TOLEDO
EDISON

JAMES S. GRANT
Vice President
Energy Supply
(419) 259-5232

Docket No. 50-346

License No. NPF-3

Serial No. 1-78

July 6, 1979

Mr. James G. Keppler
Regional Director, Region III
Office of Inspection and Enforcement
United States Nuclear Regulatory Commission
799 Roosevelt Road
Glen Ellyn, Illinois 60137

Dear Mr. Keppler:

IE Bulletin No. 79-02, dated March 8, 1979, requested that we review and verify the pipe support base plate designs using concrete expansion anchor bolts for the Davis-Besse Nuclear Power Station Unit No. 1 by July 6, 1979, 120 days from the issuance of the bulletin. Attached is our response to IE Bulletin No. 79-02.

In our response we have presented the results of our field testing program for concrete expansion anchors, preliminary results of our investigation of anchor bolt factor of safety and a discussion of our analysis of base plate flexibility which is presently in progress. We anticipate submitting our report on anchor bolt factor of safety and base plate flexibility by September 28, 1979.

Yours very truly,

J S Grant /clm

JSG:CLM

Attachment

dh a/5

cc:
United States Nuclear Regulatory Commission
Office of Inspection and Enforcement
Division of Reactor Operations Inspection
Washington, D.C. 20555

JUL 11 1979

7908080 093

503 216

Docket No. 50-346
License No. NPF-3
Serial No. 1-7°
July 6, 1979

A REPORT ON PIPE SUPPORT BASE PLATE DESIGNS
USING CONCRETE EXPANSION ANCHOR BOLTS

Response to NRC IE Bulletin 79-02

Davis-Besse Nuclear Power Station Unit 1

I. Introduction

All licensees and permit holders for nuclear power plants were required to evaluate the design practices and installation procedures used for concrete expansion anchors and pipe support base plates in accordance with NRC IE Bulletin 79-02, dated March 8, 1979 and Revision No. 1, dated June 21, 1979. In compliance with the requirements of this bulletin those pipe supports, which are located on piping systems classified as Seismic Category I by NRC Regulatory Guide 1.29, (refer to Attachment 1) and which use concrete expansion anchors, were examined by means of the following programs:

(a) An inspection/testing program to ensure proper incorporation of the design documents.

(b) A review of the design calculations to ensure that the installed pipe supports have factors of safety which are consistent with those set forth in the Bulletin.

(c) A review of the existing base plate designs to ensure that plate flexibility was accounted for when designing the anchorage systems.

The term "pipe support" shall be taken throughout this report as meaning collectively any structure which performs a supporting function of a pipe during any of its design modes, i.e. hangers, restraints, anchors, whip restraints, etc.

On March 22, 1979, the engineering review and field inspection/testing programs were initiated. At that time the type of attribute sampling plan and sample size were selected to meet the intent of Bulletin 79-02. The available Quality Control documentation and information gathered from programs already in progress at other plants were considered in making these selections. Also, the decision was made to implement the testing and review programs simultaneously, both to meet the early completion date required by Bulletin 79-02, and because any new design load dictated by the engineering review would not increase the bolt preload above the test value. (i.e. test torque values correspond to the manufacturer's maximum allowable pullout values with the appropriate factor of safety). The field inspection/testing program was started at the jobsite on April 18, 1979, and continued through June 8, 1979, with a parallel effort being conducted for plate analysis. Revision 1 of IE Bulletin 79-02 was subsequently received by the licensee on June 25, 1979. As of the issuance of this report, all efforts have been completed except as stated in the response to action items 1 and 2. The final response to these two action items will be issued in a supplemental report.

503 217

II. Conclusions

As of the date of this report the engineering effort has not been completed. However, preliminary findings indicate that the anchor bolt factors of safety are a minimum of three, four or five as stated in the response to action item 2.

During the early construction phase of Davis-Besse Unit 1, the inherent difficulties associated with concrete expansion anchors were recognized and efforts were taken to improve construction techniques and to ensure and document proper installation. Therefore, the defective bolts encountered during the inspection/testing program were minimal.

Based upon the results of the inspection/testing program implemented on the statistical sample of concrete anchor bolts, it can be concluded that, there exists a greater than 95% confidence level of there having been installed not more than 5% defective anchor bolts.

