_{ns}/d_t\right)}{wl} \quad (25)$$

Scenario 4: In the case of multiple positions, the pressures under the track have been calculated for loaded and unloaded scenarios and for changing boom angles to the ground (θ) and swing angles (α) (see Figure 3.4). For the changing swing angles condition, the pressure can be calculated satisfying Equations (10) to (25). Again, the crane can swing between 0° and 360°, and for each swing angle there will be pressure on each track. For the changing boom angle to the ground (θ), sets of track pressures can be calculated satisfying Equations (10) to (25) for swing angles (α) between 0° and 360°. With regard to loaded and unloaded conditions, only the weight of a lifted load changes, and in the case of unloaded condition, there will be no load to be lifted (W = 0).

Scenario 5: Using the "Crane 2007" database for the truck crane, the ultimate moment M_u and total vertical load V can be calculated satisfying Equations (26) and (27):

$$M_u = (W + W_r)R - W_m d_m \quad (26)$$

$$V = W + W_a + W_m \quad (27)$$

The moments acting around the crane sides M_{ns} and the crane rear or front $M_{nr.}$ are calculated satisfying Equations (28) and (29):

$$M_{ns} = M_u \sin \alpha \quad (28)$$
$$M_{nr} = M_u \cos \alpha - V x_o \quad (29)$$

The reactions for the four outriggers—two at front, P_{fb}, P_{fc}, and two at the rear, P_{rb}, P_{rc}—are calculated satisfying Equations (1) to (4), as described above.

Scenario 6: Using the "Crane 2007" database for multiple positions, the reactions have been calculated for loaded and unloaded scenarios and for changing boom angles (θ) and swing angles (α) (see Figure 3.2). For the changing swing angle condition the reaction can be calculated satisfying Equations (1) to (4) and Equations (26) to (29). Again, the crane can swing between 0° and 360°, and for each swing angle there will be four outrigger reaction values. A set of outrigger reaction values can be obtained for the changing boom angle to the ground (θ) satisfying Equations (1) to (4) and (26) to (29) for all swing angles between 0° and 360°. The swinging operation may occur in either a loaded or an unloaded condition.

Scenario 7: In this scenario, for the crawler crane the ultimate moment about the axis of rotation M_u and the total vertical load V can be calculated satisfying Equations (26) and (27), respectively.

The moment applied at the center of bearing M_{nf} and the moment portion acting over the side M_{ns} can be calculated satisfying Equations (30) and (31):

$$M_{nf} = M_u \cos\alpha - V\, x_o \tag{30}$$
$$M_{ns} = M_u \sin\alpha \tag{31}$$

In this scenario, pressure under the track can be calculated satisfying equations (16) to (25), as described in Scenario 3.

Scenario 8:

Using the "Crane 2007" database for multiple positions of crawler crane, the pressures under the track have been calculated for loaded and unloaded scenarios and for changing boom angles (θ) and swing angles (α) as described in Scenario 3, but also satisfying equations (16) to (25), (26) to (27), and (30) to (31).

3.5 Support Design

Once the outrigger reactions or track pressures have been calculated and the soil bearing capacity has been determined from the geo-technical soil report, the design of support can be performed. 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. 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. Depending on the material type and crane type, three possible scenarios can be defined (see Table 3.4).

Table 3.4: Support Design Scenarios

Scenario	Lifting Condition	
	Crane Type	Material Type
1	Truck	Timber
2	Truck	Steel
3	Crawler	Timber

Scenario 1: The timber design for a truck crane is performed based on the maximum values of reaction for all the conditions calculated in the previous section. This design can be carried out using the followings steps:

Step 1: Assume a trial timber size, such as 12 in. X 12 in. (300 mm. X 300 mm.).

where

The actual timber width (e) = 11.5 in.

The actual timber height (d) = 11.5 in.

Step 2: Calculate the number of timber lengths (n) required

If w is the pad-width of the outrigger, then

$$n = \frac{w}{e} \tag{32}$$

If b is the total width of the n no. timbers (see Figure 3.8) then:

$$b = n * e \tag{33}$$

Step 3: Calculate the bearing area

If P is the maximum reaction value of the outrigger and s is the soil bearing capacity, then the minimum permitted bearing area (A_{min}) is calculated satisfying Equation (34):

$$A_{\min} = \frac{P}{s} \tag{34}$$

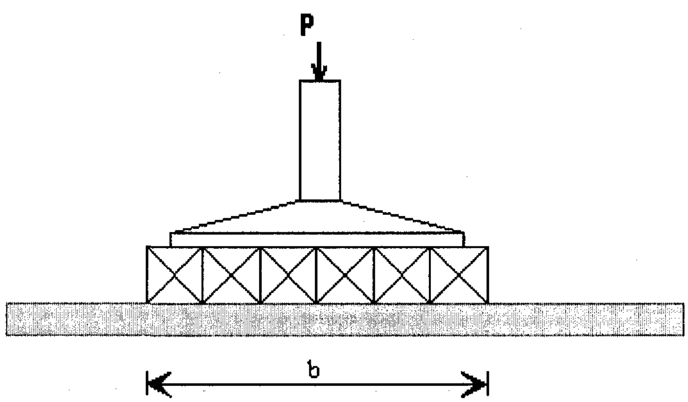

Figure 3.8 Width of Mat (b) under Outrigger Load

Step 4: Calculate timber length c (see Figure 3.10)

$$c = \frac{A_{\min}}{b} \tag{35}$$

Step 5: Check for timber bending stress

The overhanging length (a) (see Figure 3.9) can be calculated satisfying Equation (36):

$$a = \frac{c - w}{2} \tag{36}$$

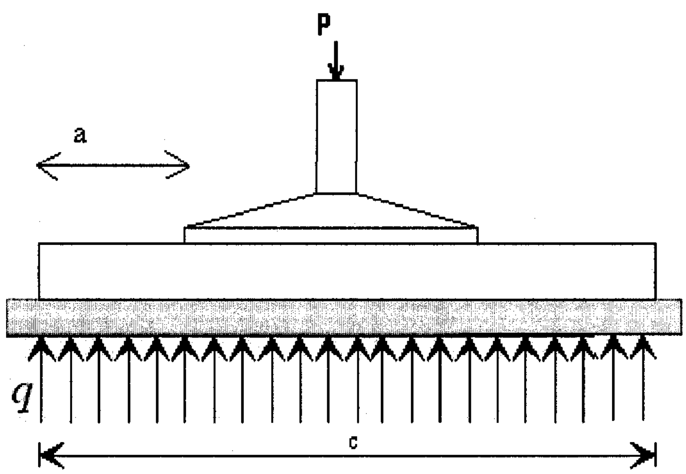

Figure 3.9 Length of Timber (c) and Overhanging Length (a) under Outrigger Load

The applied soil pressure q (see Figure 3.9) under the cribbing is then calculated satisfying Equation (37):

$$q = \frac{P}{bc} \tag{37}$$

According to Shapiro et al (1991), the bending stress (*f*) can be calculated satisfying equation (38).

$$f = \frac{3qa^2}{d^2} \tag{38}$$

The calculated bending stress (*f*), then, should be less than the allowable bending stress of the timber used. If *f* exceeds the allowable bending stress, then a greater timber size must be selected and checked for bending stress and shear stress.

Step 6: Check for shear stress

The horizontal shear stress *v* can be calculated satisfying Equation (39):

$$v = \frac{1.5qa}{d} \tag{39}$$

The calculated shear stress *v* should be less than the allowable shear stress of the timber used. Similarly, if *v* exceeds the allowable shear stress, then a greater timber size must be selected and checked for bending stress and shear stress.

Scenario 2: The steel plate design for a truck crane is performed based on the maximum values of reaction for all the conditions calculated in the previous section. This design can be carried out using the following steps:

Step 1: Calculate bearing area

If P is the maximum reaction of an outrigger and s is the soil bearing capacity, then the minimum permitted bearing area (A_{min}) is calculated satisfying Equation (40):

$$A_{\min} = \frac{P}{s} \tag{40}$$

where P and s are the maximum reaction of the outrigger and the soil bearing capacity, respectively.

Step 2: Determine plate size z

$$z = \sqrt{A_{\min}} \tag{41}$$

Step 3: Calculate plate thickness

The overhanging length (a) can be calculated satisfying equation (42):

$$a = \frac{c - w}{2} \tag{42}$$

The applied soil pressure q under the cribbing is then calculated satisfying Equation (43):

$$q = \frac{P}{bc} \tag{43}$$

The plate thickness d can then be calculated satisfying Equation (44) in order to calculate bending stress:

$$d = \sqrt{\frac{3qa^2}{f}} \tag{44}$$

where f is the allowable bending stress of the steel plate.

Scenario 3: The timber support design for a crawler crane is different from the timber support design for a truck crane due to the difference in the ground pressure applied by crawler cranes versus cranes on outriggers. Timber suppot design can be carried out using the following steps:

Step1: Assume a trial timber size and numbers forming a mat, such as four 12 in. X 12 in. timbers

where

The actual timber width $e = 11.5$

The actual timber height $d = 11.5$

Step 2: Calculate the width of the mat b

$$b = n * e \tag{45}$$

where n is the number of timbers forming a mat.

Step 3: Calculate maximum load on the mat

If P_{max} accounts for the maximum pressure on the track for all the conditions described in previous sections, P_{min} is the corresponding minimum pressure, and l is the length of zero pressure or track length (whichever is minimum), then the pressure at the lower pressure edge of the mat P_b is calculated satisfying Equation (46):

$$P_b = P_{max} - b\left(\frac{P_{max} - P_{min}}{l}\right) \tag{46}$$

and the maximum load on the mat P can be calculated satisfying Equation (47):

$$P = wb\left(\frac{P_{max} + P_b}{2}\right) \tag{47}$$

where w is the crawler track width.

Step 4: Calculate bearing area

If s is the soil bearing capacity then the minimum permitted bearing area A_{min} is calculated satisfying Equation (48):

$$A_{min} = \frac{P}{s} \tag{48}$$

Step 4: Calculate timber length

If c is the timber length where the soil pressure is acting, then c can be calculated satisfying Equation (49):

$$c = \frac{A_{min}}{b} \tag{49}$$

And the overhanging length a is calculated satisfying Equation (50):

$$a = \frac{c - w}{2} \tag{50}$$

The minimum length of the mat L required (see Figure 3.10) can be calculated satisfying Equation (51):

$$L = d_t + c \quad (51)$$

where d_t is the distance between tracks in the transverse direction.

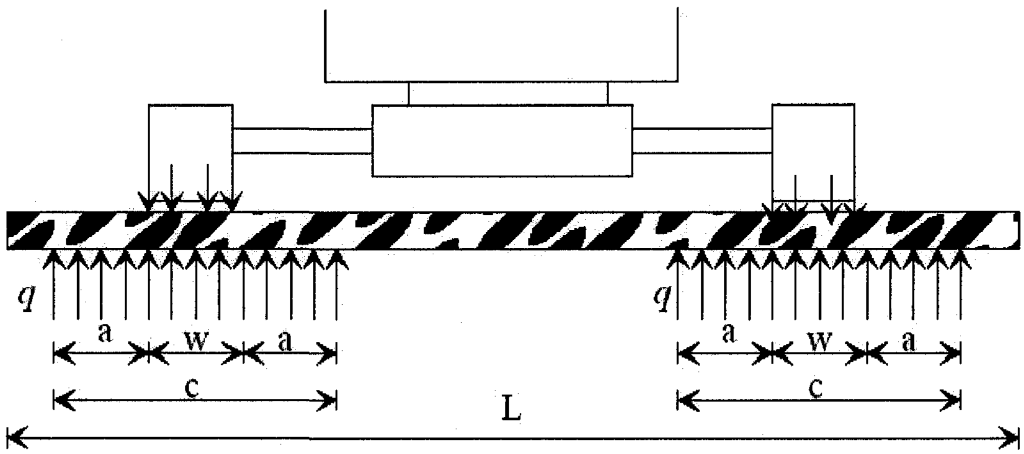

Figure 3.10 Mat or Timber Length (L) under Crawler Track Pressure

Step 5: Check for timber bending stress

The applied soil pressure q under the cribbing is calculated satisfying Equation (52):

$$q = \frac{P}{bc} \quad (52)$$

According to Shapiro et al. (1991), the bending stress f can be calculated satisfying Equation (53):

$$f = \frac{3qa^2}{d^2} \tag{53}$$

The calculated bending stress *f* should be less than the allowable bending stress of the timber used. If *f* exceeds the maximum allowable bending stress, then either a greater timber size must be selected or the number of mat layer should be increased.

Step 6: Check for shear stress

The horizontal shear stress *v* can be calculated satisfying Equation (54):

$$v = \frac{1.5qa}{d} \tag{54}$$

The calculated shear stress *v* should be less than the allowable shear stress of the timber used. If *v* exceeds the maximum allowable shear stress, then again either a greater timber size must be selected or the number of mat layer should be increased.

CHAPTER 4: DESIGN PROCESS

4.1 Introduction

This chapter summarizes the process used to develop a computer integrated system for mobile crane support design. It also describes the development of the reaction calculation module, influence chart, and foundation design, and explains how the module is incorporated with the "D-Crane" (Al-Hussein et al. 2000) and "Crane 2007" databases.

4.2 System Architecture

This system is comprised of the following four components: (1) processing modules; (2) central database; (3) design criteria; and (4) system output (see Figure 4.1). The focus of this research will be on the processing modules, which include crane selection, reaction calculation, and foundation design. The crane selection module, which has been designed by Al-Hussein et al. (2001) to assist practitioners in selecting optimum crane configurations for a given project, is used here to provide the input for the type and size of the crane to be used in the analysis. The "Crane 2007" database designed by PCL Industrial Constructors Inc. is also briefly discussed here in relation to its involvement with the work presented in this research. 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, and the foundation design module assists in designing the support foundation using either steel plates or timber. The design characteristics of both timber and steel plates are retrieved from the supporting material database.

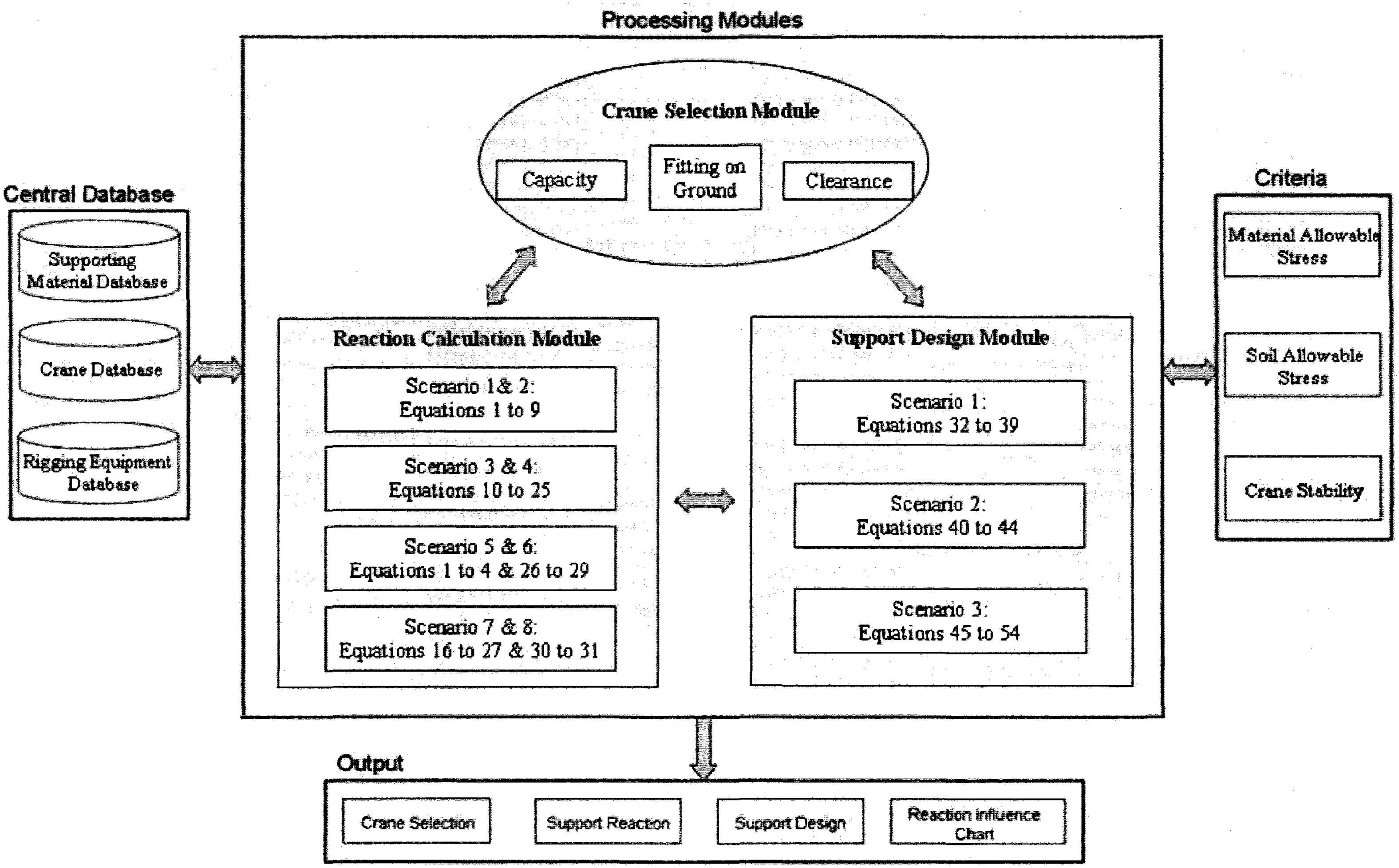

Figure 4.1 Main System Components

The central database includes the following three subsidiary databases: (1) supporting material database, (2) crane database, and (3) rigging equipment database. The supporting material database stores information about timber cross-section properties such as (1) standard dressed size (S4S); (2) cross-section areas; and (3) moments of inertia, as well as information related to material strength, including (1) timber type (name); (2) allowable bending stress; and (3) allowable shear stress. A crane database has been employed here in order to retrieve the geometric information for the selected crane, and two types of crane databases have been specifically mentioned here due to their pertinence to this research: (1) "D-Crane", which has been described elsewhere in the scholarship (Al-Hussein et al. 2000) and (2) "Crane 2007", developed by PCL Industrial Constructors Inc.

