BRASS™

Wyoming Department of Transportation

Bridge Pier Analysis System

# BRASS - PIER(LRFD)™

Version 2.4

Technical Manual

May 2016

## Disclaimer

Portions of this system were developed cooperatively by the Federal Highway Administration and the Wyoming Department of Transportation. The Wyoming Department of Transportation and the Federal Highway Administration assume no liability or responsibility for and make no representations or warranties as to applicability or suitability of this computer system. Anyone making use thereof or relying thereon assumes all responsibility and liability arising from such use or reliance. This software is a tool for the design or analysis of structures. The engineer using this software is responsible for verification of the reasonableness of the results produced by BRASS-PIER(LRFD)™

## AASHTO Specification

The BRASS-PIER(LRFD)™ program is current with the AASHTO LRFD *Bridge Design Specifications*, 7th Edition, 2014, with 2015 Interim Revisions.

## Additional Information and Technical Assistance

Additional information may be obtained from:

Wyoming Department of Transportation
Bridge Program
5300 Bishop Boulevard
Cheyenne, WY 82009-3340
Telephone: (307) 777-4427
Fax: (307) 777-4279
Web Page:
www.dot.state.wy.us/home/engineering_technical_programs/bridge/brass.html
ftp://brass:password@wydot-filestore.dot.state.wy.us

Technical assistance may be obtained from:

Telephone: (307) 777-4489
E-mail: BRASSTechSupport@wyo.gov
Web: www.wydot-brass.com

Purchasing, billing and licensing assistance may be obtained from:

Telephone: (307) 777-4489
E-mail: BRASSBilling@wyo.gov

When requesting technical assistance, please visit the incident tracking system at www.wydot-brass.com. Users without an account on the incident tracking system can request an account by clicking on the "Open a Technical Support Account" link/button and e-mailing the address or calling the phone number listed. A username and password will be created and sent to the user. With this system, you may upload your data file and a description of the incident, any error messages, any bridge drawings, and any hand computations, which illustrate the concern. An Incident number will be assigned to track the progress of resolving the incident.

# Welcome to BRASS-PIER(LRFD)™

BRASS-PIER(LRFD)™ is designed to assist a bridge engineer in the design or review of a bridge pier for a variety of pier types. Several manuals are provided to aid in the use of the program.

**BRASS-PIER(LRFD)™ Manuals**

| | |
|---|---|
| **Getting Started Manual** | Explains installation and illustrates how to run an example data file. |
| **User Manual** | Provides screenshots with detailed input instructions along with general user interface operating instructions. |
| **Technical Manual** | Provides an overview of the program and explains technical information and aspects of the program. |

**The BRASS™ Suite**

BRASS™ is a suite of programs that assist the engineer in many aspects of bridge design and rating. These programs are described below.

| | |
|---|---|
| **BRASS-GIRDER™** | Performs a design review or rating of highway bridge girders using plane frame analysis and the AASHTO Standard or LRFD Specifications. Load and resistance factor and load factor computations are performed for steel and composite steel, reinforced concrete, and prestressed concrete girders. Load and resistance factor and allowable stress computations are performed for timber girders. |
| **BRASS-GIRDER(STD)** | Performs a design review or rating of highway bridges decks and girders using plane frame analysis and the AASHTO Standard Specifications. Load factor and working stress computations are performed. This program was fully sunset after the November 2014 release. |
| **BRASS-GIRDER(LRFD)™** | Performs a design review or rating of highway bridge girders using plane frame analysis and the AASHTO LRFD Specifications. Load and resistance factor computations are performed. This program was fully sunset after the November 2014 release. |
| **BRASS-PIER™** | Performs an analysis of a bridge transverse section at pier locations. The program provides a comprehensive analysis of bridge decks, piers, and selected foundation types. All AASHTO loads and group loads are considered. Live load is automatically positioned for maximum actions. Load factor and working stress computations are performed. |
| **BRASS-PIER(LRFD)™** | Performs an analysis of a bridge transverse section at pier locations. Provides a comprehensive analysis of bridge decks, piers, and selected foundation types. All AASHTO (LRFD) loads and group loads are considered. Live load is automatically positioned for maximum actions. |

| | |
|---|---|
| **BRASS-CULVERT™** | Performs analysis or design of one, two, three, or four barrel reinforced concrete rigid or flexible box culverts, with or without bottom slab. End skews can also be defined. Wall and slab thickness may be specified or the program will set the thickness. AASHTO guidelines are followed and Service Load Design, Load Factor Design, or Load and Resistance Factor Design may be specified. Member capacities are designed based on applied truck load, soil fill, self weight and water pressure. Standard AASHTO and user defined truck loadings can be specified. Output generated by the program includes: culvert geometry; moments, shears, and axial forces at tenth points; stresses; required area of reinforcement; steel design table; splice length; weights and volumes of steel and concrete; and influence ordinates. Critical design moments, shears, and axial forces for each member are summarized. Flexural rating computations may be optionally computed. |
| **BRASS-SPLICE™** | Performs the design of field splices for rolled beam or welded plate steel girders. Design criteria are in compliance with the AASHTO Standard Specifications and WYDOT design practice. Load factor and working stress computations are performed. |
| **BRASS-PAD™** | Performs analysis and design of steel or fabric reinforced elastomeric bearing pads according to the AASHTO Standard or LRFD Specifications. |
| **BRASS-DIST™** | Performs a finite-strip element analysis to determine the factor for wheel load distribution for any axle spacing or width and any tire configuration of a truck placed at any position on the bridge deck. Standard trucks may also be used. NOTE: AASHTO formulas are based on empirical data and are applicable to six-foot axle widths. Also provides results for a simple beam "deck-to-girder" analysis for dead loads. |
| **BRASS-TRUSS™** | Performs a comprehensive working stress analysis or rating of simple or continuous truss or girder floor beam stringer type bridges. |
| **BRASS-POLE™** | Performs a working stress analysis of cantilever sign, luminaire and signal support structures. Round or polygonal steel poles may be analyzed according to the AASHTO Standard Specifications. |

# 1 Introduction

BRASS-PIER(LRFD)™ is a computer program developed to assist in the analysis and design of reinforced concrete piers for bridges. The system performs a first order analysis of a transverse (normal to the centerline of the roadway) cross-section of a bridge. Figure 1, Page 1.2 shows a general overview of the system.

BRASS-PIER(LRFD)™ presently consists of four components:

- Deck Analysis and Loading
- Pier (LRFD) Analysis and Loading
- Ultimate Strength Design/Analysis of Concrete Column Sections (PCA Column Design)
- Pier Support (Footing) (LRFD) Analysis and Design

## 1.1 Deck Analysis and Loading

The Deck Analysis and Loading Component will apply dead and live loads to a bridge deck section (one-foot-wide transverse strip) and distribute the loads as reactions to the girders.

The reactions output from the Deck Analysis and Loading Component may be used as uniform load per foot for longitudinal girder analysis. The longitudinal girder reactions at the pier are then used by the Pier Analysis and Loading Component. A study of Figure 2, Page 1.3 should help explain the interrelationship between loads and reactions on transverse and longitudinal bridge members. An understanding of how BRASS-PIER(LRFD)™ and a longitudinal girder analysis system such as BRASS-GIRDER(LRFD)™ work together to determine loads to the pier is paramount to utilizing BRASS-PIER(LRFD)™ to its fullest extent.

The Deck Analysis and Loading Component can analyze bridge decks supported on two or more girders, up to a maximum of twenty. The Deck Loading Component has three purposes. The first is to assist the engineer in the analysis of the deck itself. See BRASS-GIRDER(LRFD)™ for complete information. The second is to assist in the analysis of the longitudinal girder system with the distribution of the dead load of the deck to the girders. The third is to assist in the analysis of a frame pier with the distribution of live load to the girder bearings and hence to the pier.

The dead load distribution section of the Deck Analysis and Loading Component will calculate and apply dead loads to the deck using the dimensions of the deck, curbs, etc., and any superimposed loads input.

Up to 10 uniform and 10 concentrated loads may be applied to the deck. A wearing surface may also be applied. The limits of the wearing surface will be defined by the curbs and median, or the limits of the wearing surface may be input. The Deck Loading Component will allow stage loading of the deck. This feature is used in the analysis of a longitudinal girder system where the deck slab is composite with the girders. The construction of a typical composite girder bridge involves the placement of the fluid concrete on the girders, followed by the placement of the curbs, railings, etc., on the hardened concrete slab. In the analysis of the longitudinal girder system, this results in a two stage dead loading of the structure:

1. The load due to the weight of the fluid concrete being applied to the non-composite girder section.
2. The load due to the weight of the curbs, railing, etc., being applied to the

composite slab-girder section.

The placement of the fluid concrete on the girders is analyzed by calculating the uniform load on the girders due to the weight of the slab and applying this uniform load to the girder in a structural analysis program, such as BRASS-GIRDER(LRFD)™. BRASS-PIER (LRFD)™ treats the deck as a continuous one foot wide beam over the girders. The reactions due to this one foot wide beam are calculated. The reactions at the girders for the one foot strip of deck then become the uniform loads (in kips per foot) to be applied to the individual non-composite girders in the structural analysis. The placement of the curbs, railing, etc., on the slab is analyzed by BRASS-PIER(LRFD)™ in the same method mentioned above to determine the uniform loads to apply to the individual composite girders in the structural analysis.

The input command set for the dead load distribution run may be saved, and with minor modifications, used for the live load distribution for frame pier analysis. The live load distribution section of the Deck Loading Component will position a specified live load (truck and lane) transversely on roadway at one foot intervals and calculate the live load reaction to each girder for each position. The resulting live load reactions are stored internally for use by the frame section of the Pier Analysis and Loading Component. The live load distribution section must be executed immediately prior to, and in the same run as, the frame section of the Pier Analysis and Loading Component so that the live load reactions will be available for use in applying the live load to the pier.

## 1.2 Pier Cap Analysis and Design

The pier cap analysis component will either review flexure and shear reinforcement as specified by the user or compute the required reinforcement for flexural and shear. The review/design can be performed for both solid shaft and frame piers. The cap analysis component cap be run either as part of a full pier analysis or independently.

## 1.3 Pier Analysis and Loading

The Pier Analysis and Loading Component, using the dimensions and loads input, will apply the resulting forces to the pier and determine the resultant actions in the pier (shear and moment in the cross beam, axial load and moment in the columns). The PCA Column Design Component, when supplied the cross-section properties and applied loads, will determine the required column reinforcement. If the actual column reinforcement is input, the program will determine the adequacy of the section to resist the applied loads. The Pier Support Component takes the forces at the bottom of the columns and performs one or more types of footing design.