III. Response to Action Items

1. "Verify that pipe support base plate flexibility was accounted for in the calculation of anchor bolt loads. In lieu of supporting analysis justifying the assumption of rigidity, the base plates should be considered flexibile if the unstiffened distance between the member welded to the plate and the edge of the base plate is greater than twice the thickness of the plate. If the base plate is determined to be flexible, then recalculate the bolt loads using an appropriate analysis which will account for the effects of shear-tension interaction, minimum edge distance and proper bolt spacing. This is to be done prior to testing of anchor bolts. These calculated bolt loads are referred to hereafter as the bolt design loads."

Response:

Based on the above criteria, the pipe support base plates in general cannot be considered rigid. Therefore, an analysis is being performed on the pipe support base plates to determine if the net loads to the anchor bolts are acceptable considering the effects of plate flexibility, bolt stiffness, shear tension interaction, proper bolt spacing, and minimum edge distance.

Depending upon the complexity of the individual base plate configuration, one of the following methods of analysis will be used to determine the anchor bolt forces:

a. A quasi-analytical method, developed by Bechtel Power Corporation, for base plates having four, six or eight bolts (ref. Attachment 2).

b. The finite element method using the "ANSYS" code and/or other standard engineering analytical techniques with conservative assumptions will be employed for special cases in which the design of the base plate cannot be analyzed by the quasi-analytical method.

A review of typical base plates used in supporting the piping systems indicates that the majority are anchored either by four, six or eight bolts. The plates, in general, are not stiffened and vary in thickness from 1/2 to 1 1/2 inches.

For this type of base plate a quasi-analytical method is employed which treats the plates as beams on multiple spring supports subjected to moments and forces in three orthogonal directions. Based upon analytical considerations and the results of a number of representative finite element analyses using the "ANSYS" Code, certain empirical factors were introduced in the simplified beam model to account for the effects of the concrete foundation and the two way action of load transfer in the plate. These factors provide a method for introducing the interaction effect of plate dimensions, attachment sizes, bolt spacings, and stiffnesses on the distribution of external loads to the bolts. The results of a number of case studies indicate excellent correlation between the results of the quasi-analytical and the finite element method using the "ANSYS" Code.

Although the effect of plate flexibility is considered in the quasi-analytical method, the impact of prying action on the anchor bolts is determined not to be critical for the reasons stated in Attachment 2.

A computer program for the quasi-analytical method will be used for determining the bolt loads for standard plate configurations. The program requires plate dimensions, number of bolts, bolt size, bolt spacing, bolt stiffness, the applied forces, and the allowable bolt shear and tension loads as inputs. The allowable loads for a given bolt will be determined based on the distance to the edge of concrete, bolt spacing, embedment length, shear cone overlapping, manufacturer's value of bolt ultimate capacity, and a design safety factor. This program computes the bolt forces and calculates a shear-tension interaction value.

The shear-tension interaction in the anchor bolts will be evaluated in the following manner:

a. When the applied shear force is less than the frictional force developed in the shear plane between the steel and the concrete surface for balancing the imposed loads, no additional provisions are required for shear.

b. When the applied shear force exceeds the frictional force, the total applied shear is required to be carried by the bolts in accordance with the following interaction formula:

$$\left(\frac{T}{T_A}\right)^2 + \left(\frac{S}{S_A}\right)^2 \leq 1.0$$

where T and S are the calculated tensile and shear forces and T_A and S_A are the respective allowable values.

The results of this effort will be reported in a supplement to this report.

2. "Verify that the concrete expansion anchor bolts have the following minimum factors of safety between the bolt design load and the bolt ultimate capacity determined from static load tests (e.g. anchor bolt manufacturer's) which simulate the actual conditions of installation (i.e., type of concrete and its strength properties):

a. Four - For wedge and sleeve type anchor bolts

b. Five - For shell type anchor bolts."

Response

Based on the various manufacturers recommendations for both wedge and shell type expansion anchors, a factor of safety of four was used in the initial design of pipe supports and anchor bolts.

In the current design review the existing pipe support installations are being evaluated for the following factors of safety:

a. Service Load Conditions (i.e., thermal loads, deadweight s, and Operating Basis Earthquake loads) -

four - Wedge type anchor bolts
five - Shell type anchor bolts

b. Faulted Load Conditions (i.e. loads caused by accident conditions (LOCA), Safe Shutdown Earthquake loads, extreme environmental loads, or loads encountered only during testing) -

three - Wedge and shell type anchor bolts.

Factor of safety is the ratio between bolt ultimate capacity as stated by the manufacturer and design load.