The design process is based upon the following criteria: (1) material allowable stress for the material selected for the support 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., the probability that tipping will occur). The design output includes the following four components: (1) crane selection, where the user is provided with a list of technically feasible cranes based on the analysis used in the crane selection module of all the cranes stored in the crane database; (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 support 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 swing angle when the operator is required to rotate the boom horizontally as well as vertically. This research focuses on the process used to automate the crane support system design, including the foundation design module and the reaction calculations module. In the design of the crane support the developed computer system presents four different options: (1) Truck Crane; (2) Crawler Crane; (3) "D-Crane" Selection Mode; and (4) "Crane 2007" Database Mode (see Figure 4.2).

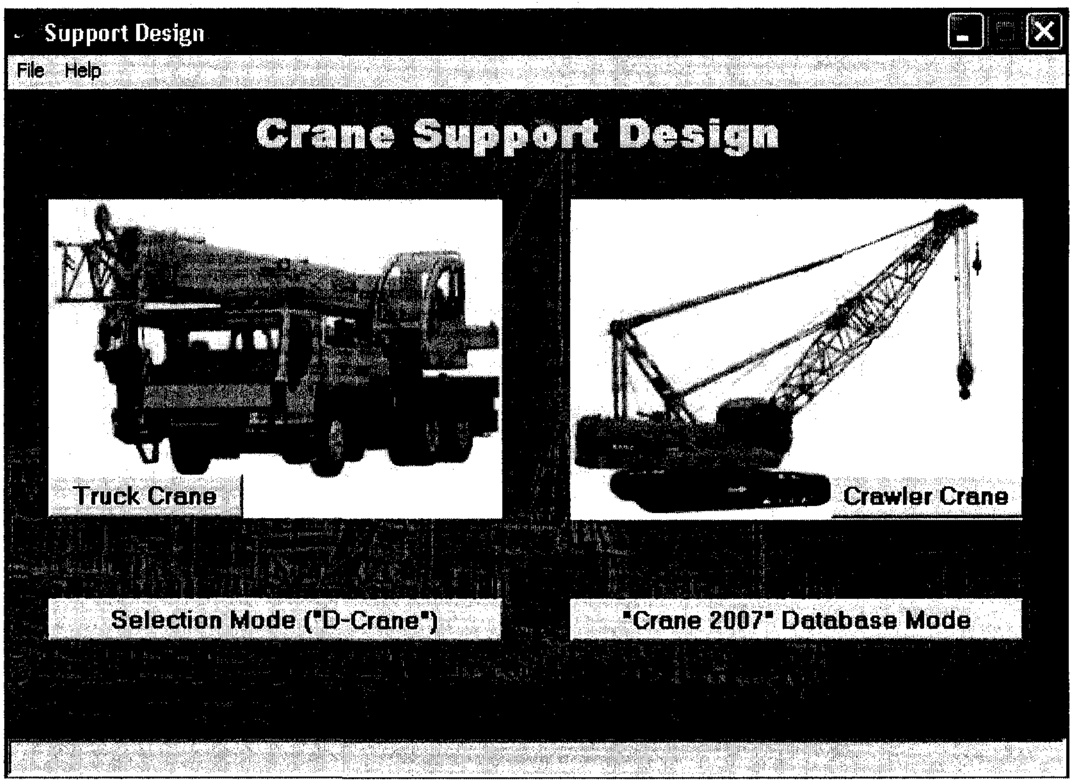

Figure 4.2 Crane Support Design Modes

4.3 Truck Crane Supporting System Design Mode

Figure 4.3 illustrates the process used in the proposed system. The user must provide the crane geometry and lifting configuration inputs in this design mode. If the user wants to input the truck crane configuration either from the crane manufacturer's manual or from any other source besides the "D-Crane" and "Crane 2007" databases, then this design mode is the best option since this mode is not linked to any database. The reaction calculation module interacts with the user inputs in terms of (1) the crane's dimensions; (2) the geometric location of the respective centers of gravity of the crane's components; and (3) the respective weights of the crane's various components (see Figure 4.4), which in turn are used in the algorithm to calculate the outrigger's reactions. 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.

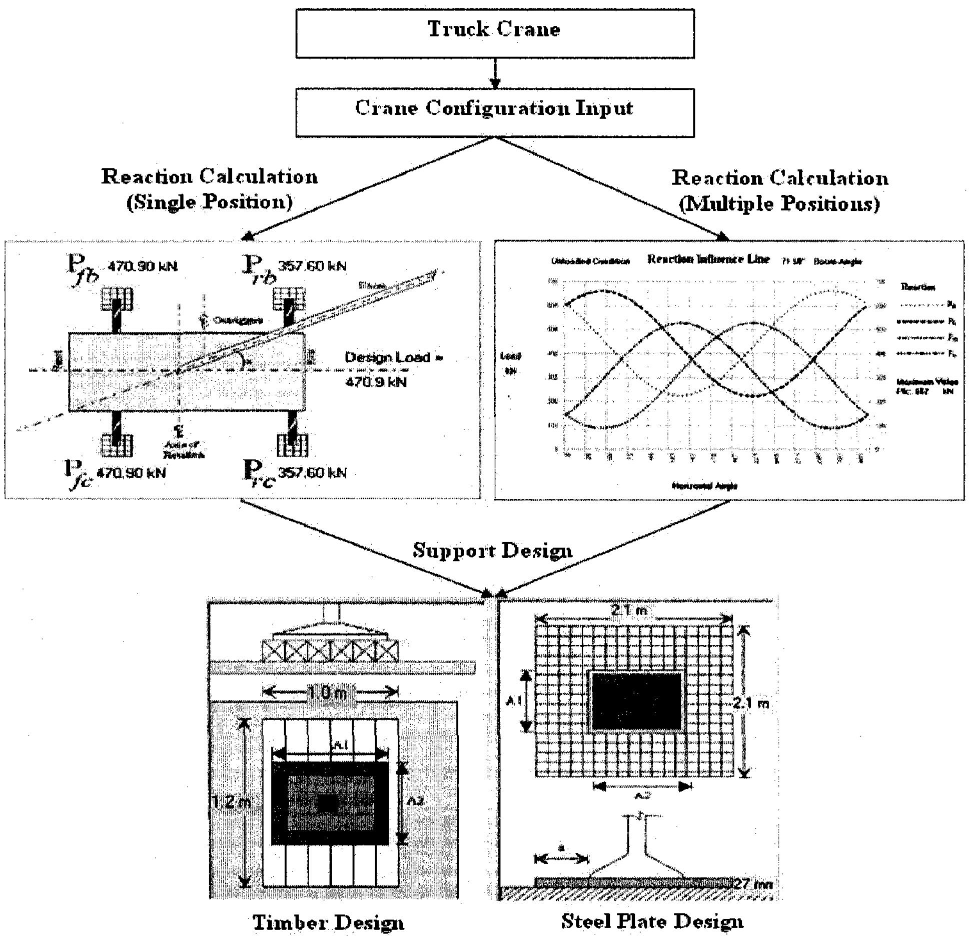

Figure 4.3 Truck Crane Supporting System Algorithm

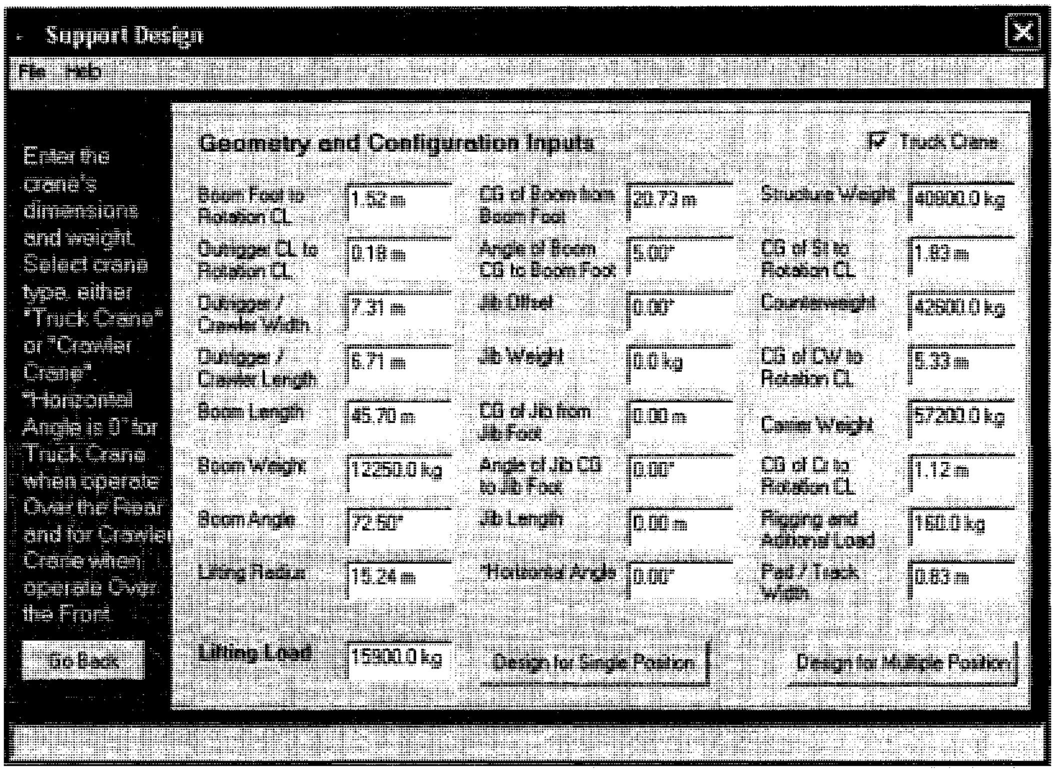

Figure 4.4 Truck Crane Geometry and Configuration Inputs Form

Scenario 1: Design for Single Position

For a single position, the reactions have been calculated for a specific boom angle and horizontal angle and for a specific load. For the truck crane, reactions have been displayed for the four outriggers at a particular position of the crane as shown in Figure 4.5.

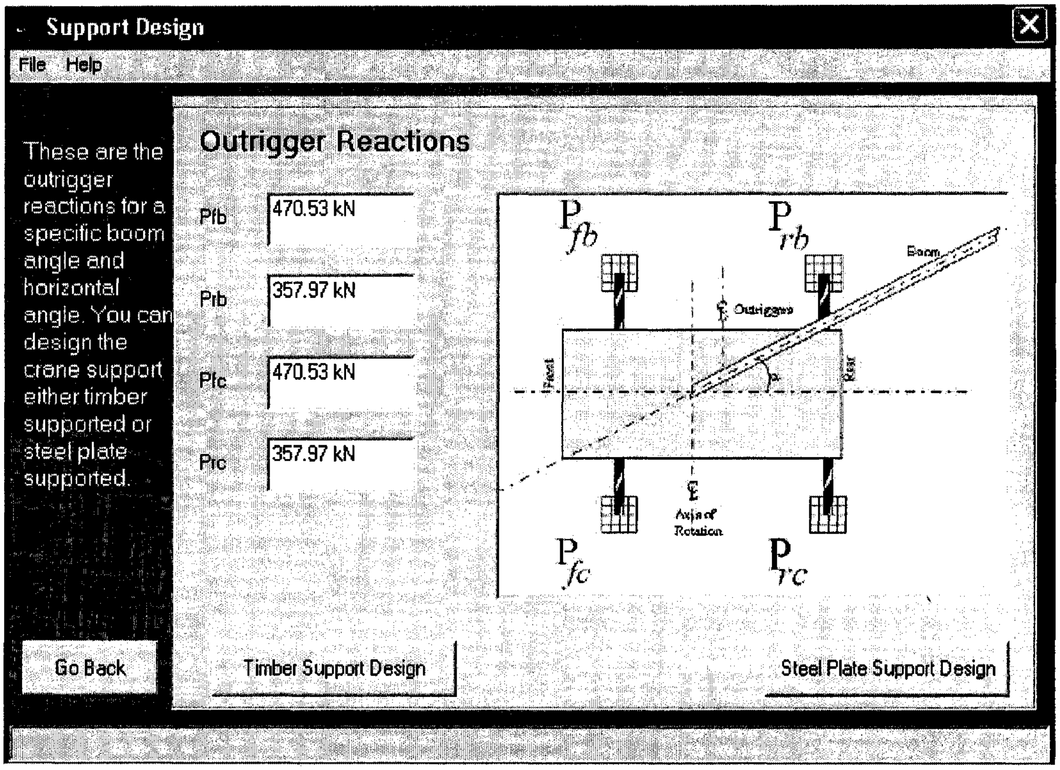

Figure 4.5 Outrigger Reactions in Single Position

The design of a support system for a truck crane can be accomplished using either timber or steel plates. The design is performed based on the maximum values of forces for all outrigger reactions calculated in the previous step. In the case of a timber design, the user is prompted to select a timber type and sectional dimensions and to enter the soil bearing capacity. 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 includes: (1) the length of timber required; (2) timber mat width; (3) the number of layers; and (4) the quantity of timber to be used in each layer. The stress output includes bending and shear stresses, which are displayed in the model as shown in Figure 4.6. 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 the type of failure, whereby the user is presented with the option to either increase the timber size, select another timber type, or reinforce the soil.

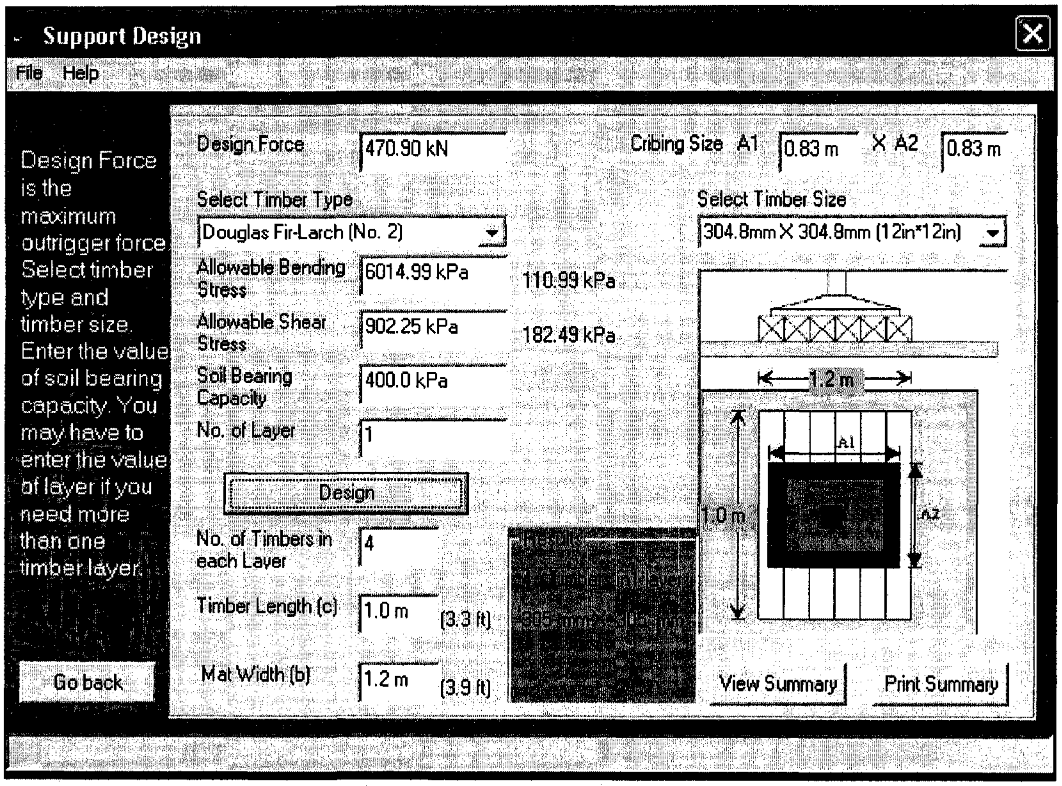

Figure 4.6 Timber Support Design for Truck Crane

The steel plate design is limited to the truck crane in this research. 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 (see Figure 4.7).