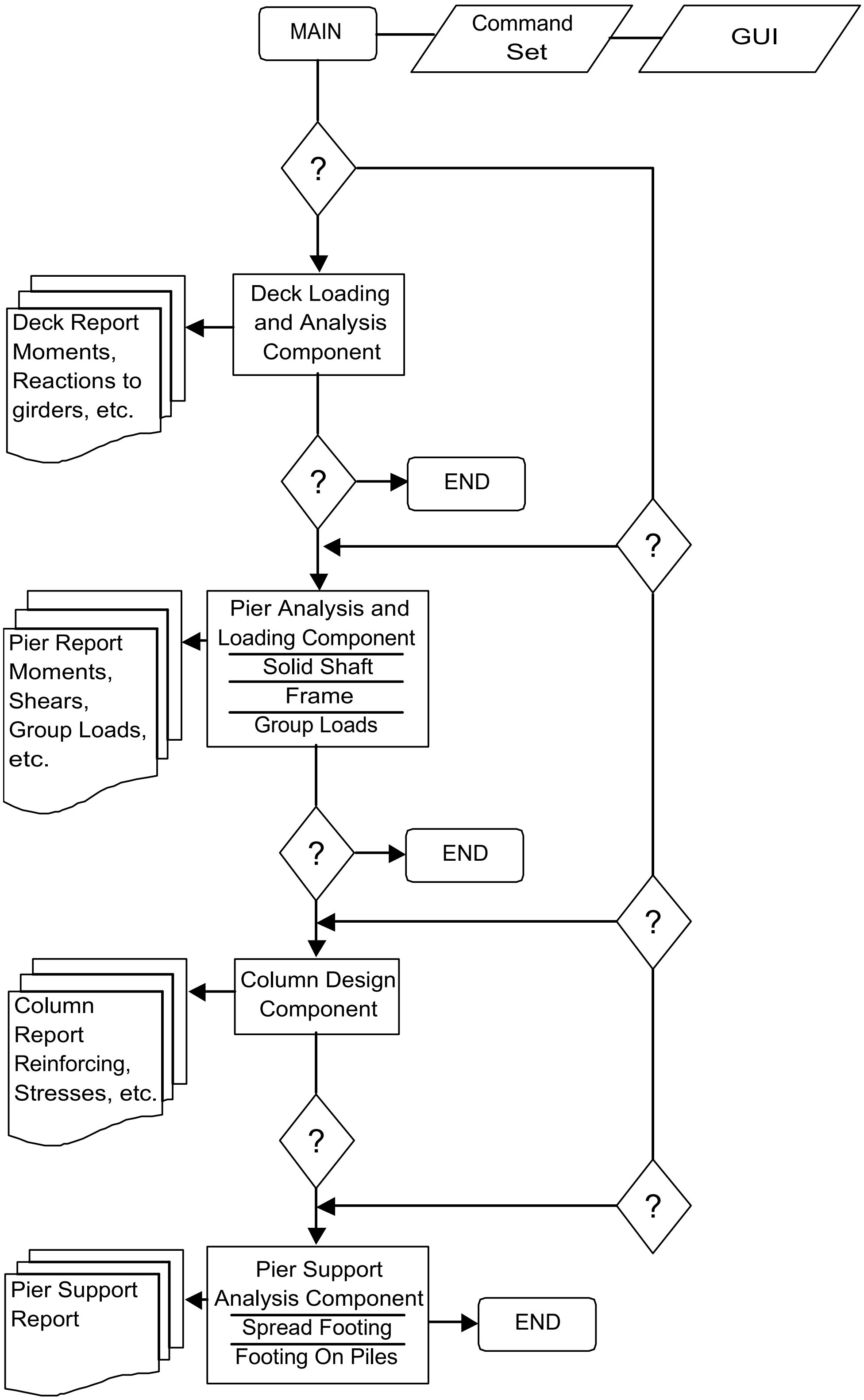



**Figure 1** BRASS-PIER(LRFD) System Overview

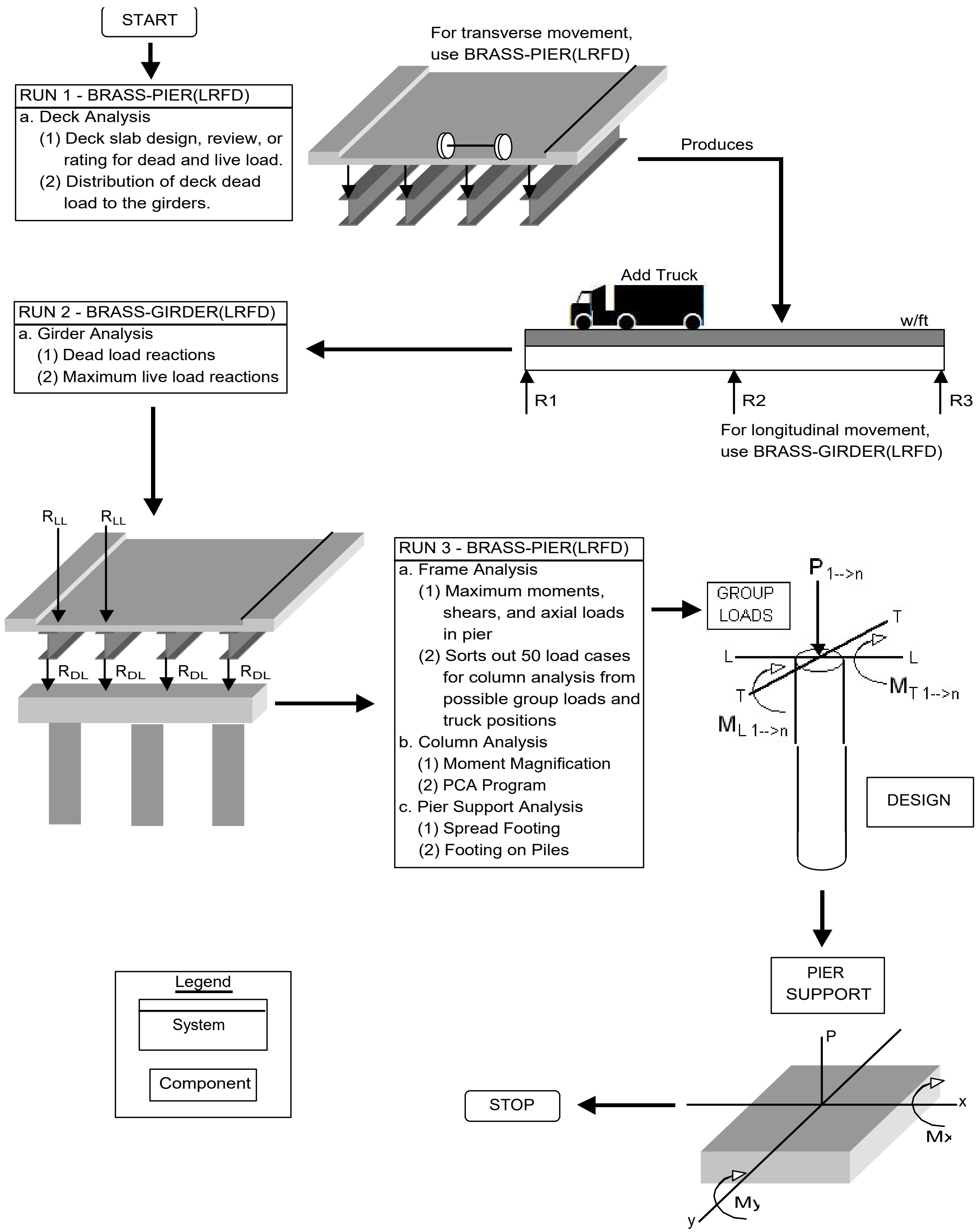



**Figure 2** Combined BRASS-GIRDER(LRFD) and BRASS-PIER(LRFD) Usage

The Pier Analysis and Loading Component will analyze either solid shaft piers or frame piers with two to six columns. The loads which may be applied are: Dead, Live, Wind, Shrinkage, Temperature, Centrifugal Force, Longitudinal Force, Earthquake, Buoyancy, Stream Flow, and Ice Pressure. The vertical loads from the superstructure (Dead and Live load) may be applied by either input of the girder reactions or automatically through the Deck Analysis and Loading

Component. The horizontal forces from the superstructure (Centrifugal and Longitudinal, or Braking, forces) and the forces from nature (Buoyancy, Stream Flow, and Ice Pressure) may be applied by either input of the force or by input of the data required to calculate the force. Forces applied transversely to the superstructure are applied longitudinally to the substructure. Conversely, load applied longitudinally to the superstructure are applied transversely to the substructure. See Figure 3. The forces on the pier which result from the application of the various loads are combined according to the AASHTO specifications for Combination of Loads, 3.4.1.

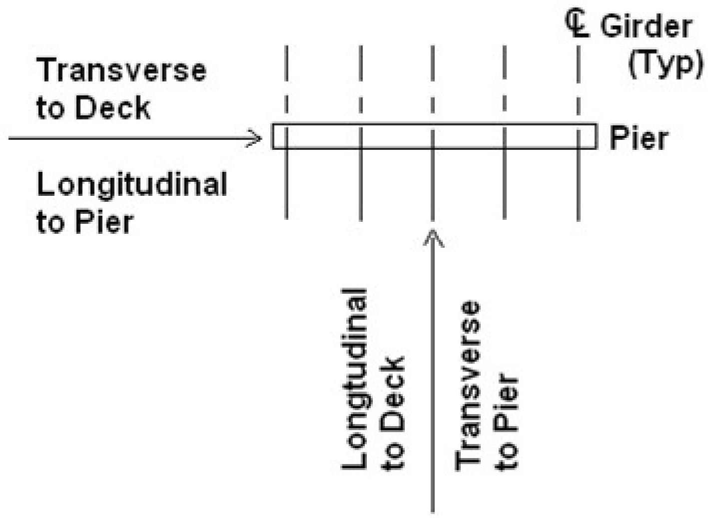



**Figure 3**

## 1.4 Column Analysis and Design

The Column Analysis Component will analyze columns from either solid shaft piers or frame piers. This component may be run independently or be included in a complete pier analysis wherein the loads will be passed automatically to this component.

As there is a very large number of load cases to consider for the design of columns in a frame pier, it is impractical to analyze each case. The many possible positions of trucks on the bridge deck and number of group load combinations create literally thousands (depending on deck width) of load cases of $M_L$, $M_T$, and P. BRASS-PIER(LRFD)™ automatically eliminates all identical load cases, and then utilizes the following procedure to reduce the number of load cases to a maximum of 50.

Each load case, c, produces a vector, $V_C$

where $V_c = \sqrt{(M_{T_c})^2 + (M_{L_c})^2 + (P_c)^2}$

The direction of the load vector is determined by its horizontal angle about the P axis and its vertical angle above the plane containing the $M_L$ and $M_T$ axes. As P is always positive and a column symmetrical about both axes is assumed, only that portion of the biaxial bending interaction diagram where $M_L$, $M_T$, and P are positive is considered as shown in Figure 4.

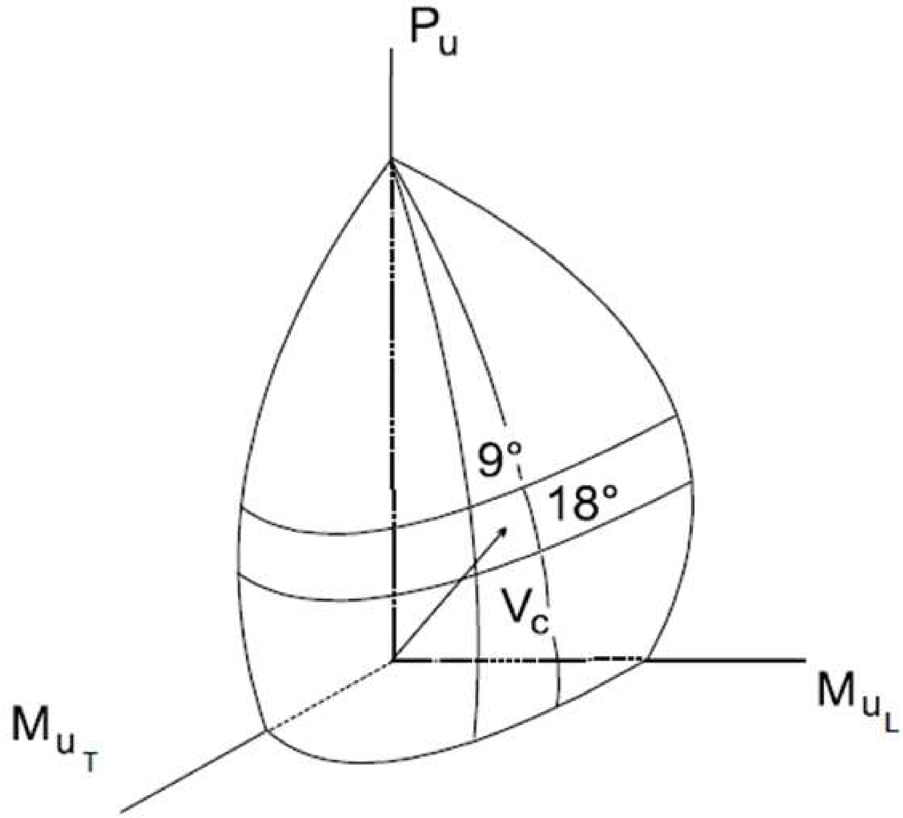



**Figure 4** Column Failure Surface

Any vector $V_C$ which projects through the failure surface formed by the diagram indicates that the column is not adequate for load case c. Therefore, the column must be designed so that no vector passes through the failure surface. To accomplish this, BRASS-PIER(LRFD)™ divides the failure surface into 50 "windows", each 9° wide horizontally and l8° long vertically as shown in Figure 4. BRASS-PIER(LRFD)™ then finds the load case having the longest vector in each window. Generally there are less than 50 because some windows will have no vectors.

For each load case, c, the Column Design Component will design the required reinforcement for a reinforced concrete compression member or will investigate the adequacy of a given cross section to resist a similar set of loadings. The method of solution is based on accepted ultimate strength theories for reinforced concrete design. It will also compute the moment magnifiers (AASHTO) to take into account slenderness effects.

### 1.5 Footing Analysis and Design

The Footing Analysis component consists of the following sections:

1. Spread Footing analysis
2. Footing on Piles analysis

This component may be run independently or be included in a complete pier analysis wherein the loads will be passed automatically to this component.

## 2 Deck Analysis and Loading

### 2.1 The Deck Analysis and Loading Component

This component can be used to compute the dead load per foot of deck to the girder. The dead load of the deck is applied to the girders based on the dimensions of the deck, the unit weight of the deck material, and the loads, which are input by the user. A wearing surface may also be applied with the limits of the wearing surface defined by dimensions of the curbs and median, the user having the option to override these limits by input of the desired limits.

The user then combines the deck dead load with the girder self weight to calculate the reaction at the pier. The program will then automatically calculate the dead and live load reactions to the pier. The deck may be supported by up to 20 girders.

The user may specify the sequence in which the loads are to be applied to the deck by coding the stage in which each load is to be applied.

The live loads are applied to the deck by moving a truck or lane load across the roadway, from left to right, and calculating the reaction to each girder for each position when doing a frame analysis or a cantilever analysis on a solid shaft pier. For a column analysis of a solid shaft pier, the truck or lane load is assumed to be applied directly to the pier cap. The limits of the roadway are defined by the curb and median dimensions, with the user having the option of overriding these limits. To obtain the value of the truck load to be applied to the deck, assume that one line of wheels is placed directly on the longitudinal girder section, see Figure 1. Then position the wheels to produce maximum reaction at the pier and calculate the reaction due to that placement. When a longitudinal girder analysis program (such as BRASS-GIRDER(LRFD)™) is used, the reaction may be obtained by dividing the maximum live load reaction due to the truck load by two times the live load distribution factor.

The truck load is applied as two point loads equal to the reactions input, spaced 6 feet apart, centered in a 10 foot load lane, see Figure 2. The value of the lane load to be applied to the deck is obtained by assuming that a one-foot strip of the lane load is placed directly on the longitudinal girder section, see Figure 3. The concentrated load is considered to be distributed over the 10 foot lane width, a one foot wide section of that load then being placed directly on the girder section. The uniform load and the concentrated load are then placed to produce maximum reaction at the pier and the reaction calculated. When a longitudinal girder analysis program (such as BRASS-GIRDER(LRFD)™) is used, the reaction may be obtained by dividing the maximum live load reaction due to the lane load by the live load distribution factor times the lane width (10 feet). The load lane is applied as a uniform load distributed over the 10 foot lane width. The value of the reaction input is the per foot value of the uniform load. When the live load girder reactions are to be available for use in applying the live load to a frame or solid shaft pier, the live load distribution option must be specified.

## 2.2 Dynamic Load Allowance

Truck loads, with dynamic load allowance, and lane loads should be entered. BRASS-PIER(LRFD)™ will divide out the dynamic load allowance for foundation analysis.