The use of three as a factor of safety is commensurate with the design requirements of Section B.7.2 of the "Proposed Addition to Code Requirements for Nuclear Safety Related Concrete Structures" (ACI 349-76) August 1978. In addition, permitting the use of higher allowable design values for faulted conditions is consistent with provisions of other codes for nuclear power plant design.

At this time the calculations for 150 pipe supports have been examined and all the anchor bolt design loads have met or exceeded the factors of safety stated above. Upon completion of this effort, the results will be issued in a supplement to this report.

3. "Describe the design requirements, if applicable, for anchor bolts to withstand cyclic loads (e.g., seismic loads and high cycle operating loads)"

Response

In the stress analyses of the subject piping systems, stresses due to deadweight loads, thermal transients, seismic and dynamic loads (including turbine trip and main steam isolation valve closure) were considered in the generation of the static equivalent pipe support design loads. Since the entire support is designed to these loads, any cyclic effect on the support has been accounted for and no additional design considerations need be applied.

Factors of safety used in selecting the concrete expansion anchors during pipe support design on the subject piping systems, were not increased for cyclic loads. Results from tests performed at the Fast Flux Test Facility substantiate this position. These test results are as follows:

503 220

a. Long term fatigue loading -

The expansion anchors being tested successfully withstood two million cycles of long term fatigue loading at a maximum intensity of 20% of the static ultimate capacity. When the maximum load intensity was steadily increased beyond this value and cycled 2000 times at each load step, the observed failure load was about the same as the static ultimate capacity.

b. Simulated seismic loading -

The dynamic load capacity of the expansion anchors, under simulated seismic loading, closely approximate the corresponding static ultimate capacities.

4. "Verify from existing Q.C. documentation that design requirements have been met for each anchor bolt in the following areas:

   a. Cyclic loads have been considered (e.g. anchor bolt preload is equal to or greater than bolt design load). In the case of the shell type, assure that it is not in contact with the back of the support plate prior to preload testing.

   b. Specified design size and type is correctly installed (e.g., proper embedment depth).

If sufficient documentation does not exist, then initate a testing program that will assure that minimum design requirements have been met with respect to sub-items (a) and (b) above. A sampling technique is acceptable. One acceptable technique is to randomly select and test one anchor bolt in each base plate (i.e., some supports may have more than one base plate). The test should provide verification of sub-items (a) and (b) above. If the test fails all other bolts on the base plate should be similarly tested. In any event, the test program should assure that each Seismic Category I system will perform its intended function."

Response

Background

During the construction period of 1972 to 1973 at Davis-Besse Unit 1 it was noted that inconsistent results were obtained while installing the wedge type expansion anchors. A testing program was therefore initiated to develop proper installation techniques and correlation between torque values and bolt preload for the concrete type and strength used.[2,3] Upon completion of this testing program the installation methods were revised to include lubrication of threads, new torque values, use of multiple washers, etc. This information was issued as an attachment to the piping and pipe support installation specification[4] and necessitated re-installation of all wedge type expansion anchors installed prior to October 1974. The contractors were required to expand the scope of their Quality Control surveillance of anchor bolt installations to include torque verification, bolt size and length verification and proper washer orientation (where applicable). Bechtel Power Corporation Quality Control also included these items in their surveillance programs to ensure that the contractors were properly monitoring their installations.

In April 1977 an inspection program was conducted by NRC Region III inspectors to verify the installed lengths of several pre-selected concrete anchors. Seventeen pipe supports were checked by ultrasonic examination (a total of 93 anchor bolts); all of which satisfactorily met design length requirements.

In response to Bulletin 79-02, all of the available Quality Control documentation was obtained for the systems listed in Attachment 1. These records consisted of field inspection reports, installation acceptance checklists and torque certificates (available for approximately 60% of the wedge-type anchors). This documentation established sufficient confidence that the contractors adhered to the installation/verification program requirements. After evaluating the available documentation, it was decided that the operability of each system could be assured by proving the validity of the original field program through a statistical sampling plan of randomly selected anchor bolts.