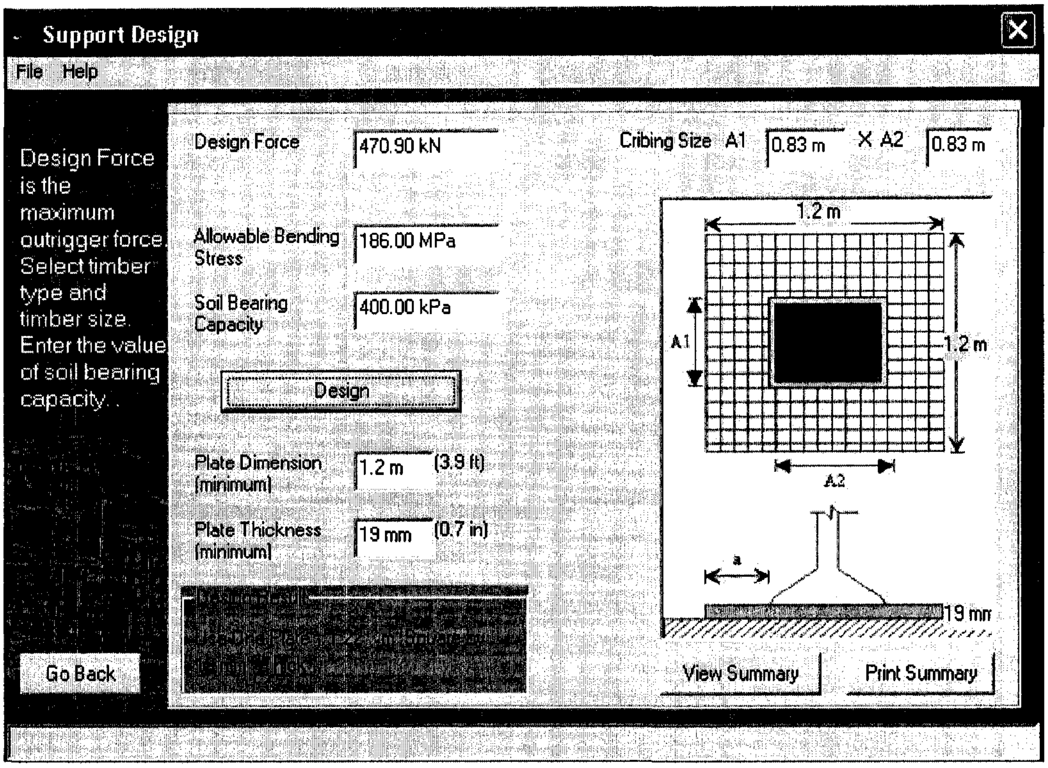

Figure 4.7 Steel Plate Design for Truck Crane

Scenario 2: Design for Multiple Positions

For multiple positions, the reactions have been calculated for loaded and unloaded scenarios and for both changing boom angles θ and changing swing angles α (see Figure 3.2). The user is given the option to specify the start and end swing angles α and the required increments of change for these angles; the user can also change the angle of the crane boom to the ground θ, specifying the minimum and maximum boom angle to be at the ground and the required increments of change of these angles as shown in Figure 4.8. A reaction influence chart for a 360° field of swing angles α in increments predetermined by the user has been integrated into the system in order to illustrate the variability in the outrigger's reaction with respect to a change in swing angle α over 360° for each boom angle to the ground θ and for either loaded or unloaded condition (see Figure 4.8). The reaction influence chart will change with either a change in boom angle (horizontal and vertical) or a change between loaded and unloaded condition.

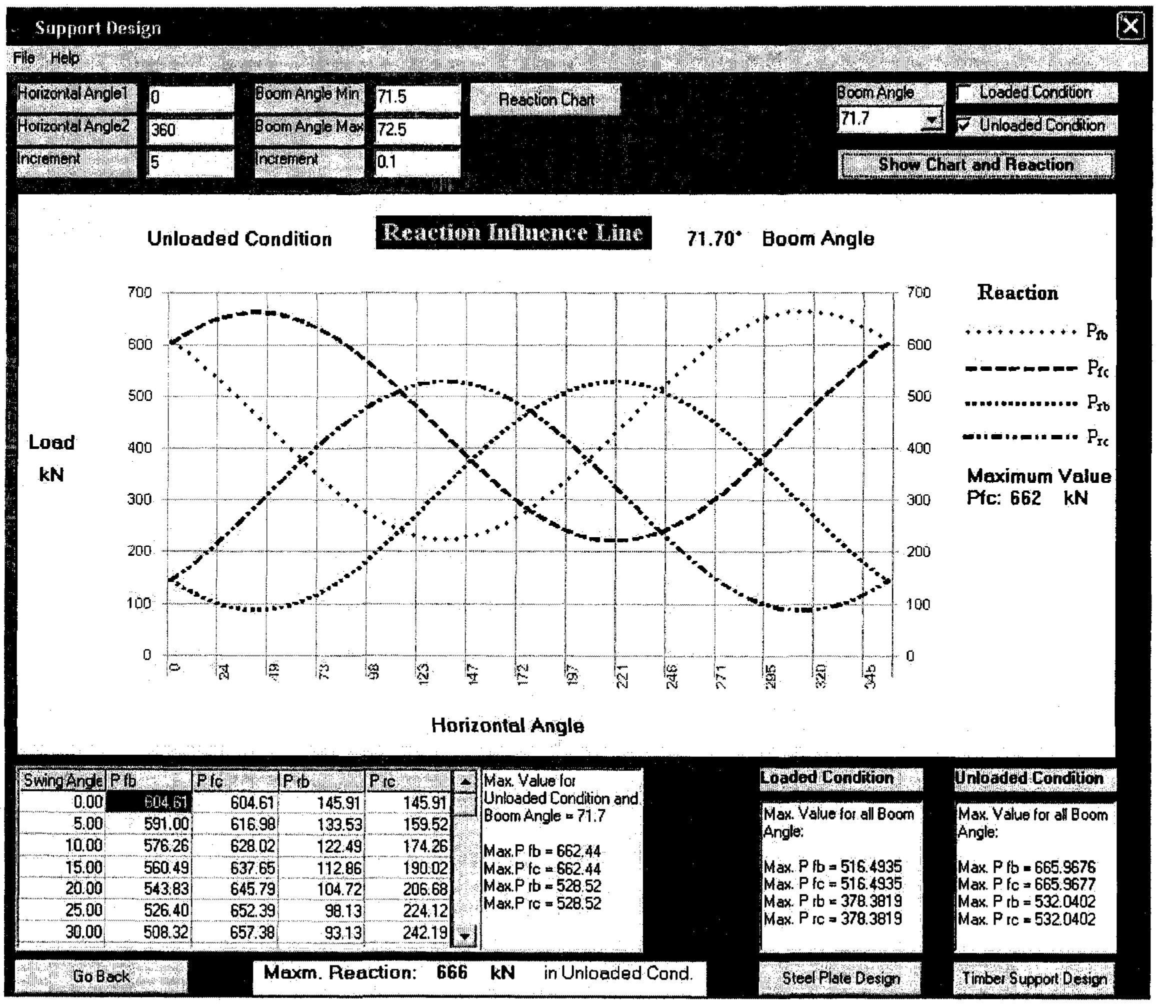

Figure 4.8 Reaction Influence Line for Truck Cranes at Multiple Positions

The chart shown in Figure 4.8 is an extension of the outrigger reaction calculations, and it provides the user with the following information: (1) a global view of the pattern of reaction values for 0° to 360° swings; (2) the horizontal boom position associated with a particular potential for tipping failure; and (3) the maximum values for an outrigger's reaction with respect to the boom's horizontal position (swing angle), boom angle to the ground, and loaded versus unloaded condition. These charts are generated automatically based on either the default values or the user inputs. 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, for reference, below the influence chart as shown in Figure 4.8. Also, the unsafe rotation is highlighted in that table for any case in which the outrigger reaction becomes negative. The user can also view the maximum reaction value for each outrigger with respect to all swing angles and boom angles to the ground for loaded and unloaded condition. Again, the user can view the load distribution in each outrigger (see Figure 4.9) for any swing angle by selecting any of the swing angles in the table.

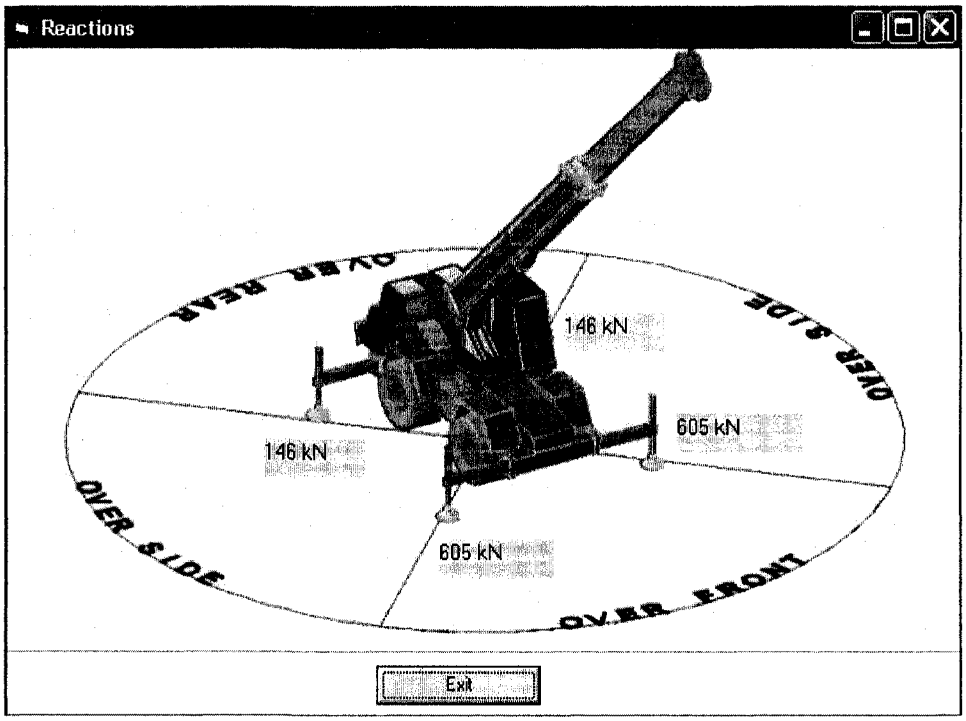

Figure 4.9. Load Distribution in Each Outrigger

The support design is performed for multiple positions based on the maximum reaction values for all the boom angles and swing angles and for loaded and unloaded conditions as addressed in the previous step. The design of a support system for a truck crane can be accomplished using either timber or steel plates and can be designed using the same forms as described for the single position (see Figure 4.6 for timber support design and Figure 4.7 for steel plate design).

4.4 Crawler Crane Supporting System Design Mode

Figure 4.10 illustrates the process used in the proposed system. The user must provide the crane geometry and lifting configuration inputs as shown in Figure 4.11. This design mode is the best option if the user wants to input the crawler crane configuration from the crane manufacturer's manual or any other source besides the "D-Crane" and "Crane 2007" databases. 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.

Scenario 1: Design for Single Position

For a single position, the track pressure has been calculated for a specific boom angle and horizontal angle and for a specific load. The reaction calculation module determines the pressure under the tracks in the case of the crawler crane (see Figure 4.12).