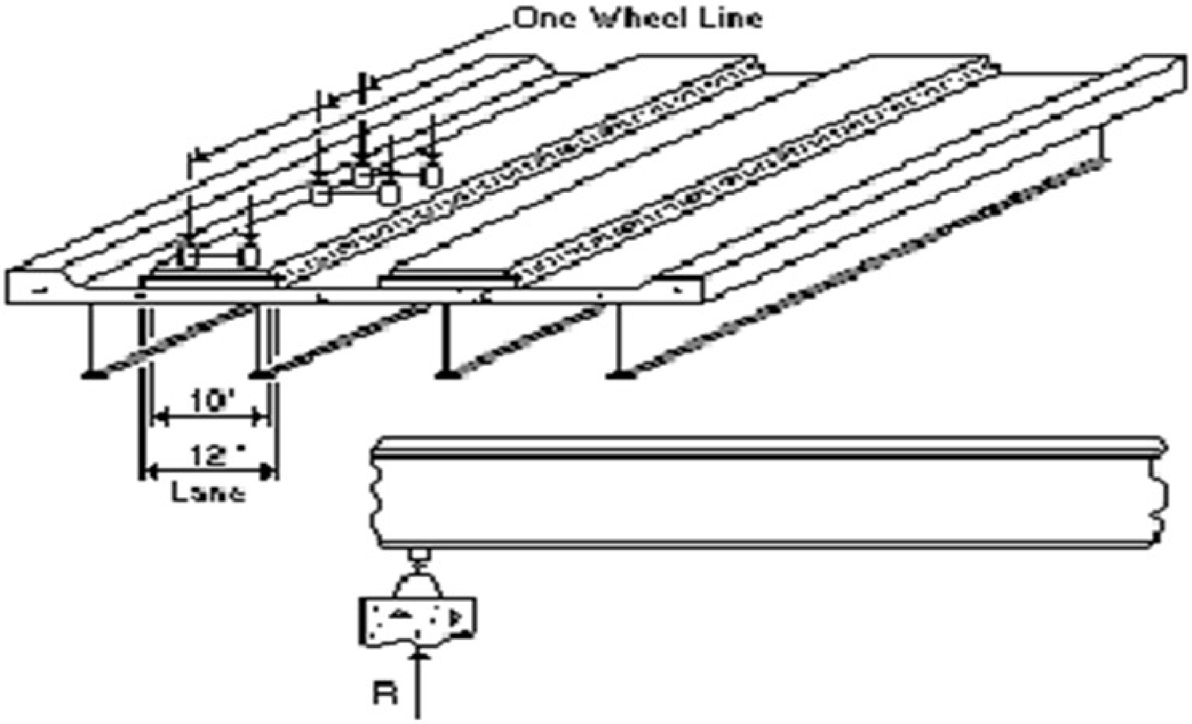



**Figure 1** Placement of Truck on Girder

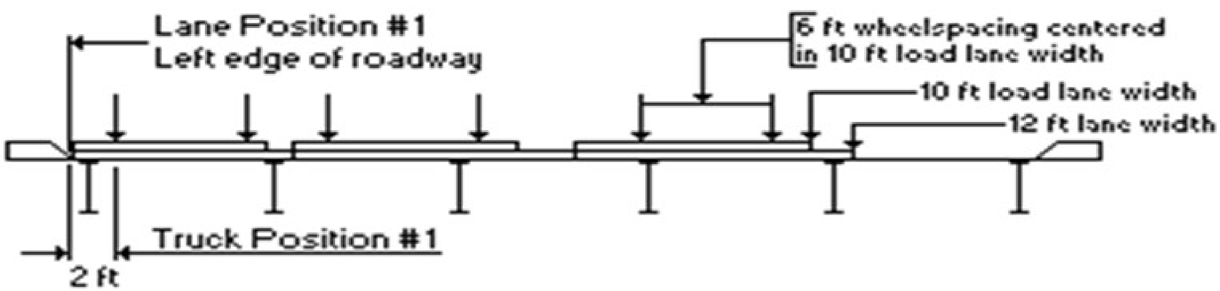



**Figure 2** Placement of Truck on Deck

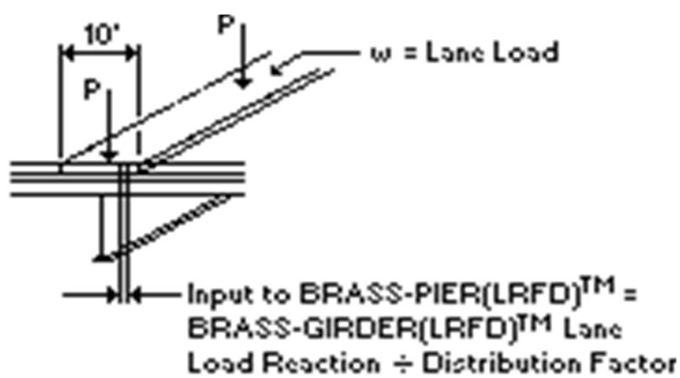



**Figure 3** Placement of Lane Load on Girder

# 3 Pier Cap Analysis and Design

The pier cap analysis and design component will perform a review or design of the flexure and shear reinforcement for the pier cap. The actions (axial loads, shears, and moments) due to the various loadings are combined according to AASHTO 3.4.1 (Load Factors and Combinations).

For a review problem, the program will analyze every tenth point for each of the interior pier cap spans, and fifth points of the cantilevers. The program performs strength and serviceability (maximum steel, minimum steel, fatigue, and crack control) checks for flexure at each location. Compression steel is not currently considered by the program. The rebar is input based on the layout depicted in Figure 1. Rows one through three resist positive flexure, while rows four through six resist negative flexure.

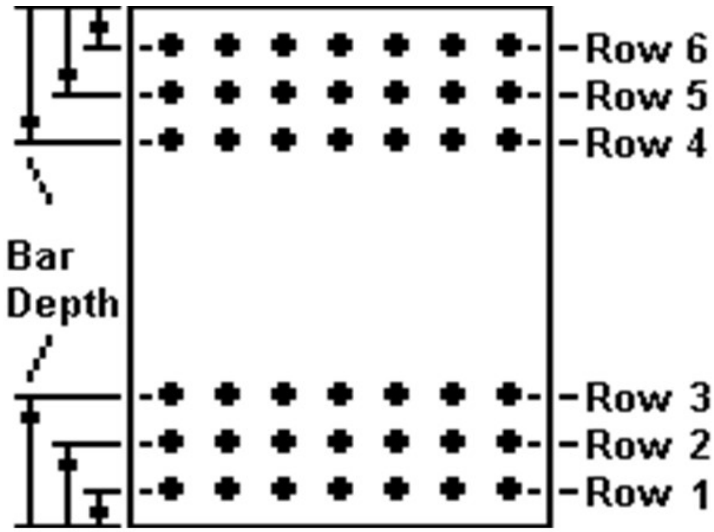



**Figure 1 Rebar Layout**

For a shear review, the program will compute the shear resistance and compare it to the applied shear. The shear resistance can be computed automatically by the program using the modified compression field theory (the general procedure outlined in AASHTO 5.8.3.4.2), or the user can enter values for theta and beta. By entering 45 degrees and two for theta and beta, respectively, the simplified procedure from AASHTO 5.8.3.4.1 is used.

The flexural design algorithm computes the area of steel required at each tenth point (fifth point for cantilevers). This value will not be checked against serviceability requirements. The design component will also find the maximum positive and negative flexure locations and select a group of bars. The bars selected for the maximum positive and negative moments are checked against all requirements.

The flexure design algorithm will try to fit all the rebar in one row. The program will start with the minimum bar size specified by the user and increment the bar size as necessary to meet code. If the maximum bar size specified by the user will not meet the specifications requirements in one row of steel, a second row will be added. The program will then start at the minimum bar size in two rows of steel and increment up to the maximum bar size in two rows of steel. If an acceptable design cannot be achieved with two rows of steels, the same process will be used for three rows of steel.

The shear design routine determines the spacing and size of the stirrups required at each tenth point (fifth point for cantilevers).

# 4 Pier Analysis and Loading

## 4.1 Pier Analysis

The Pier Analysis and Loading component will analyze a solid shaft or a frame pier for all AASHTO Loadings, i.e., it converts the loadings to the pier into axial loads, shears (crossbeam of a frame pier only), and moments at various locations on the pier.

The actions (axial loads, shears, and moments) due to the various loadings are combined according to AASHTO 3.4.1 (Load Factors and Combinations).

The Solid Shaft Pier section will analyze a pier with a single column.

**Figure 1** Solid Shaft Pier Examples

The Frame Pier section will analyze any single-story, open frame bent with a minimum of two and a maximum of six columns. Cantilevers are permissible on one or both ends of the bent. Columns may be either round or rectangular in cross section and each one may have a different length. Crossbeam spans between columns may be of different length and size, and haunches may be straight or parabolic.

The user can set the method type (Direct Stiffness considering or ignoring axial effects) to be used in analyzing the pier. This option is only available if the Cap option is checked. Choosing Direct Stiffness (Considering Axial Effects) will analyze the pier by the direct stiffness method. Choosing Direct Stiffness (Ignoring Axial Effects) will analyze the pier with infinite axial stiffness for each member. The results of this analysis can be compared directly to a moment distribution analysis. Fixity of the columns at the footing may vary from a pin connection to a rigid connection and is left as an option to the designer.

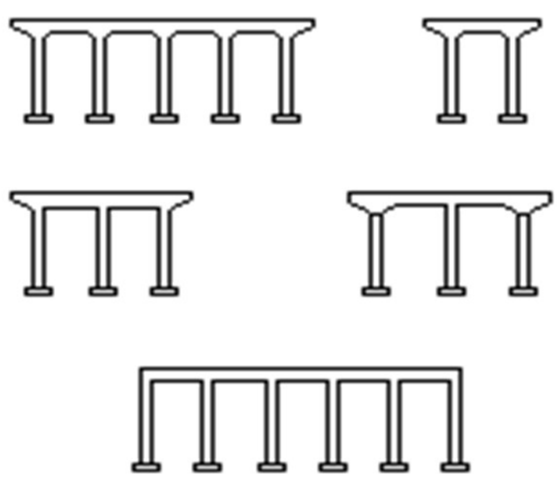


**Figure 2** Frame Pier Examples

Most of the loads applied to the pier are applied through the girder bearings. Therefore, it is necessary to define the location and the position of the bearings on the pier, i.e., distance from the left end of the pier to the centerline of the bearing and offset from the centerline of the pier to the centerline of the bearing (for a double bearing pier only). For a single bearing pier the bearing is assumed to be placed over the centerline of the pier, Figure 3.

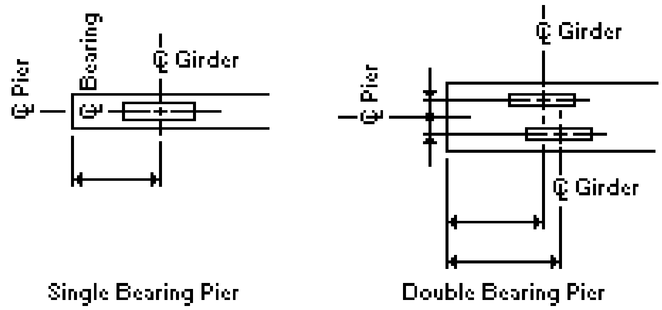



**Figure 3** Single and Double Bearing Piers

When defining the location of the bearings (or the loads to be applied to the bearings) for a double bearing pier, it is necessary to indicate which line of bearings is being defined. The bearings are described as being either back-on-line or ahead-on-line, Figure 4.

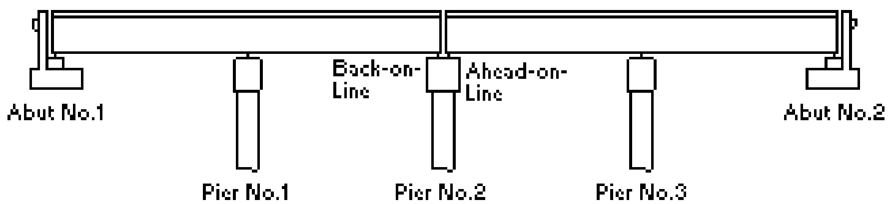



**Figure 4** Description of Back-on-Line and Ahead-on-Line

The orientation of the girder bearings refers to the relationship between the centerline of bearing and the centerline of the pier, normally called the skew. If the centerline of bearing is parallel to the centerline of the pier, the skew is 0° and the pier is referred to as a normal pier, Figure 3. When the centerline of bearing is not parallel to the centerline of the pier, the pier is referred to as a skewed pier and the angle between the centerline of bearing and pier (called the skew) must be given in decimal degrees. A right hand skew is positive and a left hand skew is negative, Figure 5.

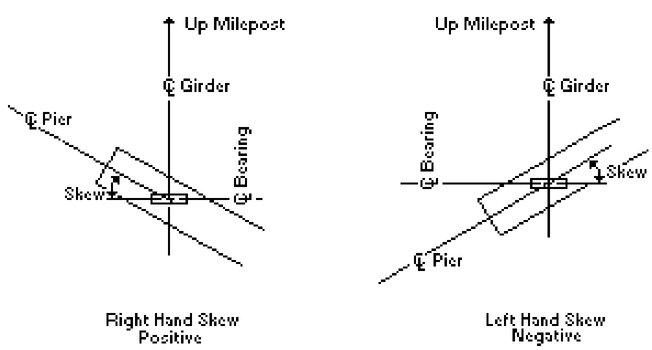



**Figure 5** Skew Conventions

## 4.2 Pier Loading

This component will apply the following AASHTO loads to a pier:

- ✓ Component Dead Load
- ✓ Wearing Surface Dead Load
- ✓ Live Load

- ✓ Wind Load
- ✓ Centrifugal Force
- ✓ Braking Force Due To Live Load
- ✓ Buoyancy and Stream Flow
- ✓ Ice Pressure
- ✓ Earthquake
- ✓ Shrinkage
- ✓ Temperature

The dead load of the pier will be calculated and applied based on the dimensions of the pier and the unit weight of the concrete input by the user. For a solid shaft pier, the dead load of the pier is applied as an axial load and a moment about the longitudinal axis (for a pier with non-identical cantilevers). For a frame pier, the dead load of the crossbeam is applied as a uniform load (or a non-uniform load if there are haunches) to the frame and the dead load of the columns are applied as axial loads. If a double bearing pier has a step, the weight of the step is applied as an axial load to a solid shaft pier and is applied as a uniform load to a frame pier.

The dead load and live load of the superstructure are applied to a pier as point loads at the locations of the girder bearings. The dead load reactions (and the live load reactions for a solid shaft pier analysis) are input by the user. The live load reactions for a frame pier analysis may be either input by the user or generated by BRASS. The live load reactions generated by BRASS are the result of one truck (or lane) being moved from left to right across the deck at one foot intervals. Two methods of combining live load reactions for multiple loaded lanes are available. The first method is to *automatically* apply the live load to the frame and generate actions due to each truck position. The second method is to *manually* input the truck positions and allow BRASS to generate actions due to each truck position. For both methods, BRASS will combine the actions due to all possible placements of trucks on the roadway and search for maximums. For multiple lanes loaded, multiple presence factors are applied to the input truck and lane reactions according to AASHTO LRFD Section 3.6.1.1.2. Placement of the trucks on the bridge roadway to search for maximum actions is accomplished as follows:

The maximum number of lanes possible for the given roadway is determined and the structure is loaded with the maximum number of lanes, all lanes shifted to the far left of the roadway, Figure 6.