Statistical Sampling Plan

Initially, an attribute sampling plan of hypothesis testing was selected based upon the hypergeometric distribution. This plan would develop a 95% confidence that no more than 2% defective anchor bolts exist in the total population[5]. After initiation of the field inspection program, it was decided that although the hypothesis testing approach is common in nuclear materials quality control, it did not lend itself readily to the evaluation of installed anchor bolts (i.e., established values were not available for the probability of rejecting an acceptable bolt (B), the acceptance quality level (AQL) or the rejection quality level (RQL), all of which would be required to properly evaluate the statistical inference of the test results). The method of parameter estimation was therefore substituted for hypothesis testing and subsequently has been found consistent with the sampling plan proposed in Revision 1 of Bulletin 79-02. By this method an upper confidence limit on the number of defects (D) in the total population (N) is constructed, based upon the hypergeometric distribution:

$$h\ (x;n,D,N) = \sum \frac{\binom{D}{x}\binom{N-D}{n-x}}{\binom{N}{n}} \leq \alpha \qquad \text{for } x = 0,1,2,\ldots,\ x_o$$

(written in in binomial coefficient notation)

where: x_o = number of observed defects in the sample

n = sample size

$(1-\alpha)\ 100$ = confidence level

The acceptance criteria is a 95% confidence level that there are 5% or fewer defective anchor bolts in the total population[5].

The total population of concrete expansion anchor bolts to be investigated was defined as all expansion anchor bolts located on pipe supports for Q-listed piping systems which are 2 1/2" and larger. It was not considered necessary to include those piping systems which are 2" and smaller since: most of the supports are located and designed in accordance with the conservative chart analysis method; magnitude of the stress values is generally quite low for the minimum standard size components; and the installation/verification programs were the same as those in effect for 2 1/2" and larger systems. This population was segregated into two sub-populations, Wedge-type and Shell-type. Initially, sample sizes were selected as 4% of the respective sub-populations. The actual number tested was approximately 4.7% for wedge type and 4.2% for shell type. Randomness of the sample was guaranteed through preselection of each pipe support and anchor bolt with no prior knowledge of location, accessibility, installation contractor or any other factor that might invalidate the test. Each sample was evenly distributed among the 57 system isometric drawings which reflect the piping systems investigated, with no more than one anchor bolt to be tested per base plate.

503 222

Inspection/Testing Program

The inspection/testing program[6] included the following series of dimensional and pullout checks on each subject anchor bolt to determine its ability to function as designed.

a. Torque tension check - each anchor bolt was loaded to a value equal to the maximum design preload for that size and then checked for movement to determine the pullout capacity of bolt. This check did not prove the as-found preload equal to or greater than the design load for the following reasons. Pipe supports are subjected to both static and dynamic loads with the dynamic loads being short duration cyclic loads caused by a seismic event. This type of cyclic load does not induce fatigue and the amount of bolt preload present will not greatly affect the performance of the anchorage. If the initial torque on the bolt accomplishes setting of the wedge, the ultimate capacity of the bolt is not affected by the amount of preload present in the bolt at the time of cyclic loading. For vibratory loads during plant operation, expansion anchors have been shown to successfully withstand a long term fatigue environment as discussed in action item 3. In addition, bolt preload is gradually lost over the life of the plant through creep and other similar phenomena. Base plates were shimmed and leveling nuts removed as necessary, to ensure accurate loading of shell-type inserts. Any anchor bolt with a nut that turned two full revolutions or less (wedge-type) or an insert that moved 1/16" or less (shell-type) were determined acceptable.

b. Embedment length check - wedge-type anchor bolts were nondestructively examined by Ultrasonic Testing to determine the overall length from which the embedment length was calculated; shell-type anchor bolts were dimensionally checked after removing the bolt from the insert to determine the embedment length. These lengths were then compared to the design drawing or the manufacturer's recommended value.

c. Thread engagement check - each bolt was dimensionally checked for minimum thread engagement necessary to develop the capacity of the bolt.

d. Shoulder to cone check - for each shell-type anchor bolt the dimensions taken in b. were interpreted to determine if the cone was fully inserted.

e. Anchor bolt check - each anchor bolt was checked for compliance with the drawing identifying diameter, type, manufacturer's name and overall length.

All nonconformances that were noted during the above five checks were documented on Toledo Edison Nonconformance Reports (NCR's) and forwarded to Bechtel Power Corporation for resolution. Engineering evaluation was performed for each nonconforming condition and those anchor bolts which would not meet the factors of safety stated in the response to action item 2 were considered "failures" and were either repaired or replaced. The distribution of these "failures" was such that the operability of no one system would have been impaired. In addition, an anchor bolt "failure" only constitutes the inability of an anchor bolt to function as designed and does not necessarily indicate that the entire support structure would fail or that the piping system would not operate.

All the original documentation for the testing program including: system identification, location, method of test, type of anchor bolt, test results, date of test, and signatures of reviewing engineer and Quality Control Inspector are maintained by Toledo Edison.