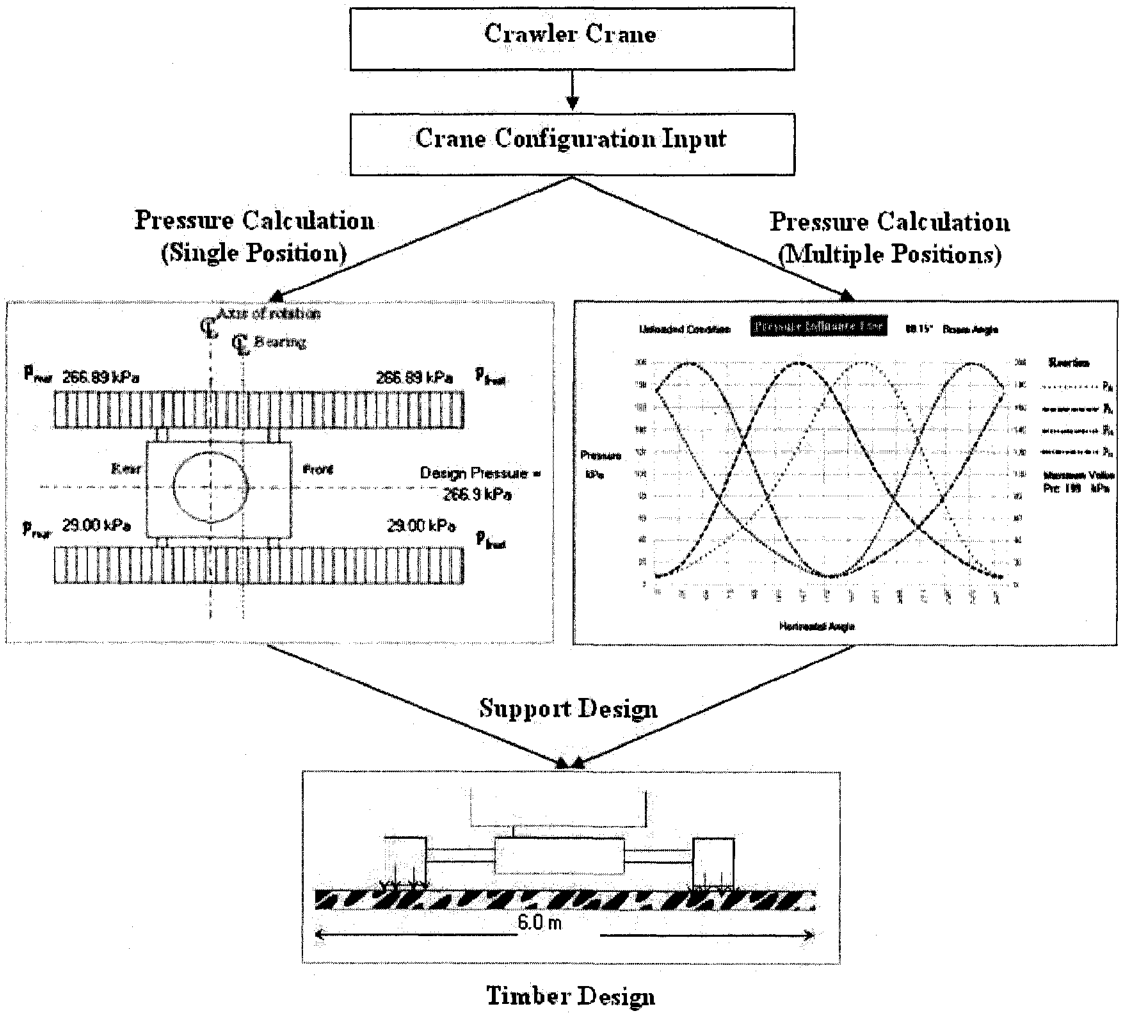

Figure 4.10 Crawler Crane Supporting System Algorithm

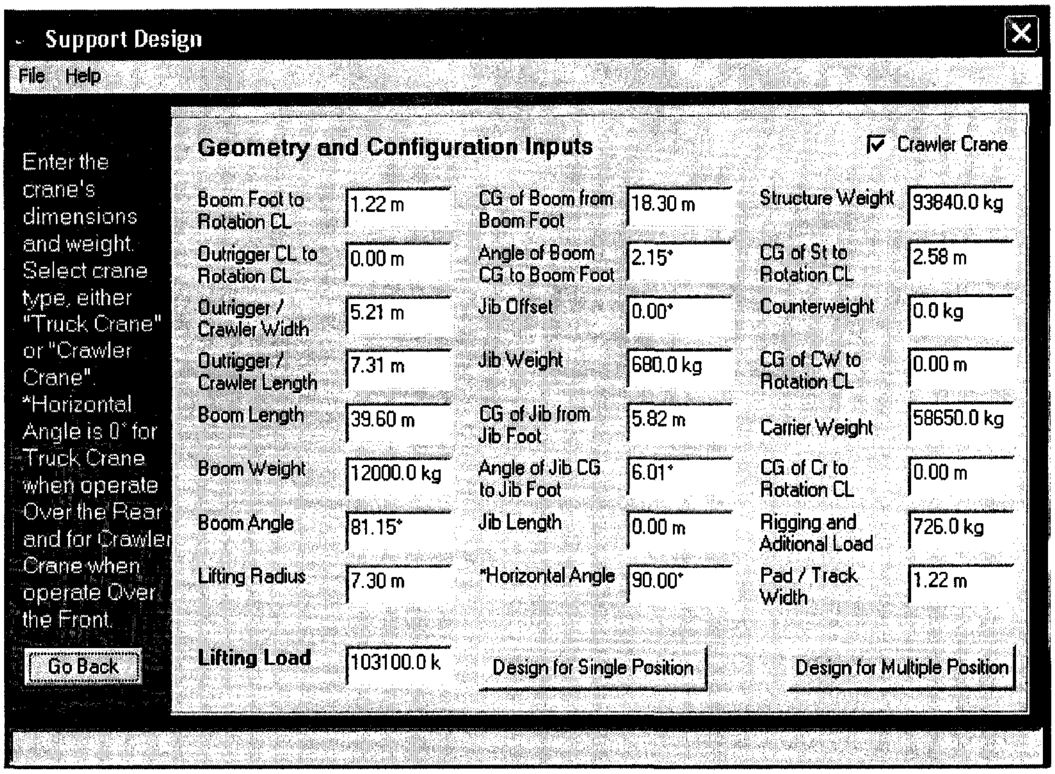

Figure 4.11 Crawler Crane Geometry and Configuration Inputs Form

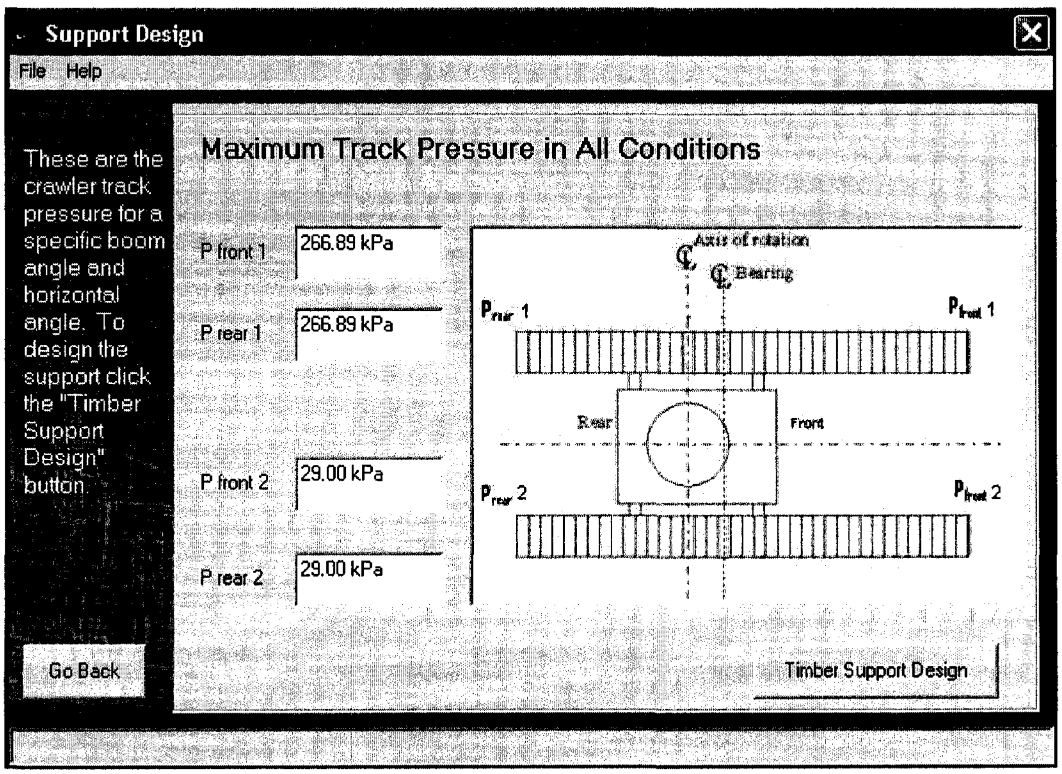

Figure 4.12 Crawler Tracks Pressure in Single Position

The design of a support system for a crawler crane can be achieved using timber mats. The user is prompted to select a timber type and sectional dimensions, and to enter the soil bearing capacity. The geometric output will be different for a crawler crane (on tracks) than for a truck crane (on outriggers), however. For the crawler crane, the geometric output includes (1) the mat width; (2) the length of mat required; (3) the total number of mats in each layer; (4) the number of layers required and (5) the quantity of timber to be used in forming a mat where a mat is a group of timbers, usually four 12 in. X 12 in. and bolted together to form a unit. The stress output includes bending and shear stresses, displayed in the model as shown Figure 4.13. Both stresses are compared with the maximum allowable stress for the selected type of timber, and the result is highlighted along with the type of failure in the case of potential failure.

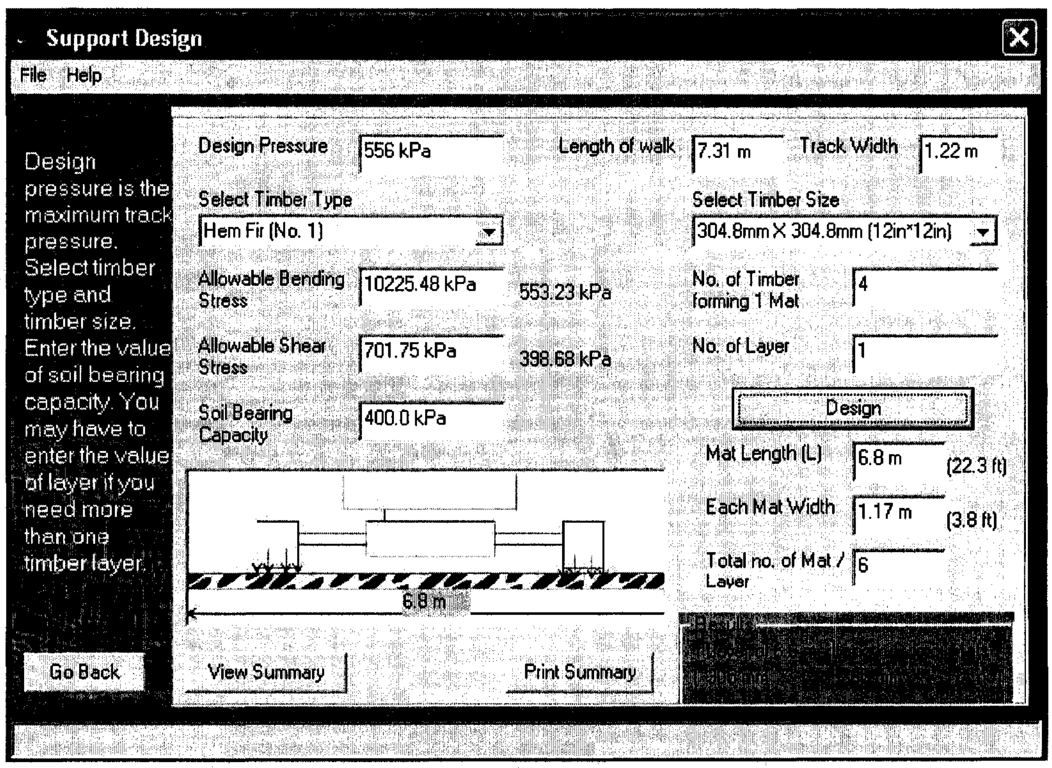

Figure 4.13 Timber Support Design for Crawler Crane

Scenario 2: Design for Multiple Positions

For multiple positions, the track pressure has also been calculated for both loaded and unloaded crane and for changing horizontal swing angles α and vertical boom angles θ. These pressures are presented in a similar influence chart and table to those used for truck crane (see Figure 4.14).

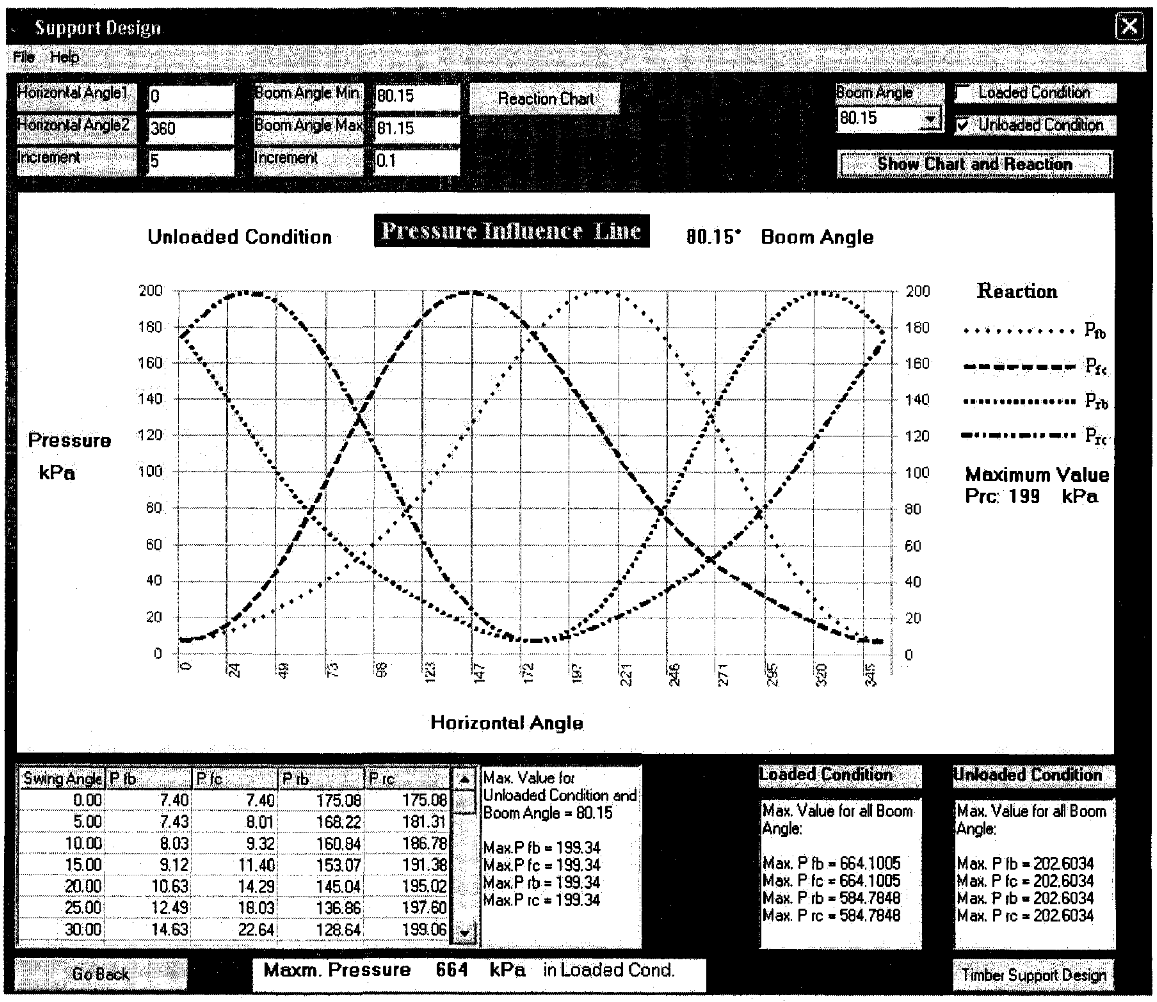

Figure 4.14 Pressure Influence Line for Crawler Cranes at Multiple Positions

The user can view the pressure distribution in each crawler track for any horizontal swing angle (as shown in Figure 4.15) by simply selecting and clicking on any of the swing angles in the table under the influence chart as shown in Figure 4.14. When any track pressure becomes negative the rotation is highlighted in this table indicating that tipping may occur.

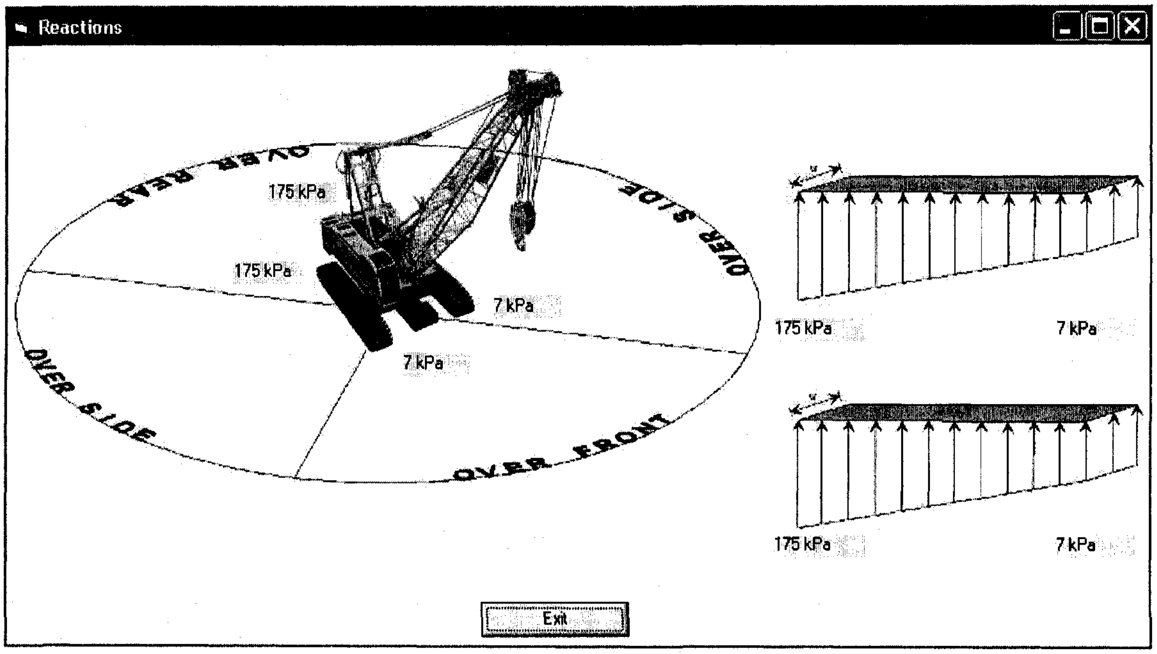

Figure 4.15 Pressure Distributions in Each Track

The support design is performed for multiple positions based on the maximum pressure values for all boom angles θ and swing angles α and for loaded and unloaded conditions calculated in the previous step. The support design for a crawler crane can be accomplished using timber mats and can be designed using the same process as described for a single position (see Figure 4.13).

4.5 Integrating Crane Supporting Design with "D-Crane" Selection Module

Figure 4.16 illustrates the process used in the proposed system. As mentioned, the design process has been incorporated into a computer system, "Selectomatic", utilizing an algorithm already developed for crane selection (see Al-Hussein 2005);

this algorithm has been designed to assist practitioners in the optimization of crane selection for construction sites. In order to design the crane support, a crane must be selected to perform the lift configuration through the "Selectomatic" software from a list of all technically feasible cranes as shown in Figure 4.17.

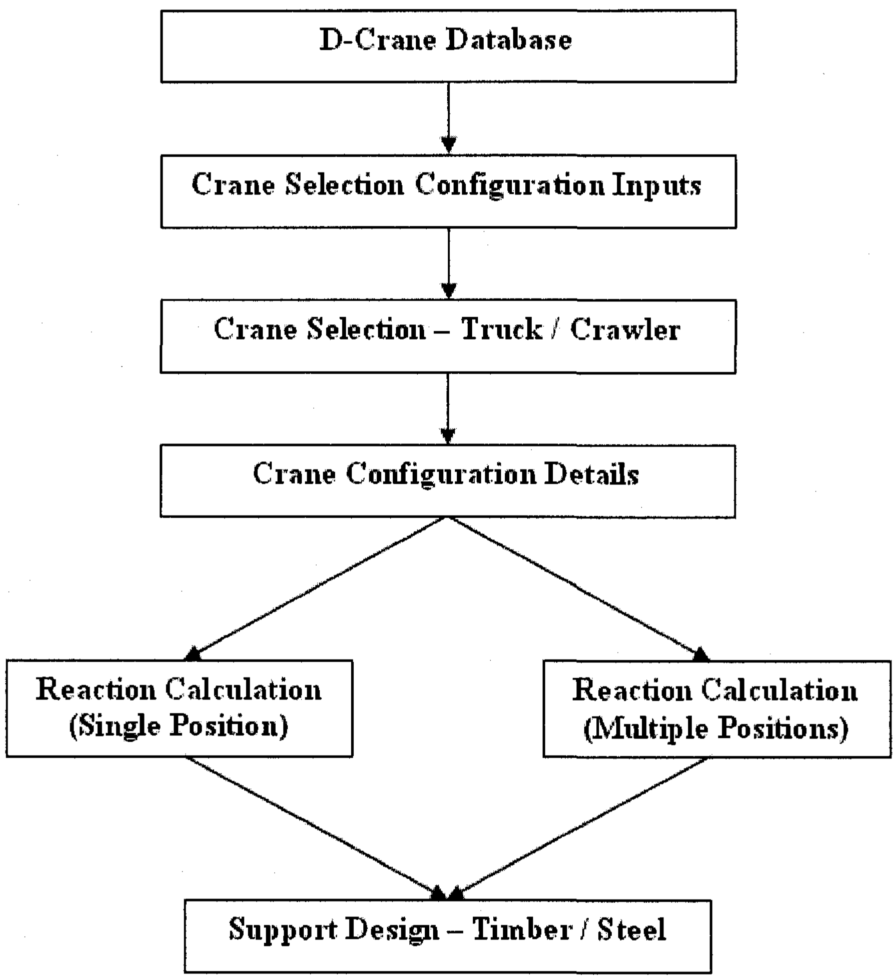

Figure 4.16 "D-Crane" Selection Mode System Algorithm

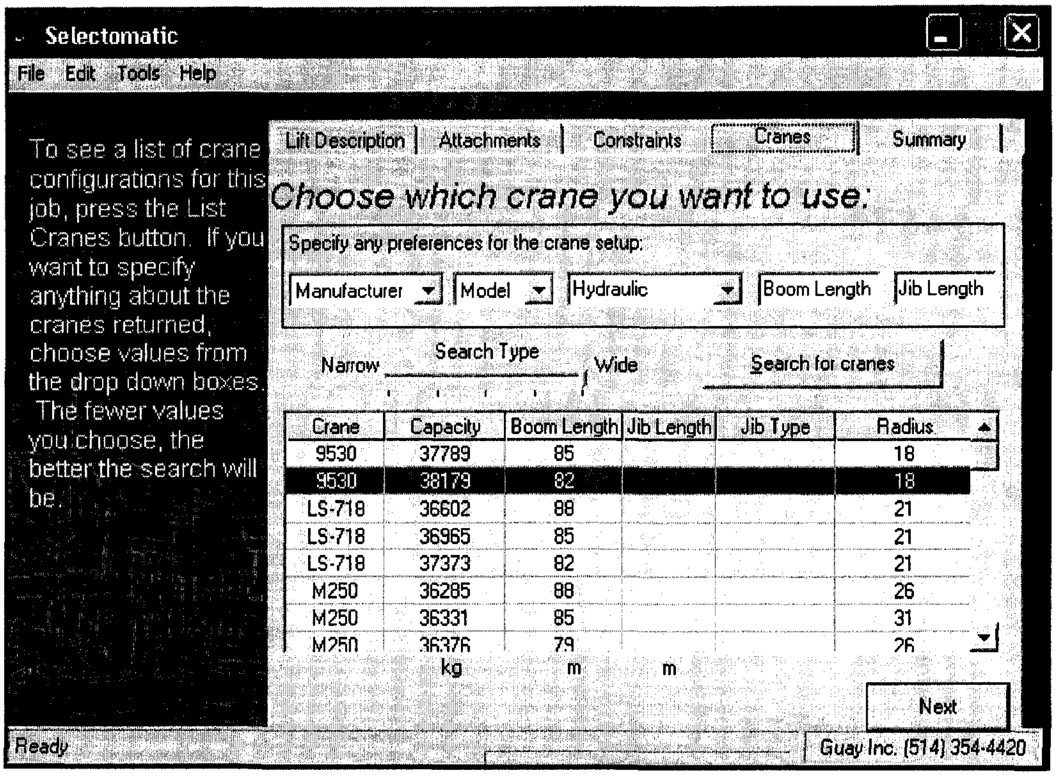

Figure 4.17 List of Technically Feasible Cranes

Once the crane has been selected, based on the type of crane the geometric information module interacts with the "D-Crane" database to retrieve the crane's geometric information (see Figure 4.18). At present, the structure weight, carrier weight, and center of gravity locations (for the truck or crawler body), and pad/track width are not available in the "D-Crane" database. Boom weight, jib weight, and their CG locations are also left out of the database, although the system has developed relationships between boom weight and boom length and also between jib weight and jib length. As such, the user must input the correct values for each of these fields of data within the crane geometry inputs form. After the crane configuration has been added, the user can design the required support for either a single position or multiple boom positions—as described in Truck Crane Design Mode and Crawler Crane Design Mode—depending upon the type of crane selected.