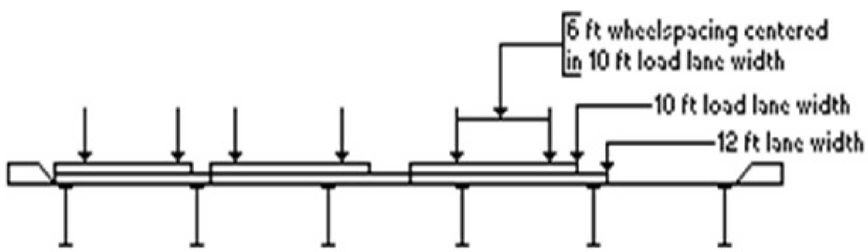



**Figure 6**

The rightmost loading lane is then shifted to the right at 1 ft. increments, until the lane reaches the far right of the roadway, Figure 7.

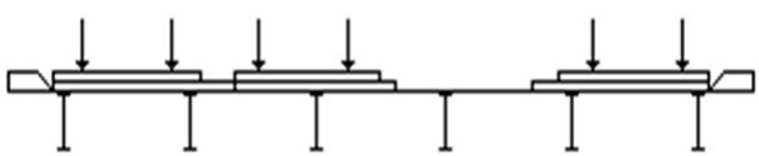


**Figure 7**

Each time the lane is moved, the new position of the lane combined with the positions of the remaining lanes defines a load case and the actions due to that load case are checked for maximums. The next to the rightmost lane is then shifted to the right by a 1 ft. increment and the rightmost lane is shifted as far left as it will go, Figure 8.

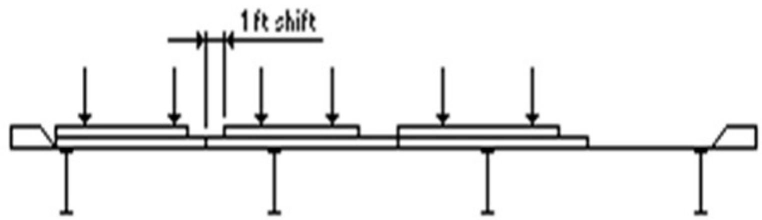



**Figure 8**

This procedure of shifting each lane to the left when the lanes to the right have reached the far right is repeated until all lanes are as far to the right as possible, Figure 9.

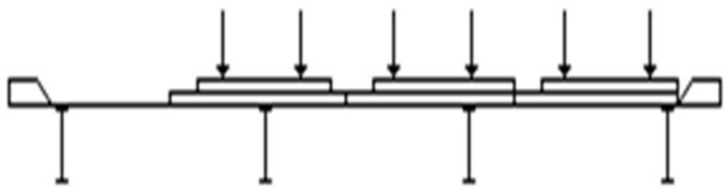


**Figure 9**

When this happens, the lanes are all shifted back to the far left and the rightmost lane is removed and the above procedure repeated. This procedure of removing the rightmost lane when all lanes have been shifted as far right as possible is repeated until only one lane is left and it has been shifted to the far right.

As the lanes are being moved across the roadway, the crossbeam actions (shears, moments, reactions) are searched for maximums and the column actions are searched for the maximum vector length ($\sqrt{P^2 + M_1^2 + M_2^2}$) in each of the 50 "windows" of the failure surface. See Chapter 2 for more information.

The output will show the positions of the trucks and lanes, which produce the maximum actions. For the crossbeam actions, the number will appear as: aa bb cc ...., where aa refers to the position of the first truck, bb refers to the position of the second truck, etc. For the column actions, the number will appear as: a bb cc dd ...., where a specifies the type of load - 1 = truck, 2 = lane, bb refers to the position of the first truck, cc refers to the position of the second truck, etc. Position No. 1 refers to a truck with its left edge of load lane at the left edge of the roadway and its left wheel 2 ft. from the left edge of the roadway, Figure 10

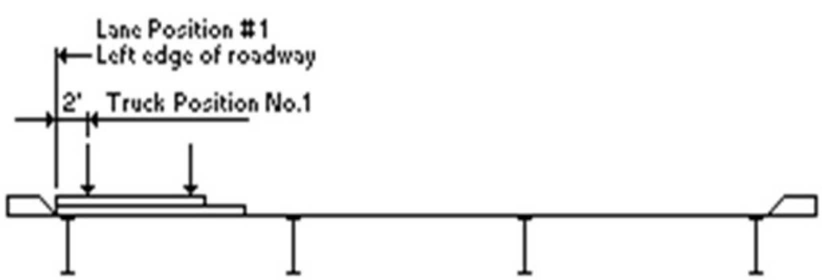



**Figure 10**

Therefore, the distance from the left edge of the roadway to the left edge of the load lane, in feet, is equal to the Position No. minus 1 and the distance from the left edge of the roadway to the left wheel of the truck, in feet, is equal to the Position No. plus 1, Figure 11.

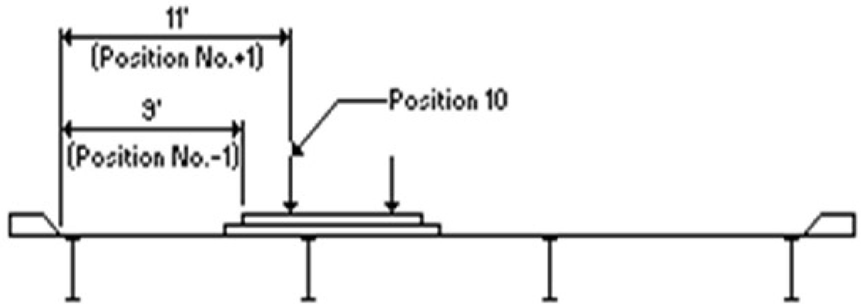



**Figure 11**

For a solid shaft pier, the option to input the action due to dead and live load (Axial load, Moments about longitudinal and transverse axis) is also available. (See Figure 3, Page 1.5 for the definition of the axes). For the live load to a solid shaft pier, the option is also available to input the reaction at the pier due to the placement of a truck or a lane load on the superstructure. The program will then place the truck or lane loads on the pier in numbers and positions to produce maximum actions on the pier.

The wind load forces will be calculated and applied to the pier if requested. The wind load forces are calculated as per AASHTO 3.8, which specifies two methods for calculation and application of the wind load forces. The first method specifies that the forces due to the wind load be calculated for various angles of wind direction, Figure 12.

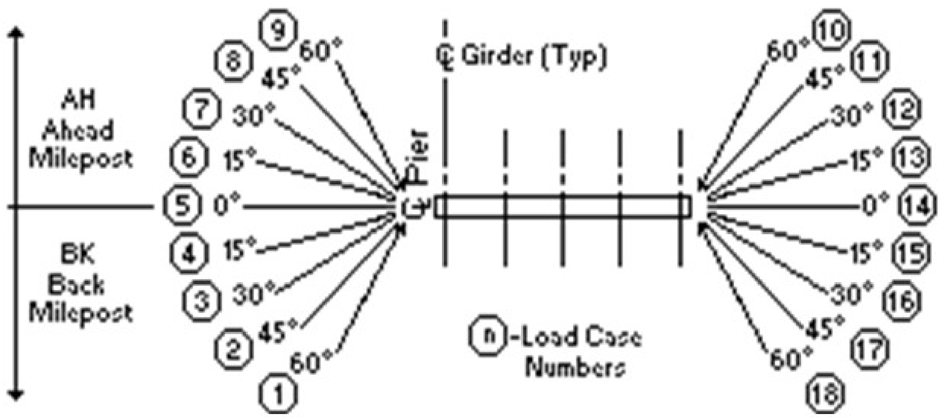



**Figure 12** General Method for Wind

For skewed bridges, the General Method has wind loads applied to the structure as shown in Figure 13.

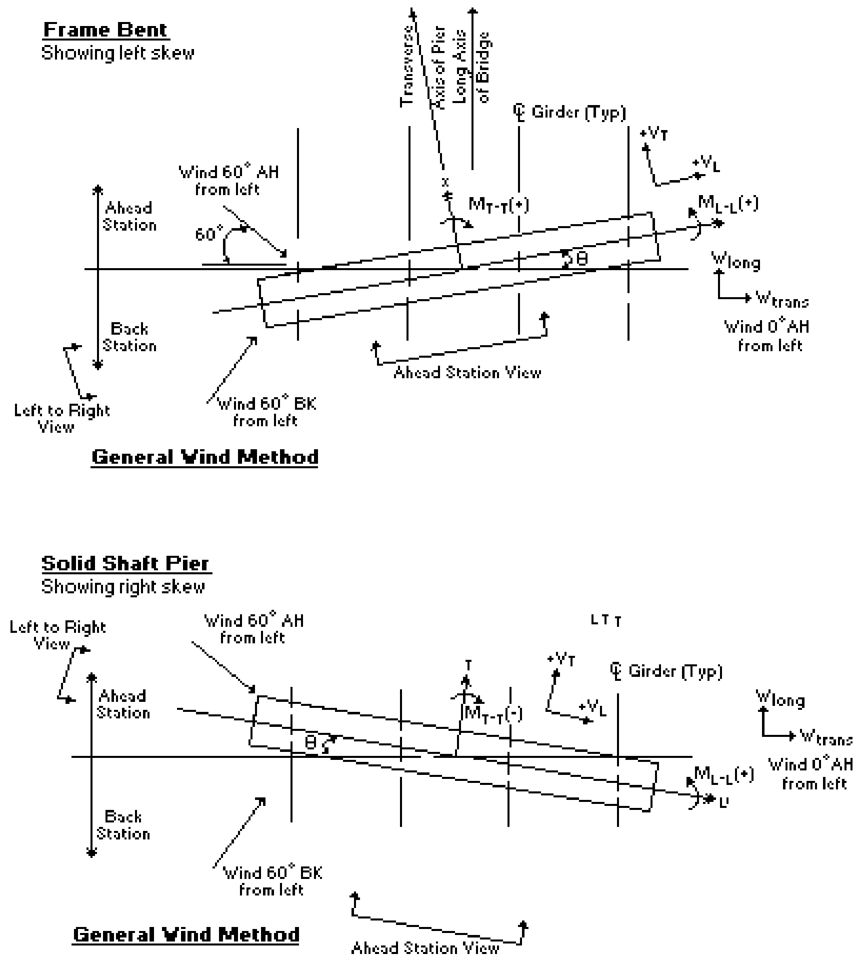



**Figure 13** Sign Convention for Wind Analysis

In addition to the wind load applied directly to the superstructure and transmitted to the pier, a wind load is applied to a moving live load and transmitted to the pier through the superstructure.

An upward force is applied at the windward quarter point of the transverse superstructure width, Figure 14. The user may select an option to ignore this force.

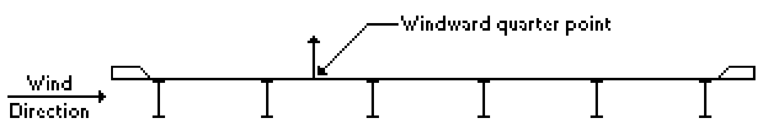



**Figure 14**

Normal design procedure, for ease of computations, is to apply the uplift force at a point on the pier cap, which is directly beneath the quarter point of the transverse superstructure section, Figure 15.

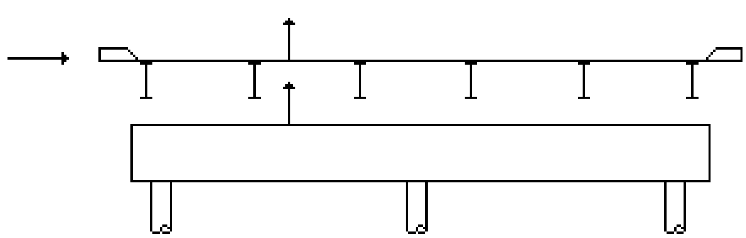


**Figure 15**

A more realistic approach is to distribute the uplift force to the girders and then to the pier through the girder bearings, Figure 16. Either method may be used in BRASS-PIER(LRFD)™.

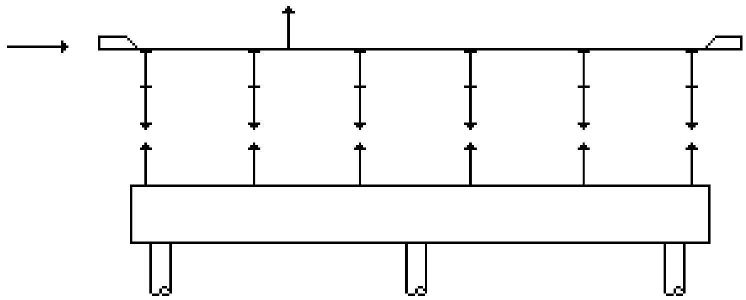


**Figure 16**

The user may input the girder reactions due to a unit uplift force applied at the quarterpoint. These reactions due to the unit uplift force will be multiplied by the actual uplift force to obtain the reactions to be applied to the pier.

For structures on a horizontal curve, the program will apply a centrifugal force to the pier. The force may be either input by the user or calculated from the data input by the user. The centrifugal force is applied at the top of the pier cap (or the top of a fixed bearing) parallel to the centerline of bearing, Figure 17.

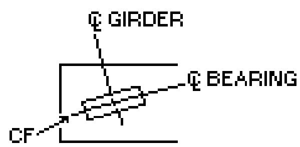



**Figure 17**

Braking of the vehicles on the bridge creates a force on the bridge deck, which transfers a force to the pier. For a fixed bearing pier, the force calculated by BRASS-PIER(LRFD)™ is equal to 25% of the design truck or design tandem per lane placed in all lanes headed in the same direction (AASHTO 3.6.4). For an expansion rocker bearing, the longitudinal force must be input by the user. The longitudinal force is applied at the top of the pier cap (or the top of a fixed bearing) parallel to the centerline of the girder, Figure 18.

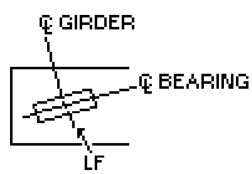



**Figure 18**

If the structure is skewed, the component of the longitudinal force parallel to the pier cap is applied at the center (top to bottom) of the pier cap, Figure 19.

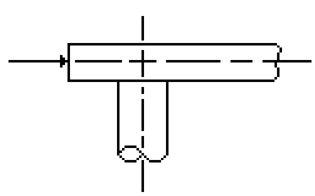


**Figure 19**

The force to the pier due to shrinkage of the superstructure may be input, or the horizontal deflection at the top of the pier may be input. The force to the pier due to the effects of change in temperature on the superstructure may be input, or the horizontal deflection at the top of the pier applied at the top of the pier cap (or the top of a fixed bearing) parallel to the centerline of the girder, Figure 18.