503 223

Sampling Plan Results

Totals:

	Wedge-type	Shell-type	Total
Population (N)	4759	5740	10499
Sample size (n)	228	241	469
Defective bolts (x)	5	4	9

Statistical Inferences:

Wedge-type Anchor Bolts

$$\alpha = 0.01565 + 0.006454 + 0.00051 + 0.00008 + 0.00001 + 0 = 0.025$$

$$(1-\alpha)\ 100 = 97.5$$

Conclusion: There is a 97.5% confidence in finding 5% or fewer defects

Shell-type Anchor Bolts

$$\alpha = 0.00401 + 0.0012 + 0.00028 + 0.00004 + 0 = 0.006$$

$$(1-\alpha)\ 100 = 99.4$$

Conclusion: There is a 99.4% confidence in finding 5% or fewer defects

References

1. Bechtel Power Corporation "Drilled-In Expansion Bolts Under Static and Alternating Leads", Report No. BR-5853-C-4 Revision 1, October 1976.

2. Bechtel Power Corporation, "Concrete (Wedge) Anchor Torque/Tension Test", Technical Report for The Toledo Edison Company, September 1974.

3. Bechtel Power Corporation, "Hilti Kwik - Bolt Torque/Tension Verification Test", Technical Report for The Toledo Edison Company, August 1976.

4. "Technical Specification for the Installation of Prefabricated and Field Fabricated Piping", Specification No. 7749-M-453, Revision 14.

5. Exxon Nuclear Company, "Statistical Methods in Nuclear Material Control", TID-26298, Richland, Washington, 1973.

6. "Inspection and Testing Procedure for Concrete Expansion Anchors", Document No. PDP-[illegible] Revision 2.

503 225

SYSTEMS ON WHICH ANCHOR BOLTS WERE INSPECTED

1. Main Steam System
2. Auxiliary Feedwater System
3. Main Feedwater System
4. Hydrogen Purge & Containment Vent Systems
5. Reactor Coolant System
6. Emergency Core Cooling Systems (Core Flooding, High Pressure Injection, Low Pressure Injection)
7. Containment Spray System
8. Decay Heat Removal System
9. Spent Fuel Pool Cooling System
10. Component Cooling Water System
11. Service Water System
12. Emergency Diesel Generator System
13. Portions of other systems performing a Containment Isolation function

503 226

DESCRIPTION OF ANALYTICAL METHOD FOR DETERMINING ANCHOR BOLT LOADS

This attachment contains a description of the quasi-analytical method, developed for use in determining loads on anchor bolts attaching steel base plates to concrete, and verification of this approach by the finite element method. The anchor bolts under consideration were wedge or shell type expansion anchors. The plates varied in thickness from 1/2 to 1-1/2 inches with symmetrical patterns of four, six, or eight bolts. The plates generally are not stiffened and the attachment member is concentric with the plate.

From an analytical viewpoint the load distribution in a flexible base plate anchorage system is complex in nature, making certain simplifying assumptions necessary to arrive at conservative yet practical solutions. These simplifying assumptions take into account the following parameters which may affect the load distribution in the anchorage system:

a. Base plate flexibility

b. Bolt stiffness

c. Prying action

Prying action will not be critical for the following reasons:

a. Where the anchorage system capacity is governed by the concrete shear cone, the prying action would result in an application of an external compressive load on the cone and therefore, would not affect the anchorage capacity.

b. Where the bolt pullout determines the anchorage capacity, the additional load carried by the bolt due to the prying action will be self-limiting since the bolt stiffness decreases with increasing load. At higher loads the bolt extension will be such that the corners of the base plate will lift off and the prying action will be relieved. This phenomenon has been found to occur when the bolt stiffnesses in the finite element analysis were varied from a high to a low value.

Method of Analysis for Anchor Bolt Loads:

A quasi-analytical approach has been formulated which takes into account the base plate flexibility and the bolt stiffness. The results of the analytical solution have been verified with appropriate finite element results and have shown good correlation for the typical cases studied.

503 227

INTRODUCTION:

THE PURPOSE OF THIS STUDY WAS TO DEVELOP AN ANALYTICAL METHOD FOR DETERMINING TENSION LOADS ON EXPANSION ANCHOR BOLTS USED FOR PIPE SUPPORT BASE PLATES. THE FINITE ELEMENT METHOD OF ANALYSIS[1] SERVED AS A DATA BASE FOR DEVELOPING THIS METHOD WHICH USES PLATE FLEXIBILITY AND BOLT STIFFNESS AS THE PRIMARY PARAMETERS. A COMPUTER PROGRAM IS AVAILABLE FOR FOUR, SIX AND EIGHT BOLT CONFIGURATIONS.