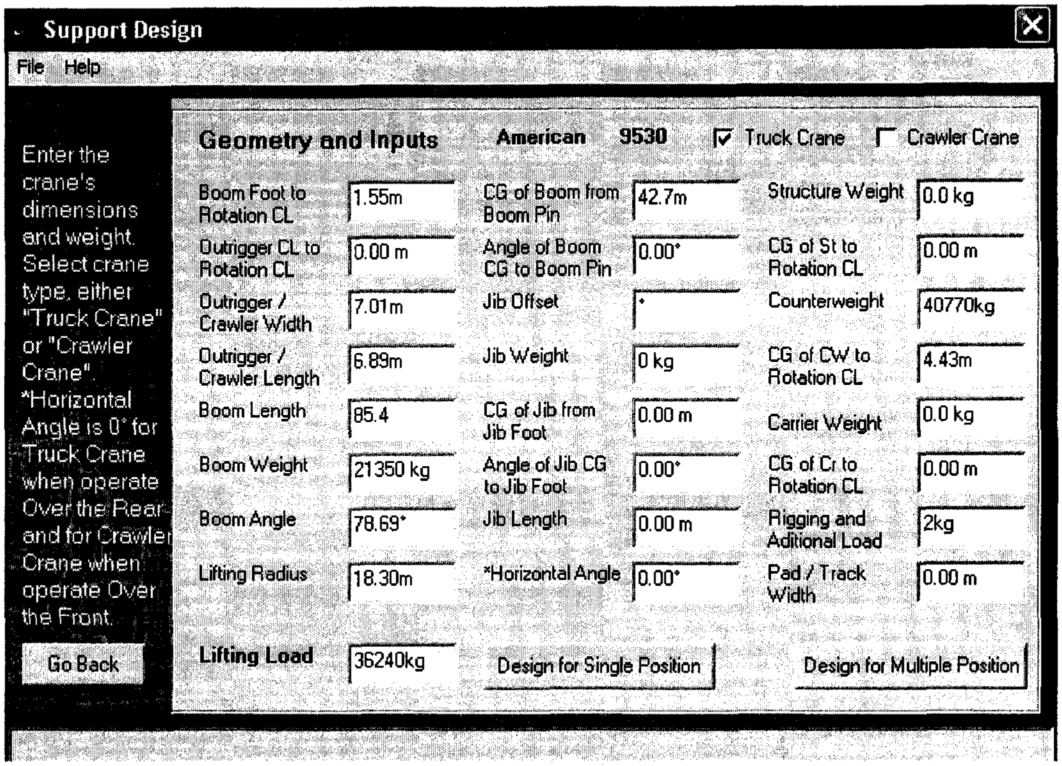

Figure 4.18 Crane Geometry Information from "D-Crane" Database

4.6 Integrating Crane Supporting Design with "Crane 2007" Database

Figure 4.19 illustrates the process used in the proposed system. The design process has been incorporated into a database, "Crane 2007", which is designed to house information such as the geometrics, weight, and lifting capacity of commercially available cranes.

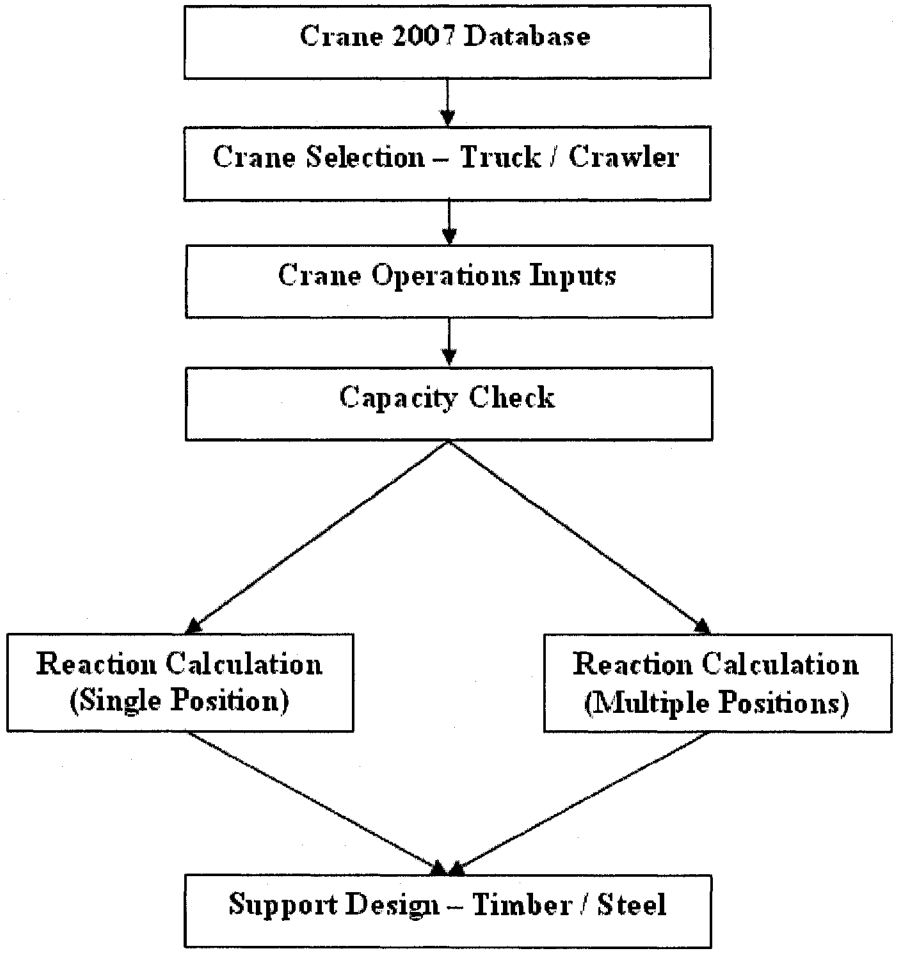

Figure 4.19 "Crane 2007" Database Mode System Algorithm

A crane must be selected to perform the lift configuration from the list of available cranes in the database as shown in Figure 4.20 in order to design the crane support. Once the crane has been selected, based on the type of crane, the geometric information module interacts with the "Crane 2007" database to retrieve the crane geometry information. In this case the user must select the lifting configurations for that particular crane as provided by the database. After the crane configuration has been selected, the system will provide the maximum capacity that can be lifted using the selected crane configuration; furthermore, the system will not allow users to lift more than the allowable capacity.

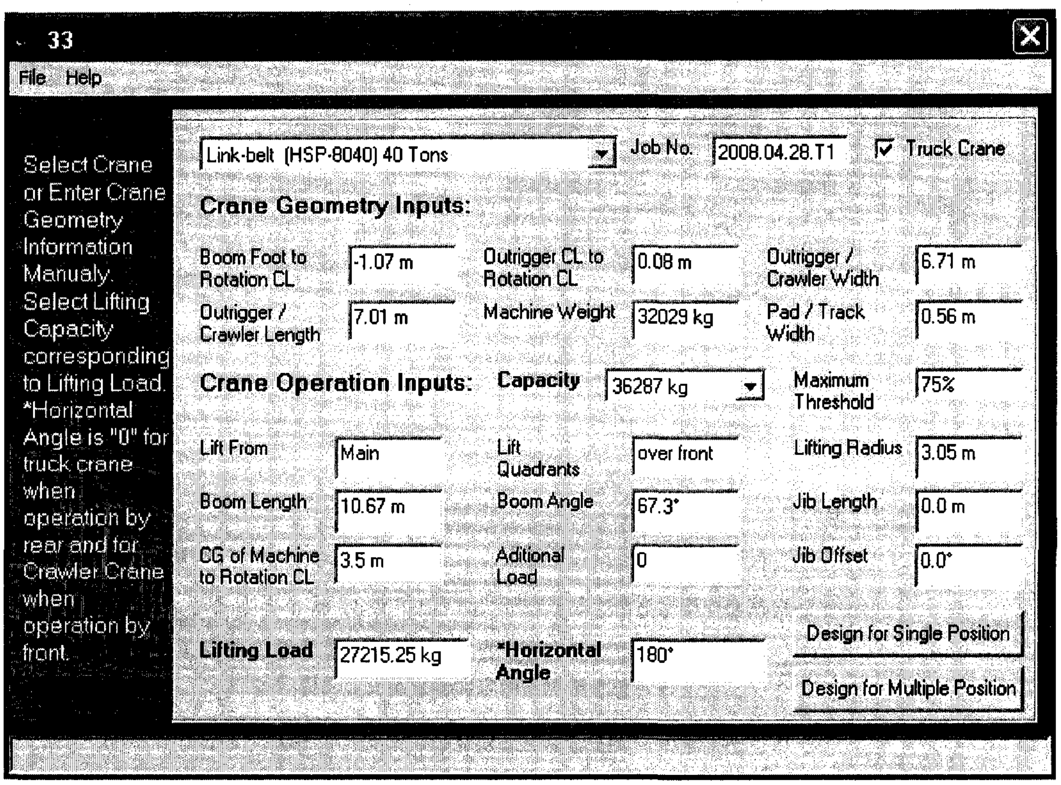

Figure 4.20 "Crane 2007" Database Mode Geometry and Operation Inputs Form

After the lifting load has been provided, the user can design the required support for either a single position or multiple boom positions— described in Truck Crane Design Mode and Crawler Crane Design Mode—depending on the type of crane selected.

4.7 Checks and Safety Considerations

The design process also encompasses certain safety precautions: (1) crane capacity, (2) crane stability against tipping failure, and (3) allowable stress for the material selected for the support system design. The "D-Crane" Selection Mode allows users to select the most feasible crane for their lifting configuration from a list of all technically feasible cranes. The "Crane 2007" Selection Mode does not allow users to select a lifting configuration which exceeds the allowable crane capacity. The reaction calculation module evaluates the crane stability against tipping by highlighting the reaction with negative values (i.e., the likelihood that tipping will occur) as shown in Figure 4.21. The support design module evaluates the strength of the selected material for the support system design by highlighting the bending or shear stresses in conjunction with the allowable stress of the selected material as shown in Figure 4.22.

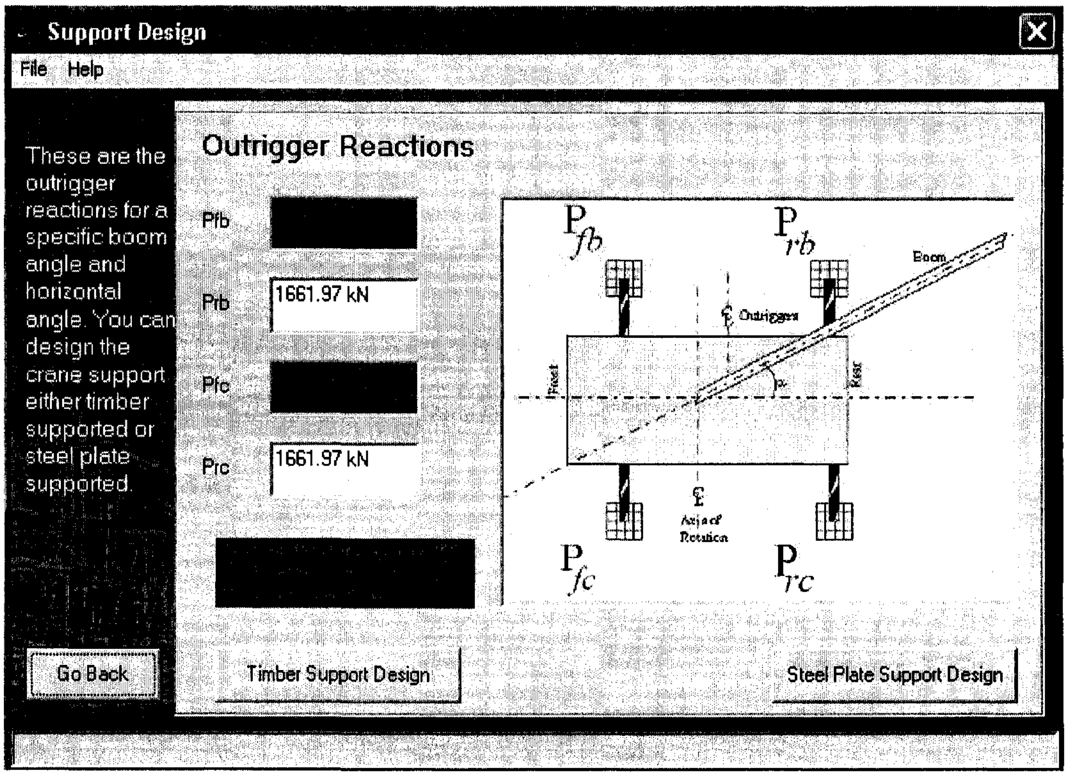

Figure 4.21 Safety Warning about Tipping Failure

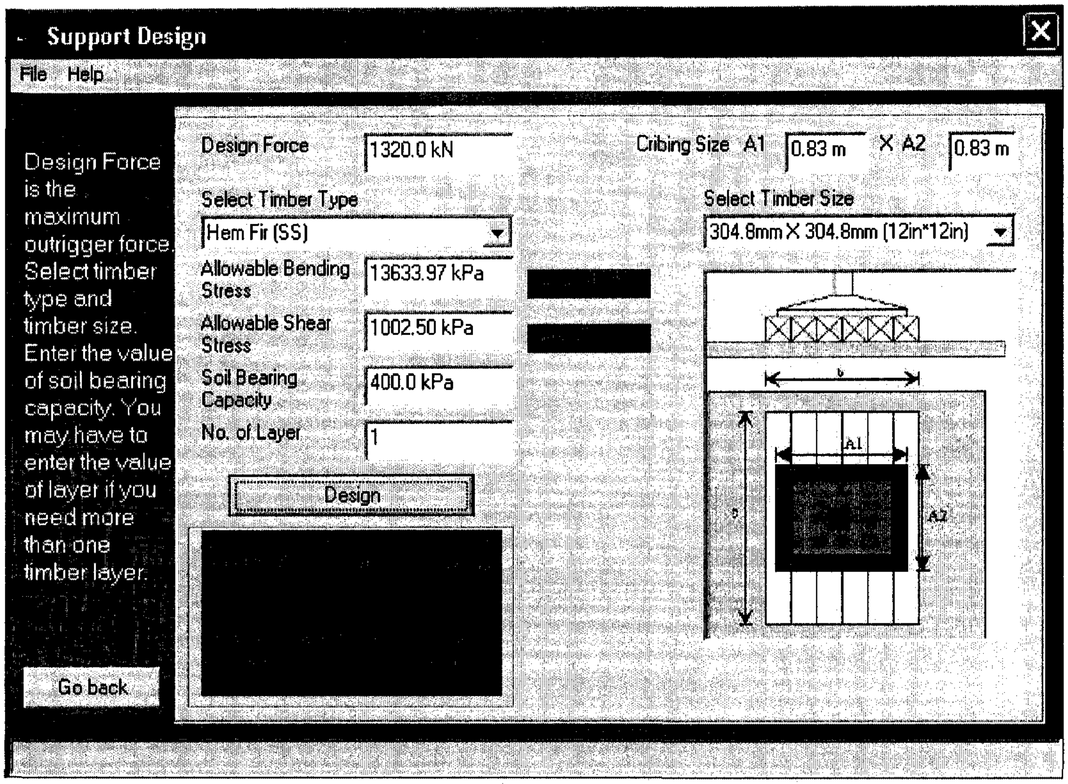

Figure 4.22 Safety Warning about Supporting Material Failure

CHAPTER 5: SYSTEM PERFORMANCE

5.1 Introduction

Two cases are used in this chapter to demonstrate the effectiveness of the proposed support system design for a mobile crane and its dynamic linkage to the databases. The first case is used to demonstrate the system's integration with the "D-Crane" database while the second case demonstrates its integration with PCL "Crane 2007" database.