The modeling of a structure to determine the response to seismic forces is a complex process and is normally performed on a system designed exclusively for seismic analysis. However, when applicable, BRASS-PIER(LRFD)™ allows the user to apply a force at the top of the pier representing the movement of the structure during an earthquake. The program will determine the actions due to the applied force. The force is input as a component parallel to the centerline of the pier and a component normal to the center line of the pier.

The forces on the pier due to water (buoyancy and stream flow) and ice may be input by the user or the data required to calculate the forces may be input and the program will calculate the forces. The buoyancy force is applied as an upward force on the columns. The stream flow force is applied to the centerline of the pier at one-half the water depth above the streambed level. The in-plane stream flow force is calculated as follows (AASHTO 3.7.3):

S = p Asf, kips

p = Cp V2/1000 = pressure of flowing water, KSF

S = stream flow force, in pounds

V = velocity of water, in feet per second

Cp = drag coefficient based on the shape of the upstream edge of the pier.

The following values of Cp are used:

| | |
|---|---|
| 1.4 | for square ends and all piers subject to drift buildup |
| 0.5 | for angle ends where the angle is 30° or less |
| 0.7 | for circular ends |
| 0.8 | Angled pier |

Asf = projected surface area exposed to stream flow

dw = Depth of water, in feet

b = Width of face of pier normal to stream flow or diameter of circular shaft

The out-of-plane stream flow force is calculated as follows:

S = pAL

p = CL V2/100 = pressure of flowing water, KSF

V = velocity of water, in feet per second

AL = Area of lateral surface exposed to stream flow

CL = lateral drag coefficient dependent on the angle of stream flow

The following values of CL are used:

Angle, θ, between the direction of stream flow and the longitudinal axis of the pier.

| | |
|---|---|
| 0° | CL = 0.0 |
| 5° | CL = 0.5 |
| 10° | CL = 0.7 |
| 20° | CL = 0.9 |
| >30° | CL = 1.0 |

The ice pressure is applied to the pier as a force parallel to the centerline of the pier and a force normal to the centerline of the pier. The forces are applied at the center of the ice layer. The forces are calculated as follows (AASHTO 3.9.2.2):

The horizontal force, F, is taken as:

If w/t ≤ 6.0, then F = the lesser of either Fc or Fb
If w/t > 6.0, then F = Fc

For which:

$F_c$ = Captw
$F_b$ = Cnpt2
$C_a$ = (5t/w + 1)0.5
$C_n$ = 0.5 / tan(α - 15)

Where:

T = thickness of the ice (ft)
α = Inclination of the nose to the vertical (degrees)
p = effective ice crushing strength
w = pier width at level of ice action (ft)
$F_c$ = horizontal force caused by ice floes that fail by crushing over the full width of the pier (kips)
$F_b$ = horizontal ice force caused by the ice floes that fail by flexure as they ride up the inclined pier nose (kips)
$C_a$ = coefficient accounting for the effect of the pier wither/ice thickness ratio where the floe fails by crushing
$C_n$ = coefficient accounting for the inclination of the pier nose with respect to vertical

Note: if α ≤ 15 degrees, ice failure by flexure is not considered a possibility.

The combination of in-plane and out-of-plane forces is performed as follows:

If the angle, θ, between the ice flow direction and the longitudinal axis of the pier is zero degrees, the provisions of AASHTO 3.9.2.4.1 apply and the transverse force is calculated as:

$$F_p = \frac{F}{2\tan\left(\frac{\beta}{2} + \theta_r\right)}$$

The following load combinations are examined in this case:

1. The in-plane force, F, is combined with an out-of-plane force of .15F.
2. The out-of-plane force, Ft, is combined with an in-plane force of .5F.

If the angle, θ, between the ice flow direction and the longitudinal axis of the pier is greater than zero degrees, the provisions of AASHTO 3.9.2.4.2 apply and the in-plane and out-of-plane forces are calculated by using the projected width of the pier to calculate F. The total force, F, is then resolved into vector components representing in-plane and out-of-plane forces. For this case, the out-of-plane force is always at least 20 percent of the total force, F.

The nose inclination, the effective ice strength, "p", the thickness of ice, "t", and the distance from the stream bed to the point of application of the ice pressure, are input by the user.

BRASS-PIER(LRFD) loads the pier with unfactored loads and factors the resulting actions. The load combinations considered by BRASS-PIER(LRFD) for a standard pier design based on the AASHTO LRFD Bridge Design Specifications are as follows:

STRENGTH-I Min = 0.9*DC + 0.65*DW + 1.75*(LLmin+CE+BR) + 1.00*WA + 0.5*(TU+SH)min

STRENGTH-I Max = 1.25*DC + 1.5*DW + 1.75*(LLmax+CE+BR) + 1.00*WA + 1.2*(TU+SH)max

STRENGTH-II Min = 0.9*DC + 0.65*DW + 1.35*(LLmin+CE+BR) + 1.00*WA + 0.5*(TU+SH)min

STRENGTH-II Max = 1.25*DC + 1.5*DW + 1.35*(LLmax+CE+BR) + 1.00*WA + 1.2*(TU+SH)max

STRENGTH-III Min = 0.9*DC + 0.65*DW + 1.00*WA + 1.4*WS + 0.5*(TU+SH)min

STRENGTH-III Max = 1.25*DC + 1.5*DW + 1.00*WA + 1.4*WS + 1.2*(TU+SH)max

STRENGTH-IV Min = 1.5*DC + 0.65*DW + 1.00*WA + 0.5*(TU+SH)min

STRENGTH-IV Max = 1.5*DC + 1.5*DW + 1.00*WA + 1.2*(TU+SH)max

STRENGTH-V Min = 0.9*DC + 0.65*DW + 1.35*(LLmin+CE+BR) + 1.00*WA + 0.40*WS + 1.0*WL + 0.5*(TU+SH)min

STRENGTH-V Max = 1.25*DC + 1.5*DW + 1.35*(LLmax+CE+BR) + 1.00*WA + 0.40*WS + 1.0*WL + 1.2*(TU+SH)max

EXTREME EVENT-I Min = 0.9*DC + 0.65*DW + $Y_{EQ}$*(LLmin+CE+BR) + 1.00*WA + 1.00*EQ

EXTREME EVENT-I Max = 1.25*DC + 1.5*DW + $Y_{EQ}$*(LLmax+CE+BR) + 1.00*WA + 1.00*EQ

EXTREME EVENT-II Min = 0.9*DC + 0.65*DW + 0.5*(LLmin+CE+BR) + 1.00*WA + 1.00*IC

EXTREME EVENT-II Max = 1.25*DC + 1.5*DW + 0.5*(LLmax+CE+BR) + 1.00*WA + 1.00*IC

SERVICE-I Min = 1.00*DC + 1.00*DW + 1.00*(LLmin+CE+BR) + 1.00WA + 0.30*WS + 1.00*WL + 1.00*(TU+SH)

SERVICE-I Max = 1.00*DC + 1.00*DW + 1.00*(LLmax+CE+BR) + 1.00WA + 0.30*WS + 1.00*WL + 1.20*(TU+SH)

SERVICE-II Min = 1.00*DC + 1.00*DW + 1.30*(LLmin+CE+BR) + 1.00WA + 1.00*(TU+SH)

SERVICE-II Max = 1.00*DC + 1.00*DW + 1.30*(LLmax+CE+BR) + 1.00WA + 1.20*(TU+SH)

SERVICE-III Min = 1.00*DC + 1.00*DW + 0.80*(LLmin+CE+BR) + 1.00WA + 1.00*(TU+SH)

SERVICE-III Max = 1.00*DC + 1.00*DW + 0.80*(LLmax+CE+BR) + 1.00WA + 1.20*(TU+SH)

FATIGUE = 0.75*(LL+CE+BR)

# 5 Column Analysis and Design

## 5.1 General Information

Mr. Jose M. Nieves developed the original version of this module while serving as Manager of Computer Services, Portland Cement Association. While the Portland Cement Association has taken every precaution to utilize the existing state of the art and to assure the correctness of the analytical solution and design techniques used in the program, the responsibility for modeling the structure to develop input data, applying engineering judgment to evaluate the output, and implementation into engineering drawings remains with the structural engineer of record. Accordingly, the Portland Cement Association does and must disclaim any and all responsibility for defects or failures in structures in connection with which this program is used.

The Wyoming Department of Transportation revised this program's input and output format and added the capability to take into account slenderness effects magnifying moments. It was then incorporated into BRASS-PIER™, which was later converted to BRASS-PIER(LRFD)™.

## 5.2 Program Description

The purpose of this program is to give engineers the capability to design reinforced concrete compression members to resist a given combination of loadings or to investigate the adequacy of a given cross section to resist a similar set of loadings. Each loading case consists of an axial compressive load combined with uniaxial or biaxial bending. The method of solution is based on accepted ultimate strength theories for reinforced concrete design.

The program will compute the moment magnifiers to take into account slenderness effects. It will magnify all input moments when axial load and moments are input.

## 5.3 Types of Members

The program recognizes round and rectangular concrete cross sections with circular or rectangular reinforcement patterns. For the purpose of definition, member types are classified as Round, Spiral, and Tied. A round member defines a circular cross section with a circular reinforcement pattern; a spiral member defines a rectangular cross section with a circular reinforcement pattern; and a tied member a rectangular cross section with a rectangular reinforcement pattern. In the investigation option, it is also possible to define irregular reinforcement patterns by means of individual bar areas and location.

## 5.4 Reinforcing Steel

The program will only design or investigate bar sizes 2 through 11, 14, and 18.

## 5.5 Design Capabilities

Under the design option, the program will magnify the moments if requested when axial loads and moments are used, and find size, number, and distribution of bars that will result in the minimum area of reinforcement with all bars of the same size required to satisfy all the loading conditions imposed on the cross section. For tied members the number of bars in the sides may be different than in the top and bottom of the cross section.

## 5.6 Investigation Capabilities

At the option of the engineer, the program has the capability of generating interaction data or of determining the adequacy of a cross section to resist a given combination of loads. For the latter case, the program will hold the eccentricity of the axial load equal to that of the case being investigated. The strength of the cross section for the eccentricity will then be computed, and the relationship between the strength and the applied loading will be reported.

## 5.7 Method of Solution

The method of solution is based on accepted ultimate strength theories for reinforced concrete design. Where applicable, the design assumptions and limits used conform to the provisions of both specifications cited in the Design Specifications section. A brief summary of the method of solution follows:

1. When requested, moment magnifiers are calculated based on the following:
   a. The unsupported length $l_U$ is considered in each direction of bending for members; i.e., $l_{UX}$ and $l_{UY}$ must be input.
   b. The radius of gyration used by the program is 0.30 times the overall dimension in the direction in which stability is being considered for rectangular members, and 0.25 times the diameter for circular compression members. Other shapes cannot be used if the moment magnifier is required. The effective length factor, k, may be calculated and input by the user.
   c. The effective length factor, k, may be calculated and input by the user.
   d. The program checks the value if $Kl_U/r$ and for members braced against sidesway ignores effects of slenderness when it is less than 34-12M1/M2. For members not braced against sidesway, it ignores slenderness effects when $kl_U/r$ is less than 22. If it is greater than 100, a message will be output and the program will terminate.
   e. The design moments are magnified per AASHTO 4.5.3.2.2b.
      i. $M_c = \delta_b M_{2b} + \delta_s M_{2s}$
      ii. $\delta_b = \frac{C_m}{1-\left(P_u/\phi P_c\right)} \geq 1.0$
      iii. $\delta_s = \frac{1}{1-\frac{\Sigma P_u}{\phi \Sigma P_e}}$
      iv. $M_{2b}$ = Moment on compression member due to factored gravity loads that result in no appreciable sidesway, always positive.
      v. $M_{2s}$ = Moment on compression member due to factored lateral or gravity loads that result in sidesway, D, greater than $1_u$ / 1500, calculated by first order analysis, always positive.
      vi. φ is set by the program at 0.70 for a tied member and 0.75 for round or spiral members.
      vii. $P_u$ is the factored axial load.
      viii. $P_e$ is calculated by $\pi^2 EI(kL_U)^2$
      ix. EI is calculated by $(E_c I_g/2.5)/(1+\beta d)$
      x. $\beta_d$ and $E_C$ are input by the user.
      xi. $I_g$ is calculated by $bh^3/12$ for rectangular members and by $\pi\ d^4/64$ for round members.
      xii. $C_M$ is calculated by $0.6 + 0.4(M_1/M_2)$ but not less than 0.4.
      xiii. $M_1$ and $M_2$ are input by the user.
   f. The program will not handle column groups.

2. Computations of strength are based on the satisfaction of the applicable conditions of equilibrium and compatibility of strains. The stress-strain relationship for concrete is assumed as shown in Figure 1.

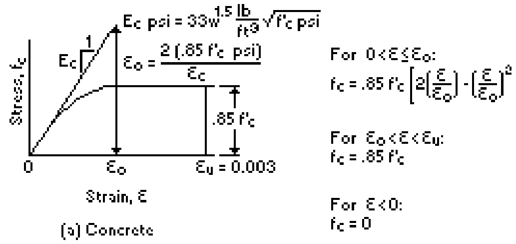



**Figure 1.** Assumed Stress-Strain Relationship for Concrete

3. There are provisions in the input to enable the user to change some of the parameters, which affect the shape of the compression block.

4. Concrete displaced by reinforcement in compression is deducted from the compression block.

5. Stress in the reinforcement below the design yield strength, fy, is directly proportional to the strain. For strains greater than that corresponding to the design yield strength, the reinforcement stress remains constant and equal to fy. The modulus of elasticity Es, is taken as 29,000,000 psi, unless otherwise changes in the input data.

6. Stress in the reinforcement is based on the strain at the actual location of each bar. Reinforcement is defined by the area of each bar and x-y coordinates referred from the centroidal axis of the cross section.

7. All moments are referred to the centroid of the gross concrete section whether the reinforcement pattern is symmetrical or unsymmetrical.

8. Computations for biaxial loading are based on a three-dimensional interaction surface. The method of solution is presented in PCA Advanced Engineering Bulletins No. 18 and 20.

9. The program first computes the theoretical strength of a member on the basis of the strength of the materials, then reduces the theoretical strength to the design strength by the capacity reduction factor.