5.2 Case 1: System Performance integrating with the Crane Selection Mode

The case considered involves the construction of a modular building in Edmonton, Canada. The operations include taking the slings and rigging from the east side (Location A on Figure 5.1) of the facility, swinging them to the north side (Location B on Figure 5.1) in order to pick up the module (with an obstruction of 3 m. in height and 12 m. in depth), and finally swinging the load to the south side (Location C on Figure 5.1) in order to place it with an obstruction of 3 m. height and 8 m. depth (see Figure 5.1). Due to the considerable size of the object, eight lifting points are required, which results in the establishment of multiple levels of rigging equipment, as shown in Figure 5.2. 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. Moreover, the solution requires selecting an appropriate crane and a suitable design for the support system for these lifts.

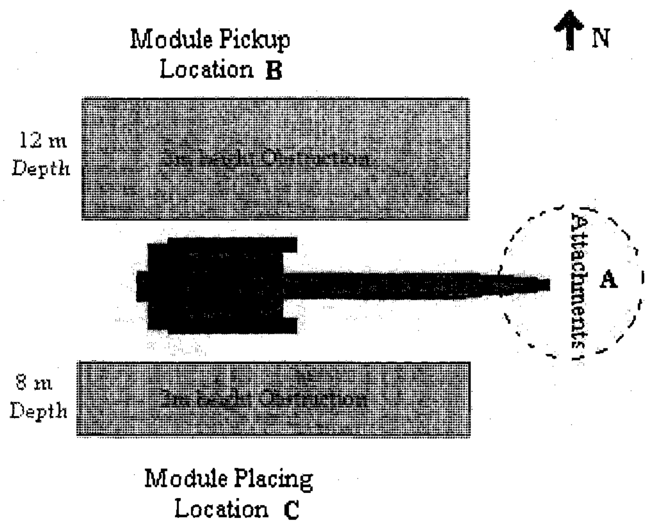

Figure 5.1. Plan View of Crane Operation

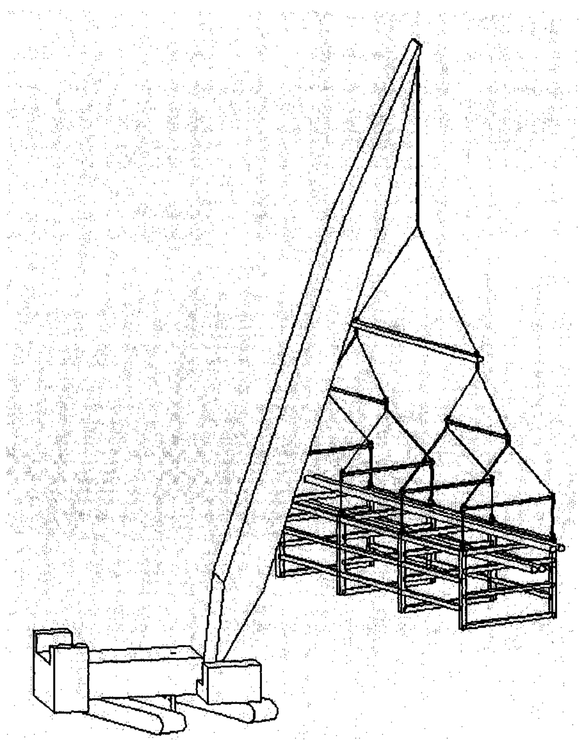

Figure 5.2. 8-Lifting Points Rigging Equipment

Step 1: This step is carried out in order to select an appropriate crane to perform these lifts. 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. Performing these configurations in Selectomatic Software (Al-Hussein et al. 2005), a list of technically feasible cranes can be generated as shown in Figure 5.3. The Manitowoc M250 has been selected as the crawler crane (on tracks) and the Demag TC2000 has been selected as the truck crane (on outriggers) to perform these lifts.

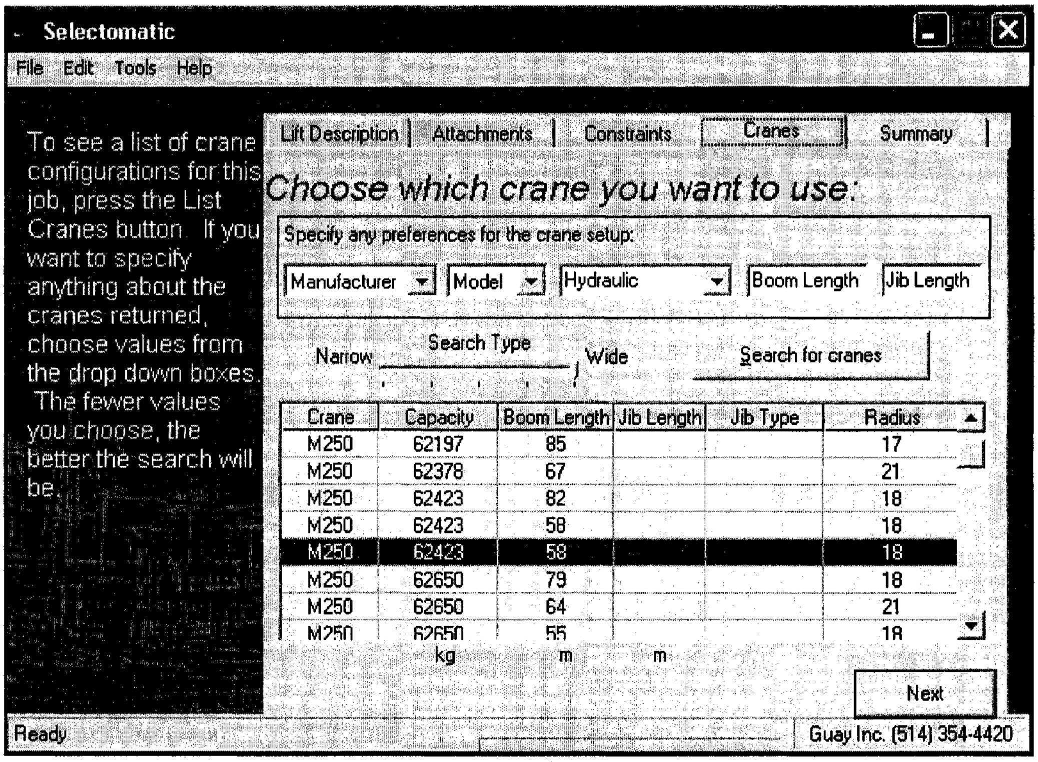

Figure 5.3. List of technically feasible cranes

Step 2: In this step, the cranes geometry and configuration are automatically transferred from the database to the geometric configuration module form as shown in Figure 5.4. At present the boom and jib weights, the structure weight, the carrier weight and center of gravity locations (of the truck or crawler body); and pad/track width are not available in the "D-Crane" database; therefore, the user must input the correct values for each of these fields of data in the crane geometry inputs forms.

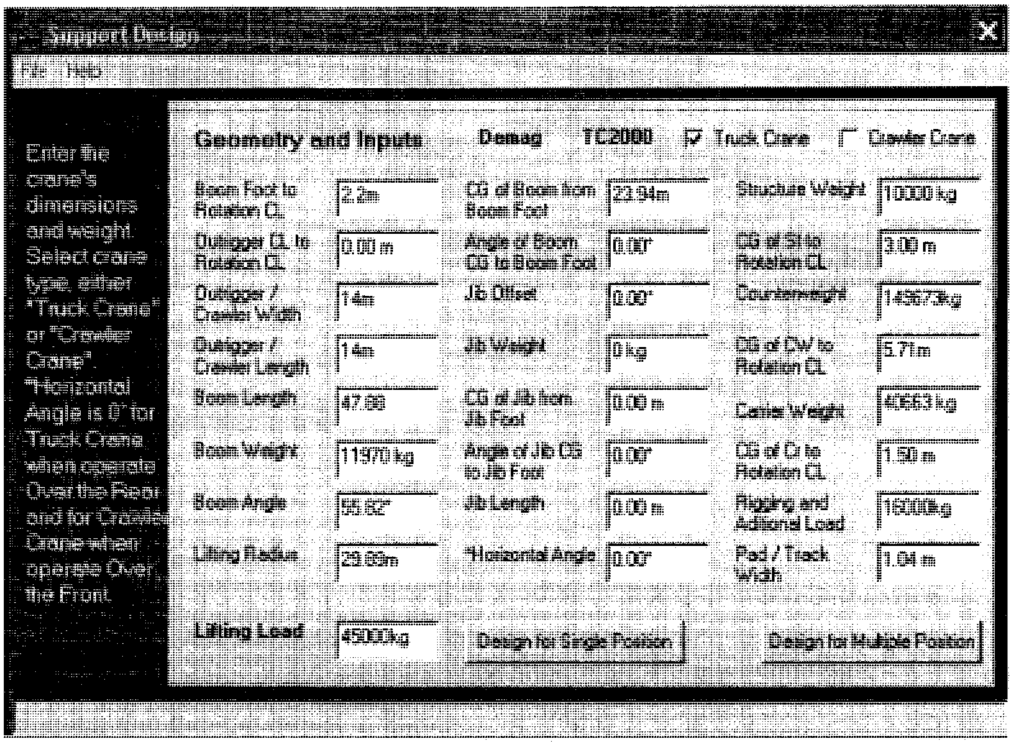

Figure 5.4. Crane Geometry and Inputs Form

Step 3: The purpose of this step is to calculate either the reactions in the outrigger pad or the pressure in the crawler track. In this step, the crane must swing to Location B as shown in Figure 5.1 to pick the load and place it on Location C as shown in Figure 5.1, 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 Demag TC2000 must be placed in such a position as to allow for the picking of the slings and the rigging equipment (Location A on Figure 5.1) from the rear position, swinging counter-clockwise to the left side at 90° (Location B on Figure 5.1) to pick the module, and swinging clockwise over the rear to the right side at 180° (Location C on Figure 5.1) to place the load. The horizontal swing angle thus ranges from -90° to +90°. The vertical boom angle must also be changed due to the varying obstruction depths; the value of the vertical boom angle to the ground is configured by the Selectomatic software to be 58.47° when initiating the lift of the module and 55.82° when placing it (see Figure 5.5). The output maximum reaction for all these swing and boom angles in either loaded or unloaded condition is 1183 KN (Figure 5.6).

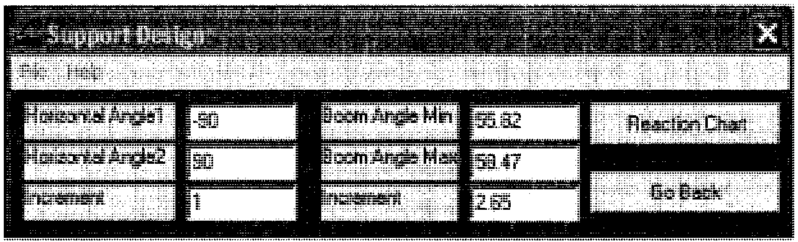

Figure 5.5. Multiple Positions Swing Angles and Boom Angles Input

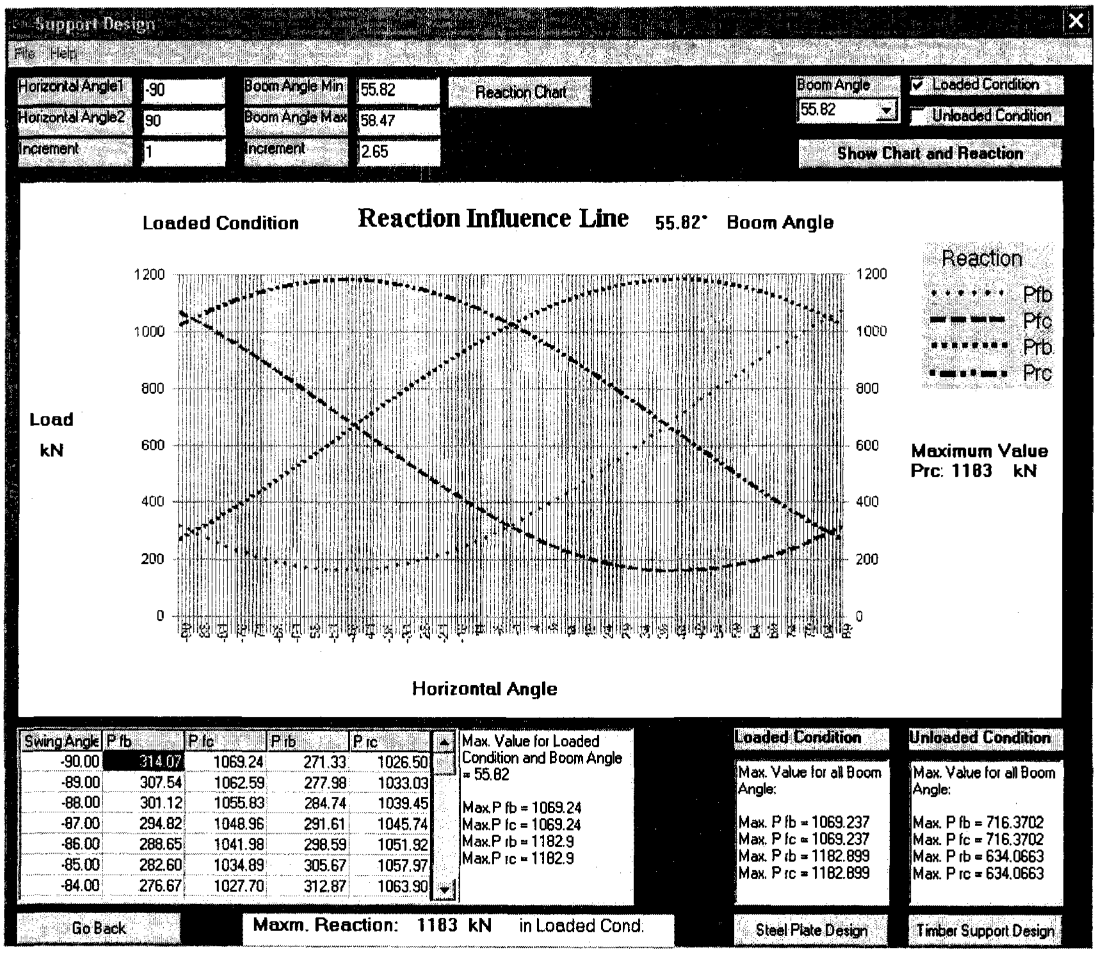

Figure 5.6. Reaction Influence Chart and Table for Demag TC2000

In the case of the crawler crane, Manitowoc M250, it must be placed front-facing to Location A (see Figure 5.1) in order to attach the sling and rigging. The horizontal swing angle will be the same, again ranging from -90° to +90°, but the vertical boom angle will differ from that of the Demag, with a value of 71.37° when picking up the module and 74.53° when placing it. The output maximum pressure for all these swing and boom angles in either loaded or unloaded condition is 350 KPa.