BRASS-PIER(LRFD)™ has been designed so that when requested, the column dimensions input to, and the loads generated by, the pier analysis component are transferred internally to the column component. The only data that is required to be input by the user is the reinforcement data. The user may, if desired, override any of the column dimensions by entering the appropriate value. For example, AASHTO 5.7.4.2 specifies that "the minimum area of longitudinal reinforcement may be that required for a component with a reduced effective area of concrete". To illustrate, consider a solid shaft (hammer head pier), Figure 2. The column has a cross section that is larger than required for load carrying capabilities.

To reduce the amount of reinforcement required for a lightly loaded column, where the minimum reinforcement ratio would govern, enter the reduced column width.

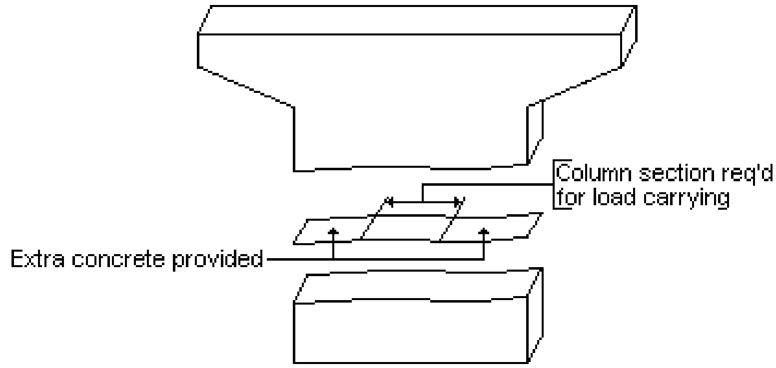



**Figure 2.**

## 5.8 General Notes on Design Option

The design phase of the column analysis component of BRASS-PIER(LRFD)™ determines the minimum amount of reinforcement that will satisfy all the loading conditions given in the input. The reinforcement pattern to be used, and any restrictions as to number of bars and bar sizes, is under the control of the engineer through the stipulations given in the input data.

If no restrictions are given, the program will investigate the full range of number of bars and bar sizes, until the optimum area of steel is found. Even though there are built-in procedures to eliminate the checking of obviously inadequate bar patterns (such as total area of reinforcement outside the reinforcement ratios permitted by the specifications, bar patterns which result in bar spacings where the clear distance between bars is less than allowed by the specifications, total area of steel more than an area which has already been found satisfactory, etc.) The amount of computer time required to solve the problem increases proportionally with the number of load cases to be checked, and the range of the limits set for number of bars and bar sizes.

Obviously, the engineer can be of great help in increasing the efficiency of the computer operation. By using proper judgment and previous experience, input data can be prepared that will shorten the computer run to solve a given problem. There are several means available:

1. A minimum ratio of reinforcement can be input, if it can be predetermined that the ratio of reinforcement will be within a narrower range than the .01 to .08 used in the program.
2. The minimum acceptable clear spacing of bars can be increased in the input if this is a detailing requirement.
3. If the approximate number of bars can be predetermined, or if restrictions can be set for bar sizes, the limits can be input.

In the design option, when it is determined that a certain bar arrangement is satisfactory, the program proceeds to compute the strength of the cross section under combined flexure and axial load, and compares this to the applied loadings. Each loading is checked in the same sequence given in the input. The first time that one of the loadings is not satisfied the checking procedure is terminated and the bar arrangement is rejected. A bar arrangement is accepted only when all the applied loadings are satisfied. In order to speed up the checking procedure, the more critical loading conditions should be input first.

The program rejects any cross section when the load strength is less than 0.99 of the applied load. It should be noted that the computed theoretical strength is reduced by the capacity reduction factor before the comparison is made. For axial loads less than 0.10 f'cAg, the factor varies between that for compression members and that for pure flexure.

The engineer may also wish to set standards for acceptance of a cross section. For example, a strength "overstress" of 5% may be acceptable instead of 1% programmed. The 5% acceptance criteria can be adopted. A factor of 0.735 will result in computed strengths 5% larger that those computed for $\Phi c = 0.7$.

It should also be noted that the method used in this solution of the strength design of compression members is more rigorous than most other methods used in current standards and design aids. For example, the solution uses a parabolic stress diagram for concrete, stress-strain compatibility is used in computing stresses, reinforcement is considered as the actual bars in the actual location (instead of the usual simplifying assumption of a line, which leads to an over-estimation of the contribution of the bars to the strength of the section), and the area of concrete displaced by bars in compression is deducted in the computations. Therefore, the solution has eliminated some of the simplifications, which, because of the possible excess load effects, require larger safety factors in the present specifications. For these reasons, it is reasonable to suggest that the engineer can use less strength reduction (higher factors) when using this program for design of reinforced concrete compression members.

The engineer should be aware that this program computes the strength of the cross section based on moments about the geometric centroid of the gross cross section. Therefore, all input moments must also be referenced to the geometric axes of the concrete section, and all output data should be interpreted likewise. The design capabilities of the program are limited to finding the minimum area of steel for symmetrical reinforcement patterns only.

However, under the investigation option, the program accepts any type of reinforcement configuration, including unsymmetrical patterns. It the engineer desires to compare applied loadings with computed strengths, then the input moments must be given about the geometric centroid.

It should be noted that any reference axis can be used for a design, as long as the applied moment and resisting moments are both referenced to that axis. The geometric centroid is most convenient, since its location is fixed and does not depend on the amount of distribution of the reinforcement. Furthermore, the frame analysis of the structure is usually made using the geometric centroid of the gross cross section. The moments thus obtained can then be used directly as input to the program. If the engineer has computed applied moments about any other axis, then the moments can be easily transferred to the geometric axis by adding a moment equal to the axial load times the distance between the two axes.

Of course, it is not the intention of this program to dictate standards or procedure for design. Every effort has been made to allow maximum flexibility to give the engineer the capability of setting his own criteria for design, and conform to the normal practices in his office. The validity of the solution, and the accuracy of the results, have been thoroughly checked and found satisfactory for all the cases tested. However, to assure proper use, it is advisable that results of the program be first checked against previous designs.

## 5.9 Description of Output

Output listings are for the most part self-explanatory. After the program identification, the information given in the title command is printed out, followed by the verification of input which shows entry by the actual command input values.

If slenderness effects are to be considered and the column is slender, the magnified moments are output next. Load case numbers correspond to the order in which the load cases are entered.

The next page of output is the design or investigations results, which gives the problem type option, and the type of member defined in the input.

Pertinent dimension data for the member will be printed in the next line. If the option is investigation, the given reinforcement data will be printed on the next line. If the option is design, the data for the selected reinforcement will be printed after the design is completed. If no reinforcement pattern was found to satisfy the loading conditions, a message will be printed after the design is completed. If no reinforcement pattern was found to satisfy the loading conditions, a message will be printed so stating.

The form of the output that will follow the reinforcement data will depend on the type of problem being solved, and on the information given in the load commands. All axial loads are given in kips and moments are given in kip-feet. The data will be printed as follows:

## 5.10 Design Option Output

For each loading condition, the following data will be printed:

1. Loading Case Number
2. The applied loadings as given in the input.
    a. AP = Applied axial load
    b. AML = Applied moment component in the direction of the longitudinal axis.
    c. AMT = Applied moment component in the direction of the transverse axis.
3. The computed strength under combined flexure and axial load for the selected reinforcement assuming that the eccentricity of the axial remains constant.
    a. UP = PU = Axial load strength.
    b. UML = ML = Moment strength component in the direction of the longitudinal axis.
    c. UMT = MT = Moment strength component in the direction of the transverse axis.
4. The ratio of the axial load strength to the applied axial load (UP/AP). This ratio will always be larger than .990.

## 5.11 Investigation Option Output

When axial or combined (axial and moments) loads are not specified:

The control points of the interaction diagram will be printed for each of the axis requested in the input. Control points are identified as follows:

PZ = PO axial load strength of section in pure compression.
PB = PB axial load strength of section at simultaneous assumed ultimate strain of concrete and yielding of tension reinforcement (balanced conditions).
MB = MB moment strength of section at simultaneous assumed ultimate strain of concrete and yielding of tension reinforcement (balanced conditions)
MZ = MO moment strength in pure flexure (PU = 0).

When axial loads are specified:

Moment strengths will be printed for each axial load listed in the input (combined bending and axial load strengths). If uniaxial interaction data was requested in the input, only the moment strength about the specified axis will be printed. If biaxial interaction data was requested in the input, the following information will be printed for each axial load:

Loading Case Number

1. UP = PU = axial load strength.
2. UML = MUL = moment strength in the direction of the longitudinal axis with bending considered about the longitudinal axis only.
3. UMT = MUT = moment strength in the direction of the transverse axis with bending considered about the transverse axis only.
4. DLM = ML = moment strength component in the direction of the longitudinal axis when the neutral axis is parallel to the diagonal axis through the corners of a rectangular cross section or a 45° axis for circular cross section.
5. DTM = MT = moment component corresponding to DLM above.
6. DRM = the resultant of the DLM and DTM moments defined above. For a circular or a square cross section DRM is the moment strength for biaxial bending about the diagonal axis.

7. BETA = a coefficient which defines the interaction contour for the biaxial moment relationship (see reference cited under Item (6), Method of Solution section).
8. EXP = n = Exponent used in the biaxial bending design formula:

$$\frac{M_L}{M_{uL}} + \frac{M_T}{M_{uT}} = 1$$

For the use of this formula refer to the references cited under Item (7) of the Method of Solution section.

When combined (axial and moments) loads are specified, the output will be a comparison of the applied loadings given in the input and the computed strength of the cross section under combined flexure and axial load. The form of the output will be identical to that printed for the design option output. The adequacy of the section investigated to resist the applied loadings can be readily determined from the ratio of UP/AP printed in the last column of the listing.

## 5.12 References:

Advanced Engineering Bulletin 18, "Capacity of Reinforced Rectangular Columns Subject to Biaxial Bending" and Advanced Engineering Bulletin 20, "Biaxial and Uniaxial Capacity of Rectangular Columns" published by the Portland Cement Association

# 6 Footing Analysis and Design

The Footing Analysis and Design component can analyze or design a spread or pile footing. Service Load or Ultimate Load requirements are used to determine the size (length and width), and the number of piles and spacing in the case of a pile footing. The thickness and reinforcement steel requirements are determined from Load Factor requirements. AASHTO Articles 10.6.3.1.5 (Eccentric Loading) and 10.6.3.2 (Geotechnical Design on Rock) are not considered.

In the case of a spread footing, the soil is assumed to resist no tension. The critical section for beam shear is a distance, d, from the face of the column, and d/2 for peripheral shear. In a design, the width of the footing in the direction of the maximum moment (M+ or M-) will be incremented unless the width ratio is exceeded.

In the case of a pile footing, the critical section for beam shear is a distance, d, from the face of the column and d/2 for peripheral shear. The program does not check the peripheral shear for an individual pile. In the design of a pile footing the program starts with a minimum (4 or the input value) number of piles at the minimum spacing. The spacing is increased as required until the maximum spacing is reached. Then a pile is added and the spacing is set to the minimum, and the process is repeated. The maximum number of piles is 25.

The thickness of the footing is increased when the beam and peripheral shear and moment capacities of the footing section are exceeded.

Dynamic load allowance is removed from the live load effects in the footing analysis/design process.

BRASS-PIER(LRFD)™ has been designed so that, when requested, the column and footing dimensions input to, and the loads generated by, the pier analysis component are transferred internally to the footing component. The only data that are required to be input are allowable stresses and the reinforcement.

In the footing design output, the final footing actions are given. The group loads are calculated according to Table 3.4.1-1 of the AASHTO specifications for each group. These loads are passed to the spread and pile footing subroutines. The service load results are not adjusted based on column 14 of Table 3.4.1-1 in the "FINAL FOOTING ACTIONS" report. The allowable soil pressure and the allowable pile loads are increased accordingly based on the value in column 14.

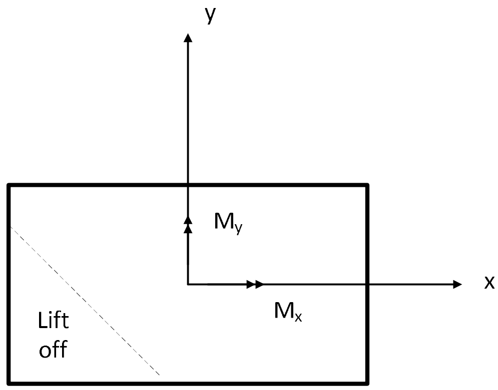
BRASS-PIER(LFRD)™ determines the 25 worst loading cases and designs the footing for the worst case.

The method that BRASS-PIER(LRFD)™ uses to compute footing soil pressures for spread footings is based on the general equation for stresses in a cross section subjected to non-symmetrical bending:

$$\sigma_{zz} = \frac{\left(M_y\, I_x + M_x I_{xy}\right)}{\left(I_x I_y - I_{xy}^2\right)} x + \frac{\left(M_x\, I_y + M_y I_{xy}\right)}{\left(I_x I_y - I_{xy}^2\right)} y$$

where:

$M_x$ and $M_y$ are bending moments, $I_x$, $I_y$, $I_{xy}$ are moments of area and $s_{zz}$ is the normal stress. See the figure below:




This general form of the stress equation is needed for cases in which a non-rectangular portion of the footing is subject to uplift, as is often the case for footings subject to biaxial bending.

In the case where there is no uplift and the entire rectangular footing staying in contact with the soil, the value of the product of inertia, $I_{xy}$, is zero (for a rectangular section), and the general equation simplifies to:

$$\sigma_{zz} = \frac{M_y}{I_y}x + \frac{M_x}{I_x}y$$

As the footing analysis begins, the section is assumed to be entirely in contact with the soil. The applied axial load $P_z$ is divided by the entire area of the footing $A_t$, and the first approximation of the pressures at each corner of the footing is determined by:

$$\sigma_i = \pm\frac{M_y}{I_y}x_i \pm \frac{M_x}{I_x}y_i + \frac{P_z}{A_t}$$

where $A_t$ is the total area of the footing and $\sigma_i$ are the pressures at each of the four corners.

If the pressures at all the corners ($i$) are positive (downward), no further iteration is needed.

If any of the corner pressures are negative, the program then computes the locations of the zero pressure points along the edges of the footing assuming a linear pressure distribution. Based on the location of these points, the program recomputes the area of the footing in contact with the soil, the moments of inertia about both axes, and the product of inertia.

The program then recomputes the pressures on the corners of the footings using the general equation and the new area of the footing in contact with the soil:

$$\sigma_i = \pm\frac{(M_y\,I_x + M_x I_{xy})}{\left(I_x I_y - I_{xy}^2\right)}x_i \pm \frac{(M_x\,I_y + M_y I_{xy})}{\left(I_x I_y - I_{xy}^2\right)}y_i + \frac{P}{A_c}$$

where $A_c$ is the area of the footing currently under compression, or in contact with the soil.

The program reports the value of $\sigma_i$ for each iteration. A negative value indicates that the corner is being uplifted. This does not indicate that tension exists between the soil and the footing. The negative value of soil pressure is necessary to compute the location of zero pressure along the edges of the footing.

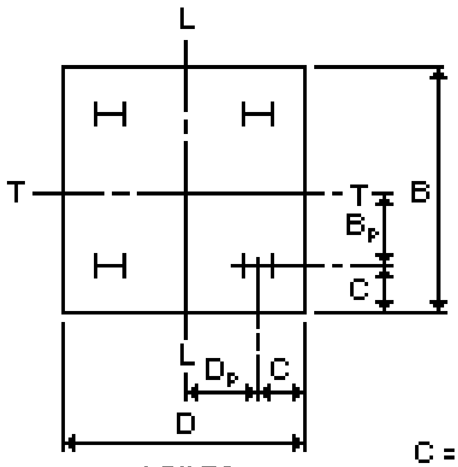
The values of $\sigma_i$ for the current iteration are compared to the values from the previous iteration, and, if they are within a tolerance, the iteration exits.

If the corner pressures, $\sigma_i$, differ from those computed in the previous iteration by more than the tolerance, another iteration is performed - the program recomputes the area of the footing in contact with the soil, the moments of inertia about both axes, the product of inertia, and the new soil pressures. This process continues until convergence is achieved or 50 iterations have failed to achieve convergence.

Typically, the eccentricity limits of half of the footing dimension are exceeded if a solution will not converge in less than 50 iterations.

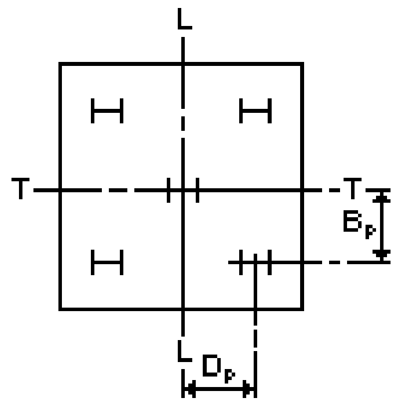
## 6.1 General Notes on Pile Option

Only the following pile configurations may be used:

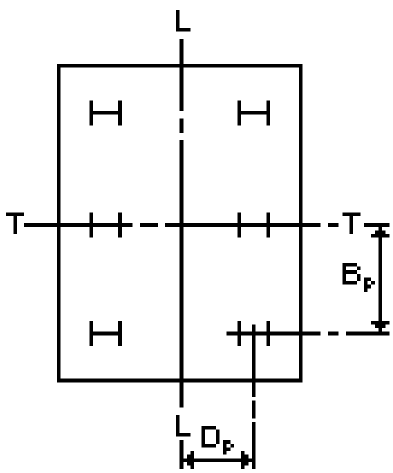



4 PILES

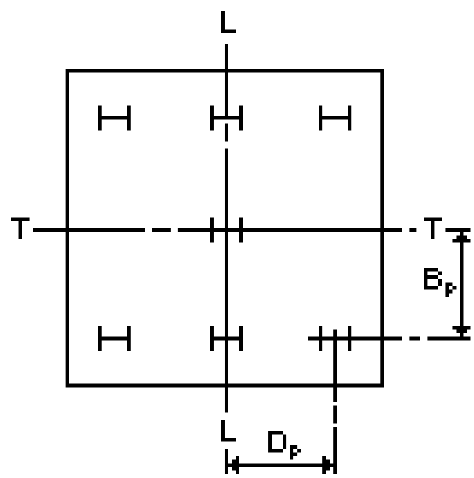
C = Edge Distance



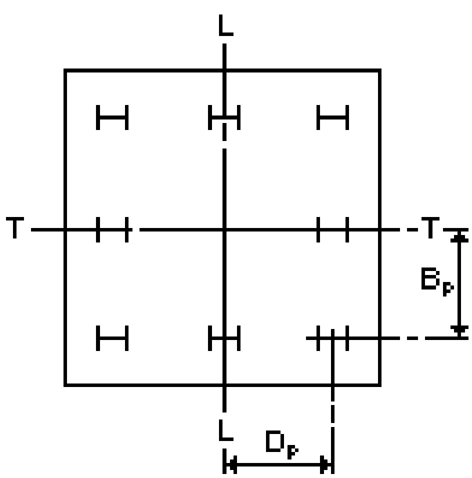

5 PILES



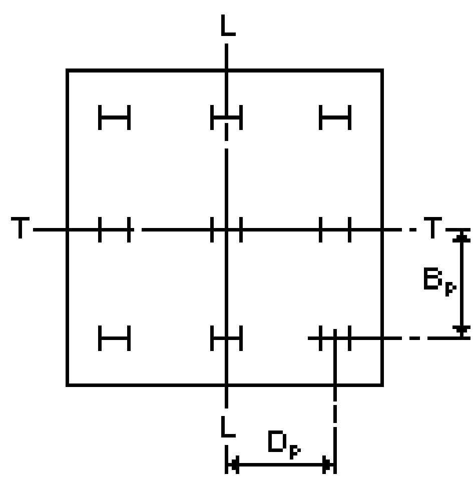

6 PILES



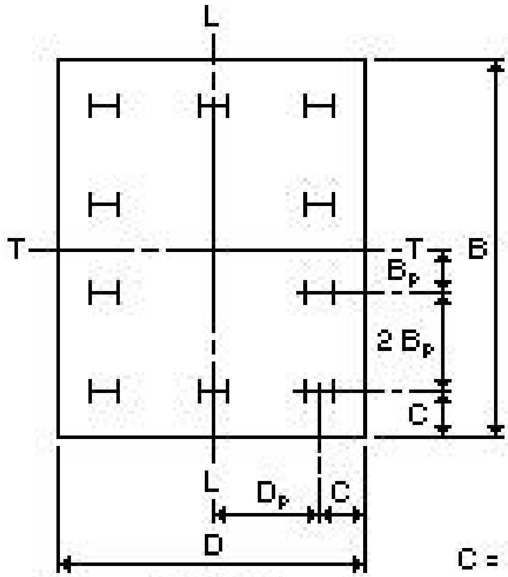

7 PILES




8 PILES

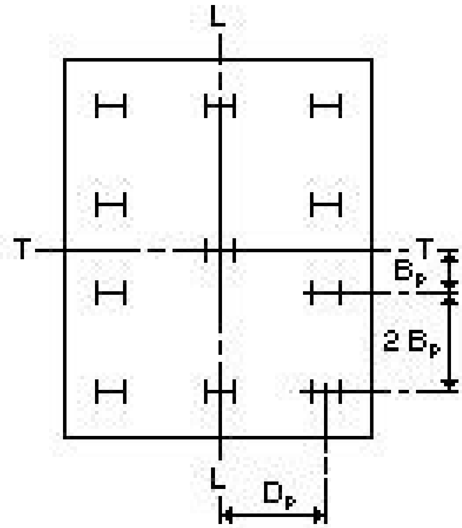



9 PILES

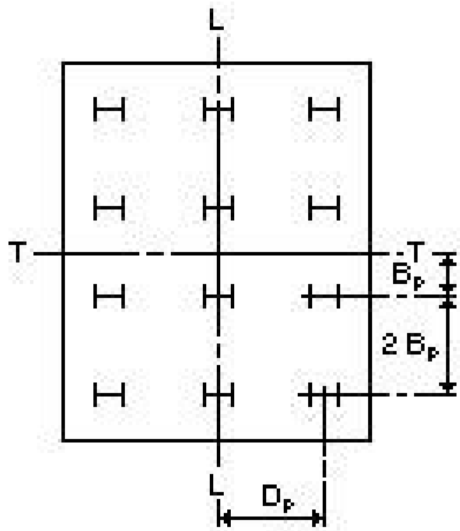



10 PILES

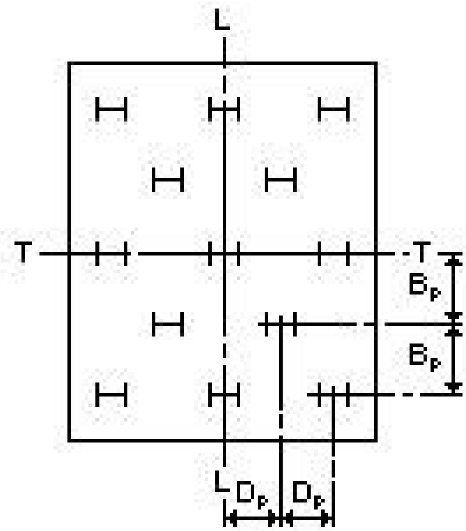
C = Edge Distance



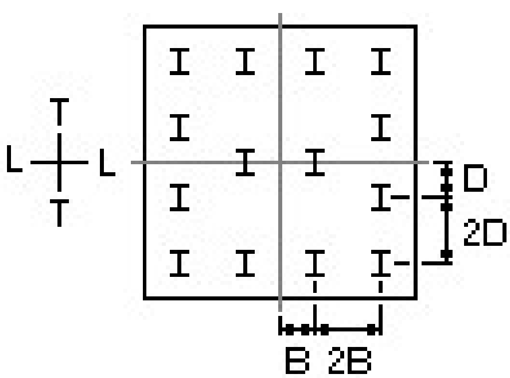

11 PILES



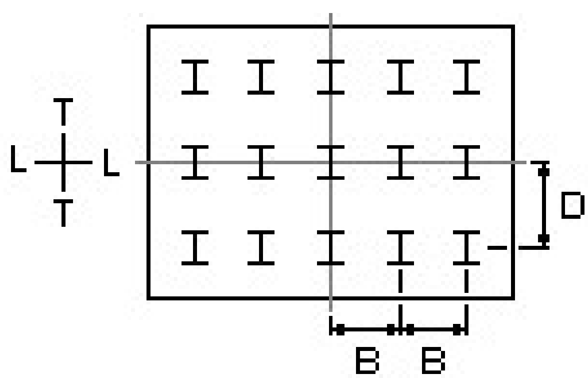

12 PILES



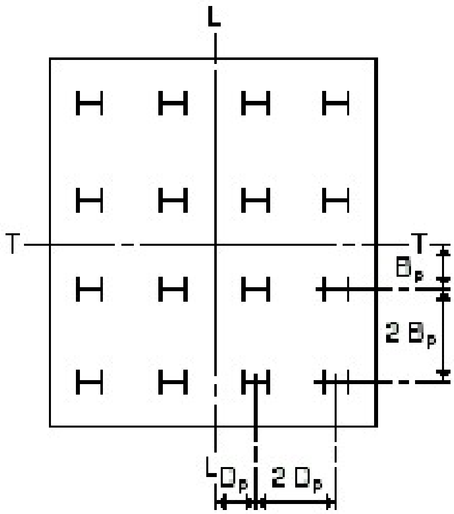

13 PILES



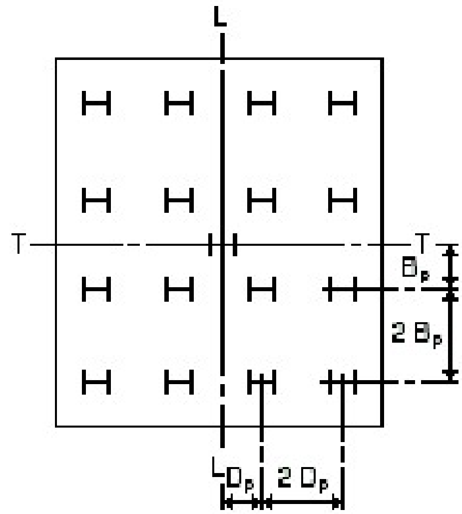

14 Piles



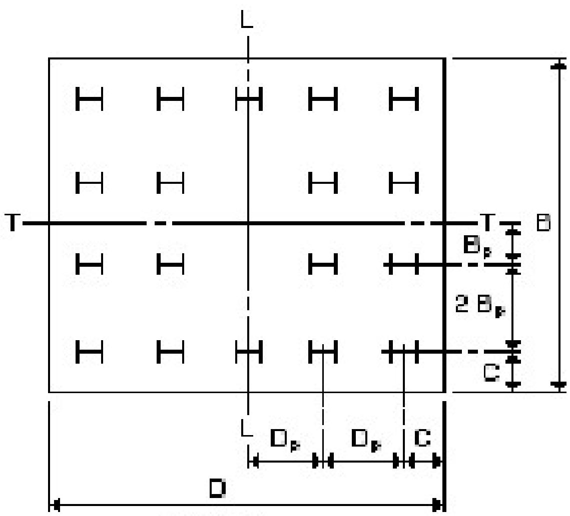

15 Piles



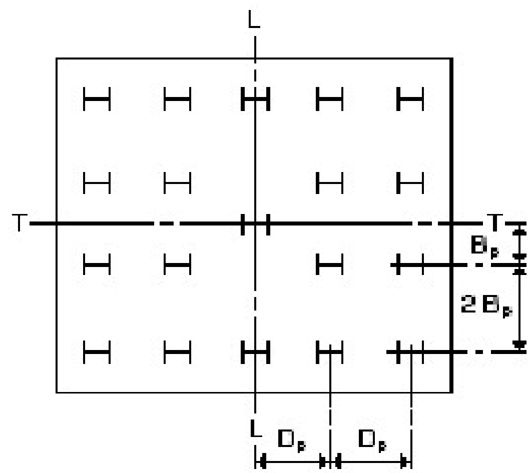

16 PILES




17 PILES

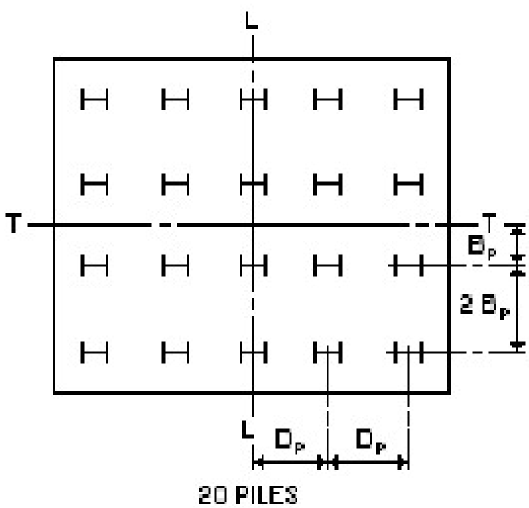



18 PILES

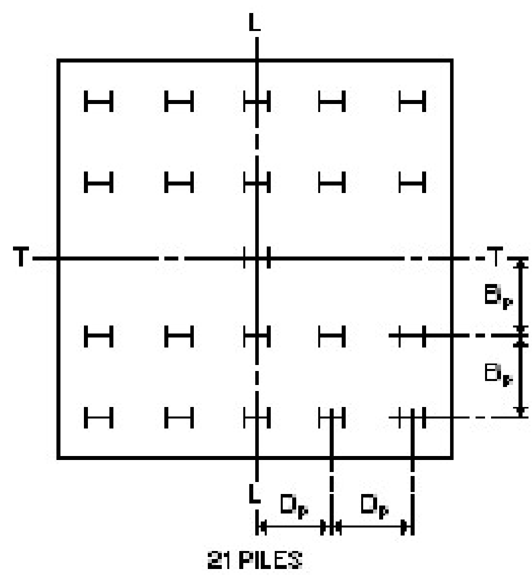



19 PILES

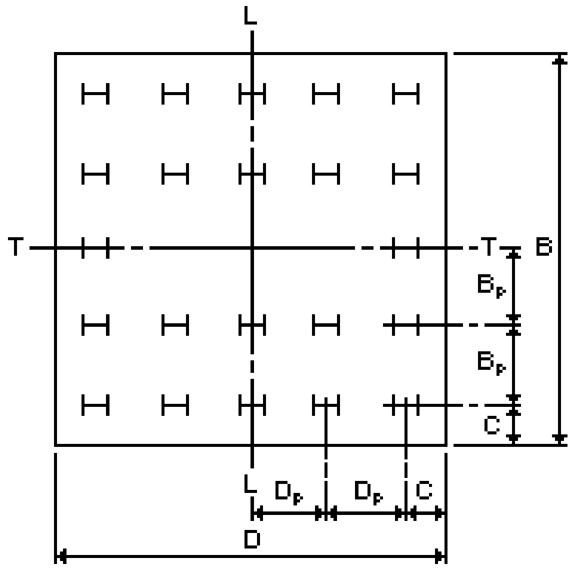
C = Edge Distance



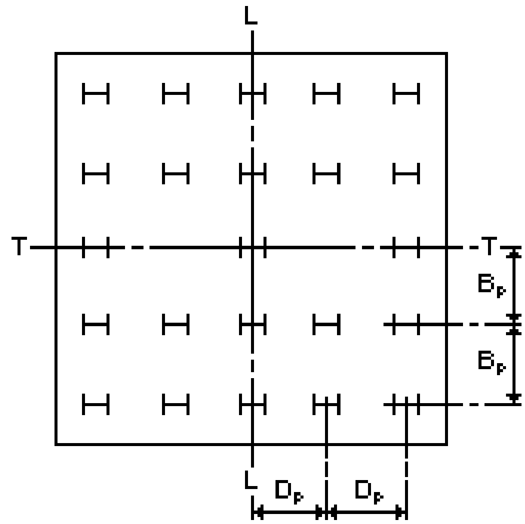

20 PILES




21 PILES

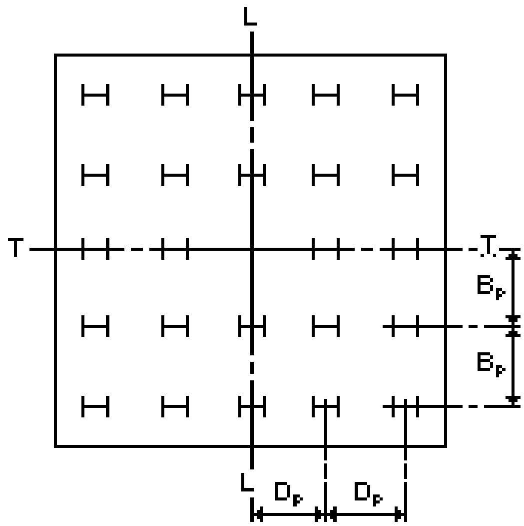


22 PILES

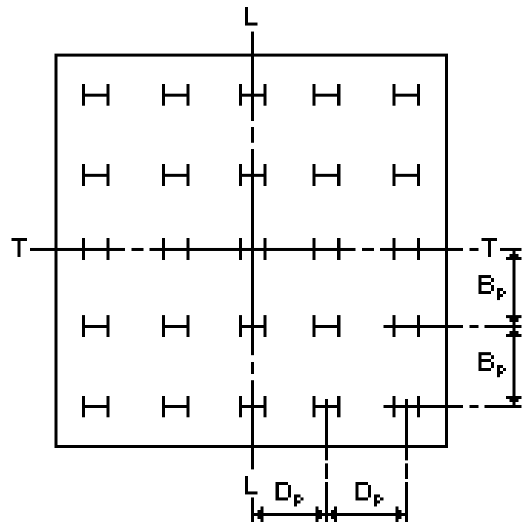


23 PILES

C = Edge Distance



24 PILES



25 PILES

Spacing Increments in feet for pile configurations and factors for minimum spacing and maximum spacing:

| Number of Piles | Delta Bp | Delta Dp | BMCF | DMCF |
|---|---|---|---|---|
| 1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4 | 0.125 | 0.125 | 0.5 | 0.5 |

| | | | | |
|---|---|---|---|---|
| 5 | 0.125 | 0.125 | 0.7 | 0.7 |
| 6 | 0.125 | 0.25 | 0.5 | 1.0 |
| 7 | 0.25 | 0.25 | 1.0 | 1.0 |
| 8 | 0.25 | 0.25 | 1.0 | 1.0 |
| 9 | 0.25 | 0.25 | 1.0 | 1.0 |
| 10 | 0.25 | 0.25 | 1.0 | 0.5 |
| 11 | 0.25 | 0.25 | 1.0 | 0.5 |
| 12 | 0.25 | 0.125 | 1.0 | 0.5 |
| 13 | 0.125 | 0.125 | 0.7 | 0.7 |
| 14 | 0.125 | 0.125 | 0.5 | 0.5 |
| 15 | 0.25 | 0.25 | 1.0 | 1.0 |
| 16 | 0.125 | 0.125 | 0.5 | 0.5 |
| 17 | 0.125 | 0.125 | 0.7 | 0.7 |
| 18 | 0.25 | 0.125 | 1.0 | 0.5 |
| 19 | 0.25 | 0.125 | 1.0 | 0.5 |
| 20 | 0.25 | 0.125 | 1.0 | 0.5 |
| 21 | 0.25 | 0.125 | 1.0 | 1.0 |
| 22 | 0.25 | 0.25 | 1.0 | 1.0 |
| 23 | 0.25 | 0.25 | 1.0 | 1.0 |
| 24 | 0.25 | 0.25 | 1.0 | 1.0 |
| 25 | 0.25 | 0.25 | 1.0 | 1.0 |

## 6.2 Design Notes on Pile Option

For design:

- ✓ The footing thickness will be incremented as needed.
- ✓ The minimum pile spacing will be used and incremented.
- ✓ The design option will place the reinforcing steel required to resist the maximum of the transverse or longitudinal moment in the bottom row of steel.
- ✓ The program will design the footing depth to carry shear loads based on an effective depth calculated using the bar size input. If the bar size selected by the program to carry moment is larger than the bar size used for shear capacity calculation, the section could be undersigned for shear.

The minimum and maximum pile spacing for a given number of piles, NP, are determined by the equations:

For spacing parallel to the y axis:

Min. Pile Spacing = BMCF (NP) x PSPMIN
Max. Pile Spacing = BMCF (NP) x PSPMAX

For spacing parallel to the x axis:

Min. Pile Spacing = DMCF (NP) x PSPMIN
Max. Pile Spacing = DMCF (NP) x PSPMAX

PSPMIN and PSPMAX are the minimum and maximum pile spacing. The minimum pile spacing is the starting point for the design cycles. If the maximum pile spacing is exceeded and the load on a pile exceeds the allowable load, then the number of piles is incremented by one.

Comments on increment control: To understand this option, look at the pile configuration for 15 piles. This arrangement as shown would typically be used to support a column when moments about the longitudinal axis are higher than moments about the transverse axis. If the designer wants to use this configuration for a case where MTT is considerably higher than MLL, the designer may code the increment control as a 2 and the actions and axes are reversed.

For best results, let the program design the number of piles. To do this, always enter 4 as the minimum number of piles. In some cases, the design will not be logical for the loading conditions and column size. In this case, try using a different Pile Design Method. An illogical design may occur as the design process makes some assumptions that may not work for the loads involved.

## 6.3 Description of Output

The Footing Design Loads will contain seven maximum load cases used in footing analysis/design process. These seven load cases produce:

1. The maximum soil stress or pile reaction (MAX.P1).
2. The maximum transverse moment in the footing (MAX.MT).
3. The maximum transverse beam shear in the footing (MAX.VT).
4. The maximum peripheral shear in the footing (MAX.VP).
5. The maximum longitudinal moment in the footing (MAX.ML).
6. The maximum longitudinal beam shear in the footing (MAX.VL).
7. The maximum soil or pile uplift (MAX.P3).

The soil uplift has no structural meaning since the soil has no tension capacity, but it does give an indication that reinforcement steel may be needed in the top of the footing. The load effect of MAX.P1 and MAX.P3 will be Service Loads. The load effects for the other five load cases will be Service Load or Factored Loads depending on the design option.

## 6.4 Load Cases

For each of the seven load cases, 20 items will be printed. These items are:

| | | |
|---|---|---|
| 1 | FG | The footing (F) which has the imposed loads (used with same designs) and the Group number (G) of the load case is given in these columns. |
| 2 | LLID | The live load case identification for the load case is given in this |

| | | |
|---|---|---|
| | | column. For Groups 2 and 5 this column will be blank. |
| 3 | WC | The wind case in the form I.J. will be given in this column. I is the wind direction and J is the combination number. An R will appear after the wind case if it is reversed. |
| 4 | ES | An E or S in this column indicates Expansion or Shrinkage is included in this load case. Otherwise, this column is blank. |
| 5 | C | A C in this column indicates centrifugal force is included in the load case. If not, the column is left blank. |
| 6 | S | An S in this column indicates stream flow effects are included in the load case. |
| 7 | P (kips) | This column contains the axial load on the footing from the column. The soil weight or footing weight is not included. Dynamic load allowance has been removed if given in the input. |
| 8 | MT (kip-feet) | MT is the moment, MT-T, at the top of the footing about the transverse axis with live load dynamic load allowance removed if given in the input. |
| 9 | VT (kips) | VT is the horizontal shear at the top of the footing parallel to the longitudinal axis with live load dynamic load allowance removed if given in the input. |
| 10 | ML (kip-feet) | ML is the moment, ML-L, at the top of the footing about the longitudinal axis with live load dynamic load allowance removed if given in the input. |
| 11 | VL (kips) | VL is the horizontal shear at the top of the footing parallel to the transverse axis with live load dynamic load allowance removed if given in the input. |
| 12 | P4 (kips or kips/sq. ft.) | P4 is the corner soil pressure or pile reaction where MT-T causes tension and ML-L causes compression. |
| 13 | P3 (kips or kips/sq. ft.) | P3 is the corner soil pressure or pile reaction where MT-T and ML-L cause tension. |
| 14 | P2 (kips or kips/sq. ft.) | P2 is the corner soil pressure or pile reaction where ML-L causes tension and MT-T causes compression. |
| 15 | P1 (kips or kips/sq. ft.) | P1 is the corner soil pressure or pile reaction where MT-T and ML-L cause compression. NOTE: The P1, P2, P3, and P4 values contain the weight of the soil and footing. |
| 16 | MTF (kips-feet/foot) | MTF is the moment in the footing at the face of the column parallel to the transverse axis per foot of footing width. |
| 17 | MLF (kips-feet/foot) | MLF is the moment in the footing at the face of the column |

| | | |
|---|---|---|
| | | parallel to the longitudinal axis per foot of footing width. |
| 18 | VBF (kips/foot) | VBF is the beam shear in the footing in the transverse or longitudinal direction at the critical section (d from the face of the column) per foot of footing width. |
| 19 | VPF (kips/foot) | VPF is the peripheral shear in the footing at the critical section (d/2 from the face of the column) per foot of peripheral length. |
| 20 | LOAD | This column contains the identification of the maximum load case, i.e., Maximum P1, moment shear, etc. |

## 6.5 Footing

The footing analysis/design results will consist of the footing size, bar reinforcement steel, and section capacities.

| | | |
|---|---|---|
| 1 | L (feet) | L is the footing length parallel to the transverse axis. In a design problem this is the required length. |
| 2 | W (feet) | W is the footing width parallel to the longitudinal axis. In a design problem this is the required width. |
| 3 | T (feet) | T is the thickness of the footing. In a design problem this is the required thickness. |
| 4 | P1/PA | P1/PA is the ratio of the maximum corner soil pressure (or pile reaction to the allowable soil stress (or pile capacity) under the design option. Under the investigation option, P1/PA is shown as zero. |
| 5 | AS (sq in) | AS is the required area of reinforcement steel per square foot. |
| 6 | NO | The total number of rebar is given in this column. |
| 7 | SIZE | The standard bar designation of the selected bar is given in this column. |
| 8 | SPAC (inches) | The rebar spacing is given in this column. |
| 9 | REBAR DIRECTION | This column indicates the direction and placement of the rebars. |
| 10 | MT (kip-feet/foot) | MT is the moment capacity of the footing per foot of width considering the footing thickness and area of steel. |
| 11 | VB (kips/foot) | VB is the beam shear capacity of the footing per foot width considering the footing thickness and steel placement. |
| 12 | VP (kips/foot) | VP is the peripheral shear capacity of the footing per foot width considering the footing thickness and steel placement. |

| | | |
|---|---|---|
| 13 | DS (inches) | DS is the distance from the top of the footing to the centroid of the rebars. |
| 14 | FC (kips/sq in) | FC is the concrete stress under the Service Load option. Under the Load Factor Option, FC is shown as zero. |
| 15 | Number of Piles<br>BP and DP (feet) | If the footing has piles, the number of piles and pile placement data will be given on the next line of output. Refer to the pile placement layouts on pages 12.10 through 12.14. |