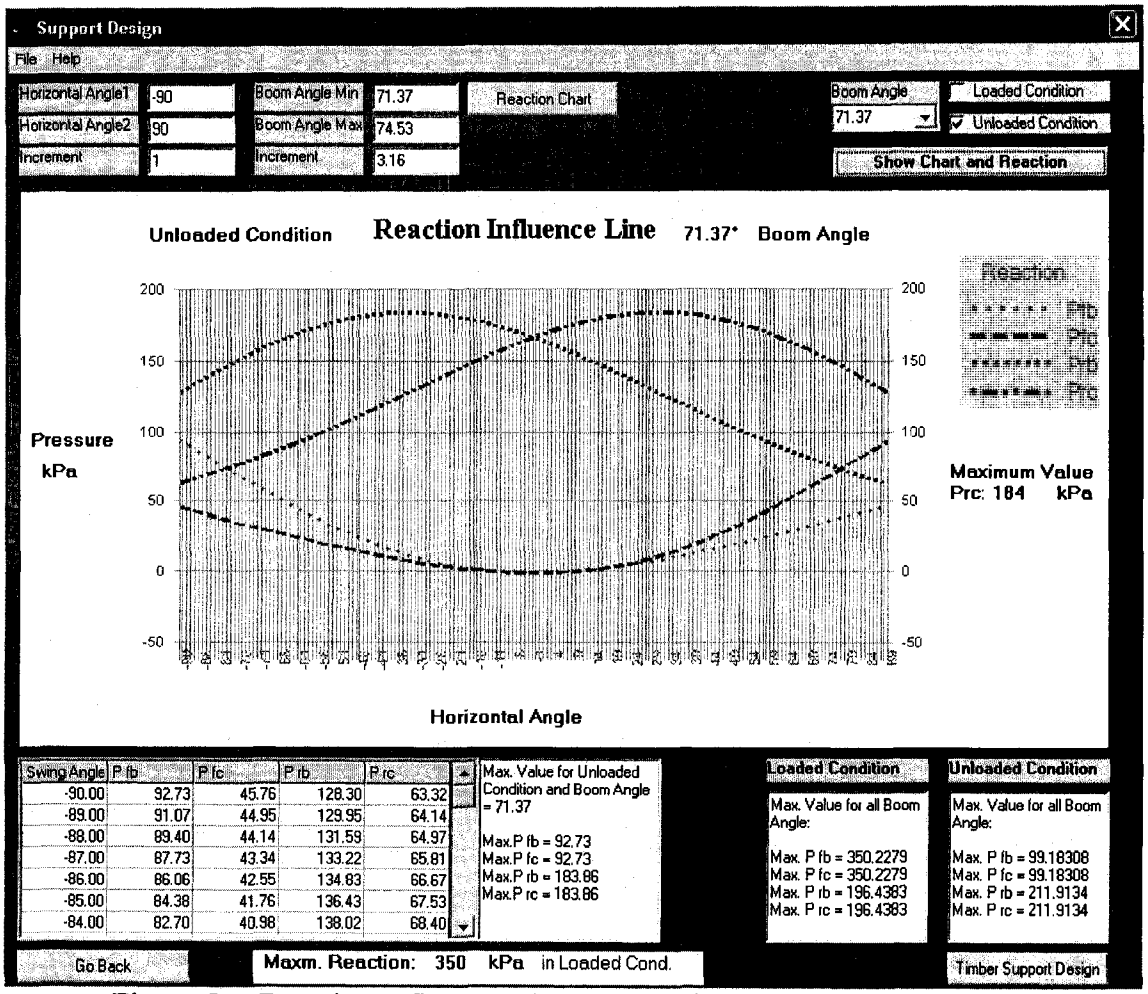

Figure 5.7. Reaction Influence Chart and Table for Manitowoc M250

Step 4: In this step, the support design is carried out based on the maximum reactions 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 mm. X 305 mm. (12 in X 12 in) timber size and entering the soil bearing capacity generated from the soil test report (400 kPa), the results given by the support system are as shown in Figure 5.8 and Table 5.1. In the case of the steel plate design, the allowable bending stress of steel was chosen to be 186 MPa. Entering the soil bearing capacity, the outputs are rendered as shown in Figure 5.9 and Table 5.1.

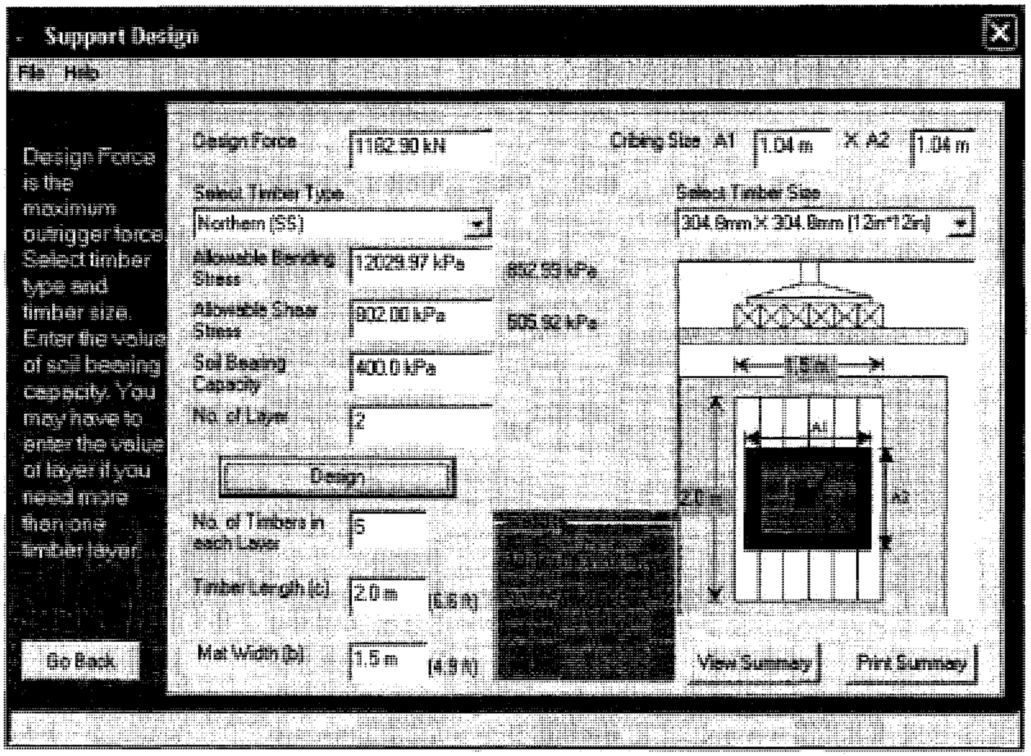

Figure 5.8. Demag TC2000 Timber Support Design Results

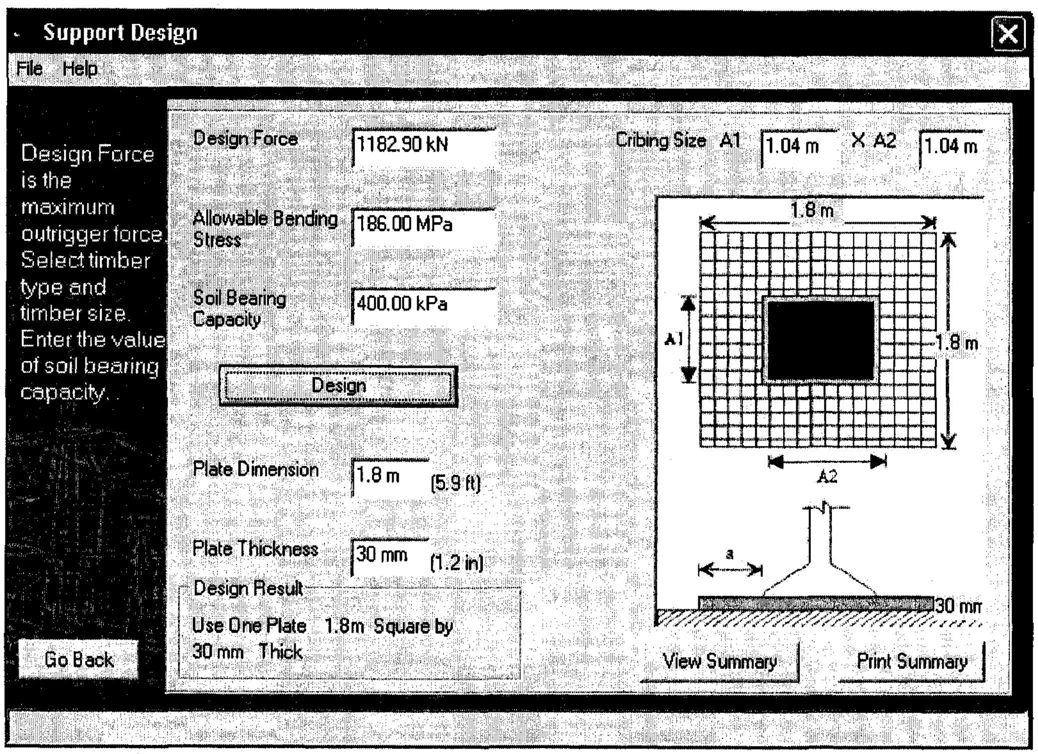

Figure 5.9. Demag TC2000 Steel Plate Support Design Results

For the Manitowoc M250, only the timber support design is carried out. Selecting the Northern (SS) timber type and the 305 mm. X 305 mm. (12 in X 12 in) timber size and entering the soil bearing capacity, the results given by the support system are rendered as shown in Figure 5.10 and Table 5.1.

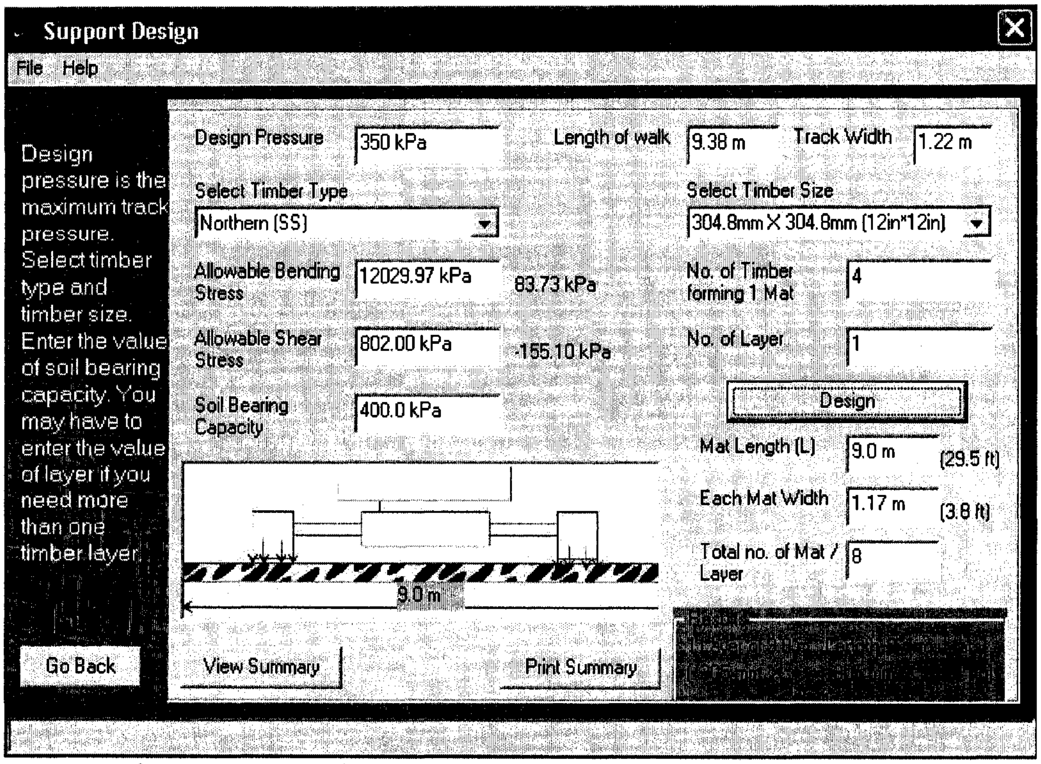

Figure 5.10. Manitowoc M250 Timber Support Design Results

Table 5.1. Crane Support Design Results

Crane Type	Timber Support						Steel Plate Support	
	Timber Size (mm)	Timber or Mat Length (m)	Mat Width (m)	No. of Layer	No. of Timber or Mat / Layer	No. of Timber forming a Mat	Plate Dimension (m)	Plate Thickness (mm)
Demag TC2000	305 X 305	2.0	1.5	2	5	-	1.8	30
Manitowoc M250	305 X 305	9.0	1.17	1	8	4	-	-

5.3 Case 2: System Performance through the integration of "Crane 2007" Database

This case describes the construction of the Light Rail Transit (LRT) extension on the south side of the city of Edmonton, Canada, which requires the moving of many different kinds of construction materials. The particular operation under discussion involves the lifting of a maximum load of 11,000 kg., then swinging it 360° with a constant boom angle to the ground θ and radius R (see Figure 5.11). The lifting radius R should be not less than 15 m. and the boom angle to the ground θ must be greater than 50° as shown in Figure 5.11. The solution requires the selection of a crane that can perform this lift, as well as a suitable design for the crane support system.

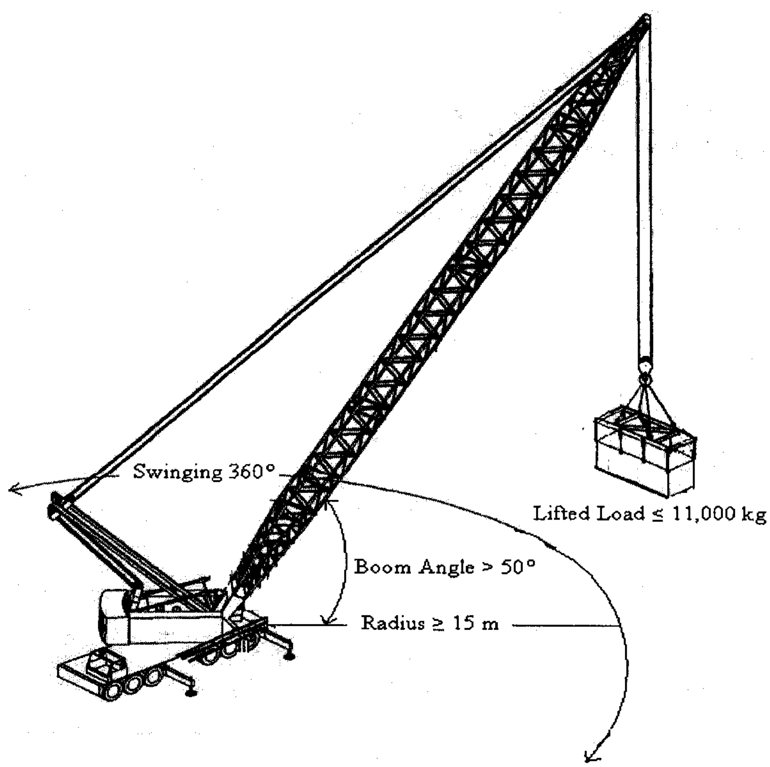

Figure 5.11 Crane Operation Requirements for LRT Construction

Step 1: This step is carried out in order to select an appropriate crane by which to perform these lifts. “Crane 2007” database has over 190 different crane types from which a crane must be selected which each have a capacity of at least 11 tons at a radius of 15 m and with a boom angle to the ground θ no less than 50° and the ability to swing 360°. The KRUPP 100 GMT, with a capacity of 120 tons, is the best choice to perform the lift with this particular configuration and was thus selected for the operation, as is illustrated in Figure 5.12.

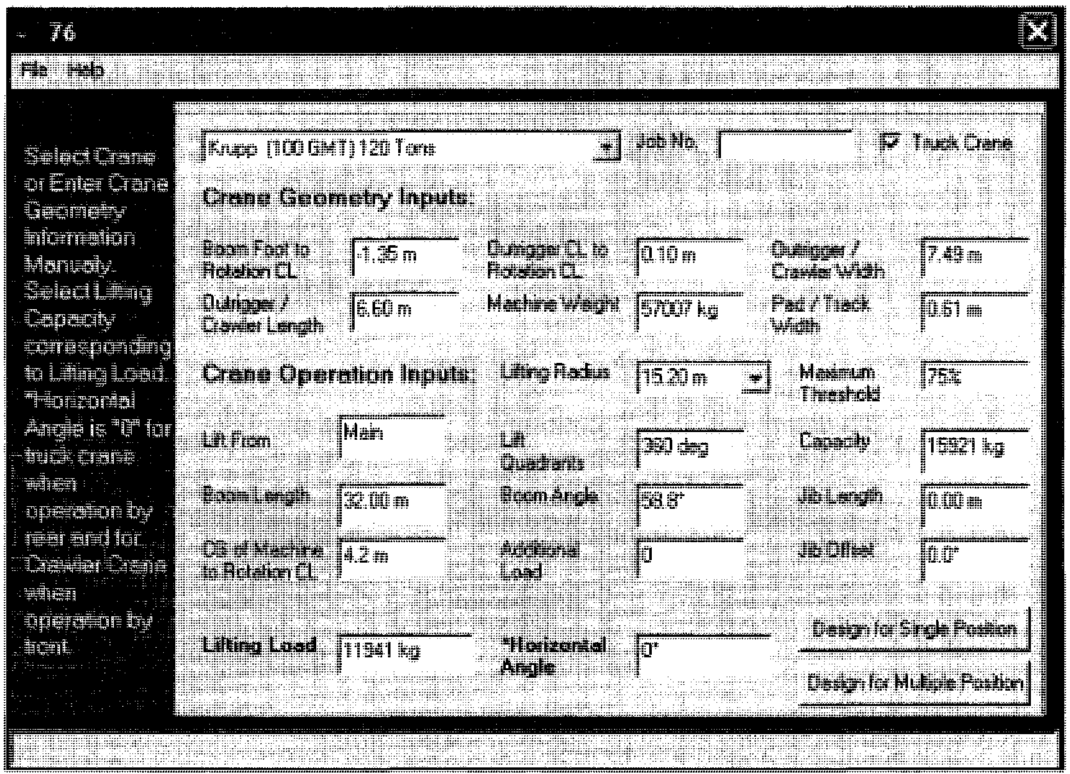

Figure 5.12 Geometry and Operation Configuration of KRUPP 100 GMT.

Step 2: This step is carried out to check the crane’s capacity. After the crane configuration has been selected, the system provides the maximum capacity that can be lifted using the selected crane configuration depending on the maximum safety margin provided by the user. The default maximum safety margin is 25%, in which case the KRUPP 100 GMT has a capacity of 15,921 kg. at a 15.2 m. radius lifting on the main boom (32 m. in length and at a 58.8° boom angle to the ground). Due to the 25% safety margin, it can lift a maximum of 11,941 kg. (see Figure 5.12). The lifted load weight with rigging weight must be less than the allowable capacity, and in this particular case the maximum lifted load is 11,000 kg., which is less than the allowable capacity.

Step 3: The purpose of this step is to calculate the maximum reactions in the outrigger pad. In this case the crane must be able to swing 360° in both loaded and unloaded condition with no need to change its vertical boom angle to the ground (see Figure 5.13). The output represents the maximum reaction for all these swing angles (over 360°) with a fixed 58.8° boom angle to the ground of 280 KN in loaded condition, as can be seen in Figure 5.14.

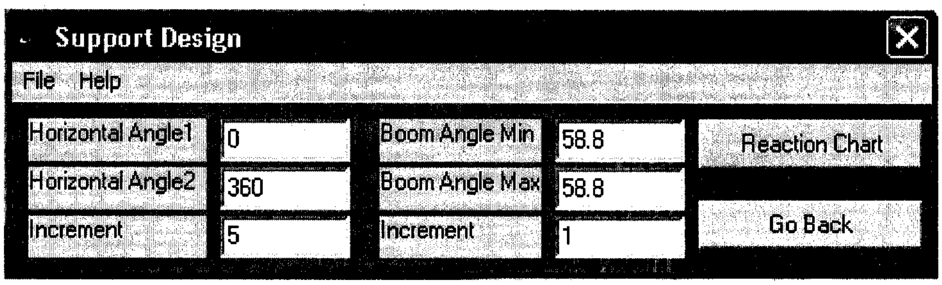

Figure 5.13 Changing Swing Angles and Fixed Boom Angles Inputs

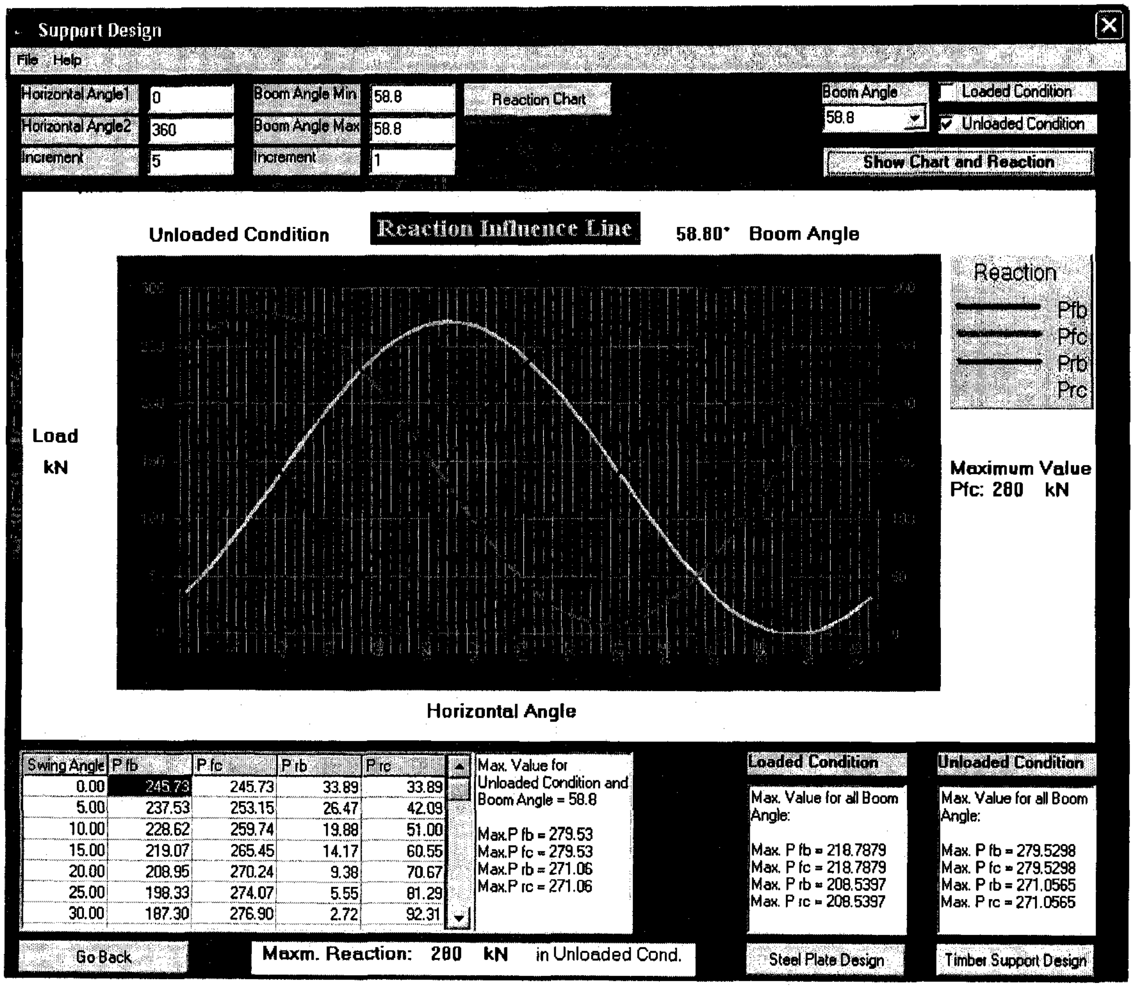

Figure 5.14 Reaction Influence Chart and Table for KRUPP 100 GMT

Step 4: In this step, the support design is carried out based on the maximum reactions, which have been determined in the previous step, using timber or steel plates. Selecting the Northern (SS) timber type for timber support design and entering the allowable bending stress of steel for steel plate design as well as the soil bearing capacity generated from the soil test report (400 kPa) for both cases, the results given by the support system are listed in Table 5.2.

Table 5.2. Crane Support Design Results for KRUPP 100 GMT

	Timber Support						Steel Plate Support	
Crane Type	Timber Size (mm)	Timber or Mat Length (m)	Mat Width (m)	No. of Layer	No. of Timber or Mat / Layer	No. of Timber forming a Mat	Plate Dimension (m)	Plate Thickness (mm)
KRUPP 100 GMT	305 X 305	0.8	0.9	1	3	-	0.9	13

5.4 System Validation

The system performance also has been validated with two real support design cases which had been carried out before and performed by Sterling Crane and PCL Industrial Constructors Inc.

Case #1 by Sterling Crane

Information provided by the industry is given below:

Crane Type: 90 Ton Link-belt HTC 8690

Counterweight: 17 500 lb

Radius: 100 ft

Boom Length: 140 ft

Jib Length and offset: 58' @ 30 deg. offset

Total Load: 3 860 lb (Incl. Equip. Wt., Ball, Rigging, Etc.)

Used Support System: 48" dia. plywood mats 6 layers thick

Design Results:

The design results given by the newly developed crane support system are as shown in Figure 5.15. The operation can be safely carried out when 3 numbers 305 mm X 305 mm (12 in X 12 in) timber with 0.9 m (3 ft) length will be placed under each outrigger.

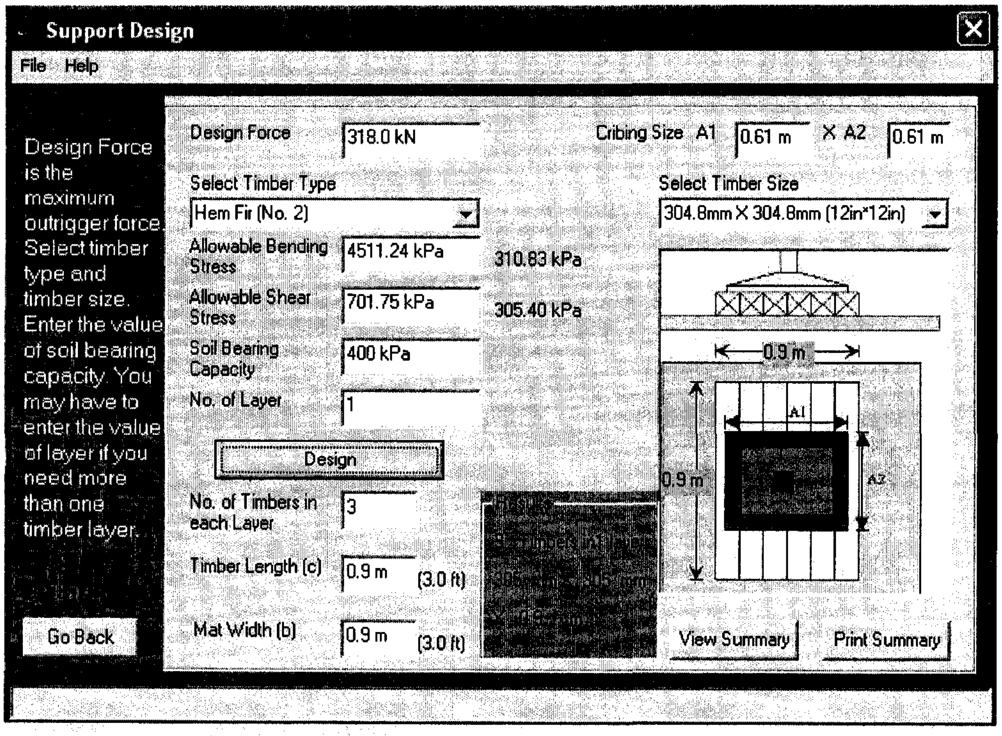

Figure 5.15 Support Design Result for Link-belt HTC 8690

Case # 2 by PCL Industrial Constructors Inc

Information provided by the industry is given below:

Maximum Crawler Pressure: 4156 psf

Allowable Soil Bearing Capacity: 4010 psf

Used Timber Mat Width: 4 ft

Used Timber Mat Length: 21 ft

Design Results:

The design results given by the newly developed crane support system are as shown in Figure 5.16. The operation can be safely carried out by using 6m (21.3 ft) length timber mat containing 4 – 12 in X 12 in timber under crawler track.

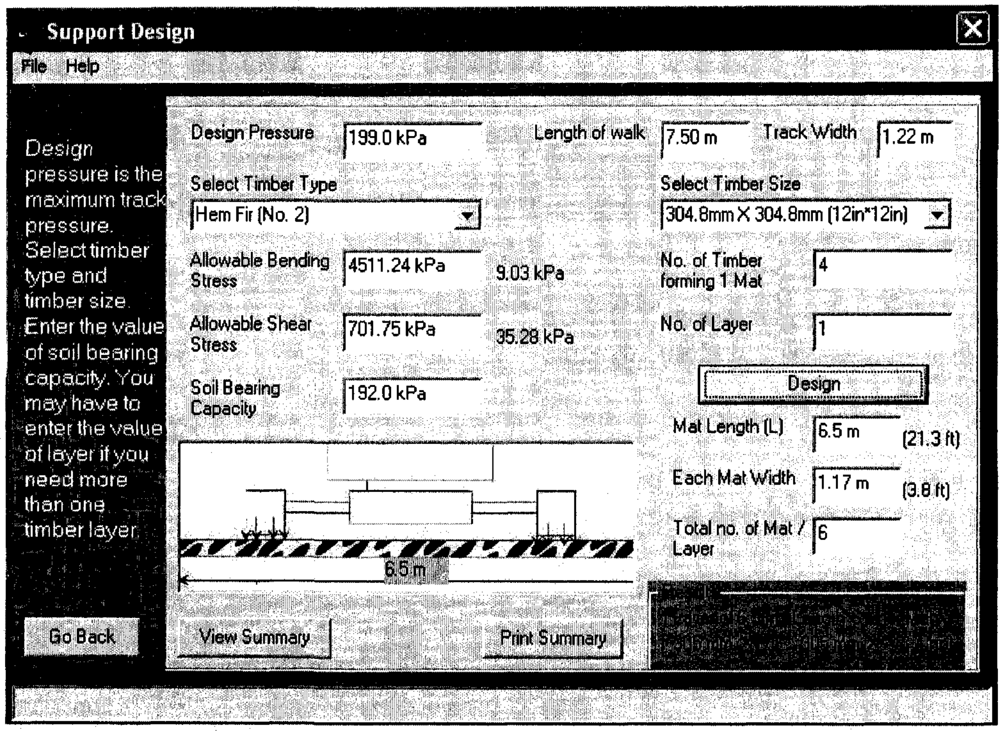

Figure 5.16 Support Design Result for a Crawler Crane

Due to the lack of some required information such as the soil bearing capacity the design results for the first case have been varied from the used support system. Whereas for the second case, the design results are nearly same as the used support system as all the required information was available. This system can work effectively and accurately only when all the information and variables required to design the crane support system are available.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Research Summary

In current practice, design of the crane support system has been carried out manually based on a number of rules of thumb. This research has been motivated by the large number of cranes used in the construction industry and the consequent need to design crane supporting systems more accurately. This research has also been motivated by the need to prevent crane accidents caused by poor design practice on construction sites. This thesis has described the development of an automated system for the analysis and design of a crane support system, and the primary focus has been on the methodology used to support planners in executing lift studies for mobile cranes. From beginning to completion of a facility or project, the developed automated system provides its users with additional graphics in the form of 2D reaction influence charts supporting the visualization of the forces being exerted upon the outriggers or crawler tracks for the planned lift. Furthermore, the developed support system integrates a previously developed set of selection modules as well as a crane database.

To these ends, the developed methodology for this research can assist with the accurate and economical design of a crane support system as well as with preventing crane accidents caused by instability and tipping failure due to poor design practice. The developed methodology was incorporated into the "D-Crane" and "Crane 2007" databases, which are designed to house information about construction cranes, including the geometrics, weight, and lifting capacity of commercially available cranes. The system was developed using Microsoft Visual Basic™ in order to control the data-integrity as well as to provide a user-friendly interface. Four design models were developed to calculate the reactions and design the support for a truck crane and a crawler crane—two based on user inputs about crane geometrics and another two which use two different databases to retrieve the crane's geometric information.

Furthermore, the methodology was 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 track pressure for crawler cranes. A reaction influence chart was also produced to show the dynamic relationship between a truck crane's outrigger reaction or a crawler crane's track pressure and the boom's horizontal swing angles and vertical boom angles to the ground. Support design was carried out using the foundation design module, which assists in designing the support foundation using either steel plates or timber. The design characteristics of both timber and steel plates were retrieved from the supporting material database, and the design was performed based on the maximum values of reaction of the outrigger for truck crane or pressure of the tracks for crawler crane.

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.

6.2 Research Contributions

The algorithm and methodology presented in this research can potentially benefit many aspects of current construction practice. A partial list of possible contributions of this research is summarized below:

- *Crane Selection*: Optimum cranes can be selected from a list of technically feasible cranes using the "D-Crane" design mode. In addition, the "Crane 2007" design mode allows users to select a feasible crane from over 190 different cranes, considering the capacity of the crane along with the operation configuration of the lifts.
- *Soil Pressure Calculation*: This research 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. It will help the geo-technical engineers to determine the level of reinforcement of the soil if the soil bearing capacity is not sufficient for operation of the crane.
- *Reaction Calculation under Dynamic Loading*: The presented algorithm calculates the reaction in each outrigger or crawler track when the crane is in motion. The outrigger reactions or track pressures have been calculated for loaded and unloaded scenarios with changing boom angles to the ground θ and swing angles α.
- *Support Design*: The developed methodology assists in designing the supporting system for both types of mobile cranes—truck cranes on outriggers and crawler cranes on tracks—using either timber or steel plates.

- *Boom Swing Control*: The developed algorithm calculates outrigger or crawler track reaction for 360° swing of boom and presented in an influence chart. Contractor or crane operator can safely rotate the boom only those positions where the reactions are positive shown in the influence chart.
- *Construction Safety*: This research also encompasses certain safety precautions: (1) crane capacity, (2) crane stability against tipping failure, and (3) allowable stress for the material selected for the support system design.

6.3 Research Assumptions and Limitations

This research has focused mainly on the calculation of the reaction of each outrigger for truck cranes, or the pressure of each track for crawler cranes; calculation of the reaction or pressure influence lines for varying horizontal swing angles and vertical boom angle to the ground; and the design of crane support systems using either timber or steel plates. Although this research considers dynamic loading condition, but all the equations used to calculate the support reaction and design the support system are queasy static. The research does not, however, account for the selection of an appropriate crane to perform the given operations. Crane selection can be performed using "Selectomatic" Software (Al-Hussein et al. 2005), and the proposed methodology has been integrated with the Selectomatic software accordingly. The proposed methodology retrieves the crane's geometric information from either the "D-Crane" database or the "Crane 2007" database depending upon the user's requirements. If any required data is missing in either of those databases, the user must provide the correct values for each of the missing data.

This research assumes that the ground area of a construction site is flat and can safely support the cranes. The proposed methodology assumes a sufficient soil bearing capacity of the ground area of the construction site where the crane will operate based on the geotechnical soil report. To design the support system using timber, either the timber type or the allowable bending stress and shear stress of the timber will be required. The allowable bending stress of the steel is required if the design is to be carried out using steel plates.

6.4 Recommendations for future work

Although this research has fulfilled its primary goal of providing the basis for support system design for mobile cranes, there are some areas that require further research. These may include:

- Developing a methodology that can calculate the outrigger reaction or track pressure and which considers wind effects.
- Developing a gravel compaction design module for crawler cranes.
- Expanding on these developments using 3D CAD in order to demonstrate the operation process and location of the crane.
- Developing a 3D ground pressure chart which reflects crane motion loading.

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