ANALYSIS:

THE QUASI-ANALYTICAL MODEL TREATS EACH PLATE AS A BEAM SUPPORTED ON ELASTIC SPRINGS.

ASSUMPTIONS:

(a) SYMMETRICAL BOLT PATTERNS

(b) CENTROIDAL LOADING

(c) ATTACHMENT DIMENSIONS SMALL COMPARED TO THE PLATE DIMENSIONS

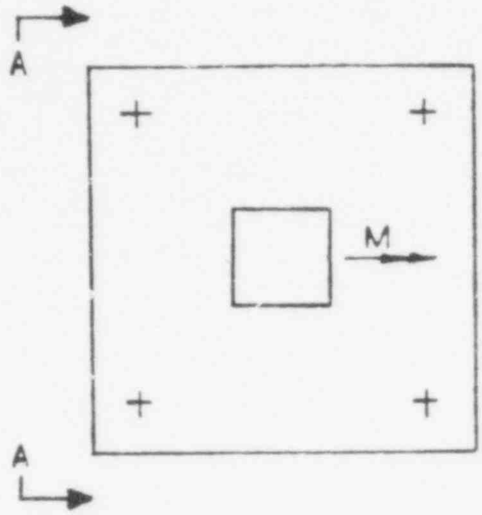
(d) UNITS FOR ALL VARIABLES:

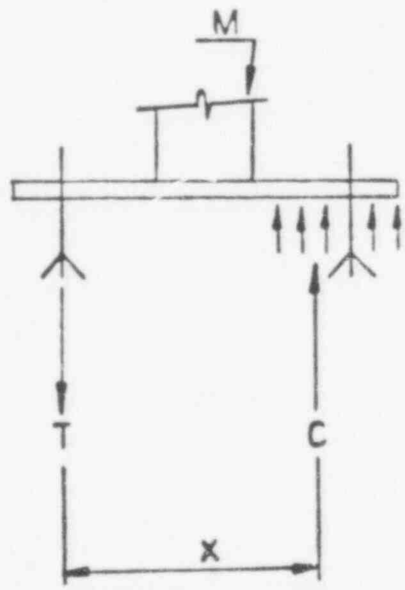
FORCE = KIPS

LENGTH = INCHES

I. FOUR BOLT PATTERN - MOMENT AND TENSION LOADING CASES

MOMENT TAKEN ABOUT ONE AXIS





SECTION A-A

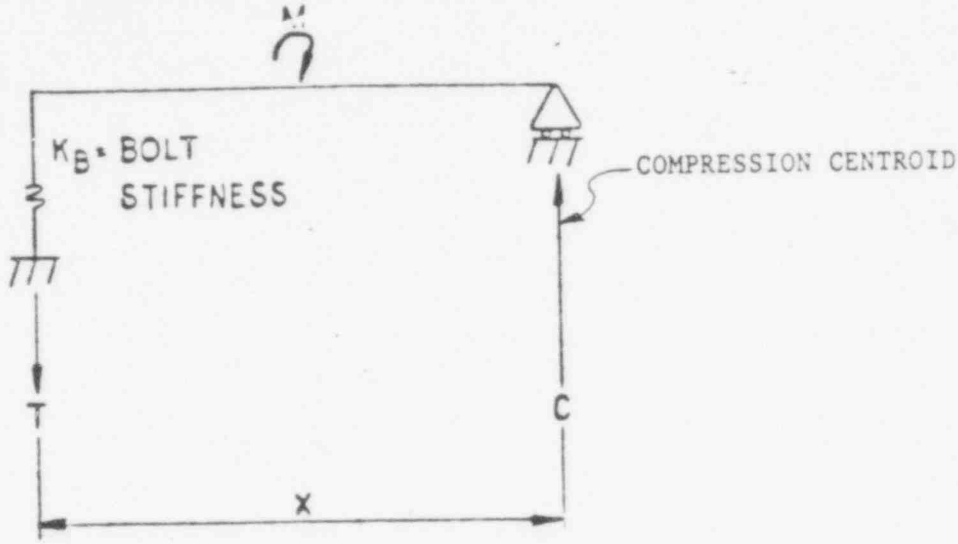
WHERE:

T=TOTAL TENSION (KIP)
C=RESULTANT OF COMPRESSIVE STRESS BLOCK (KIP)

T(X)=C(X)=M

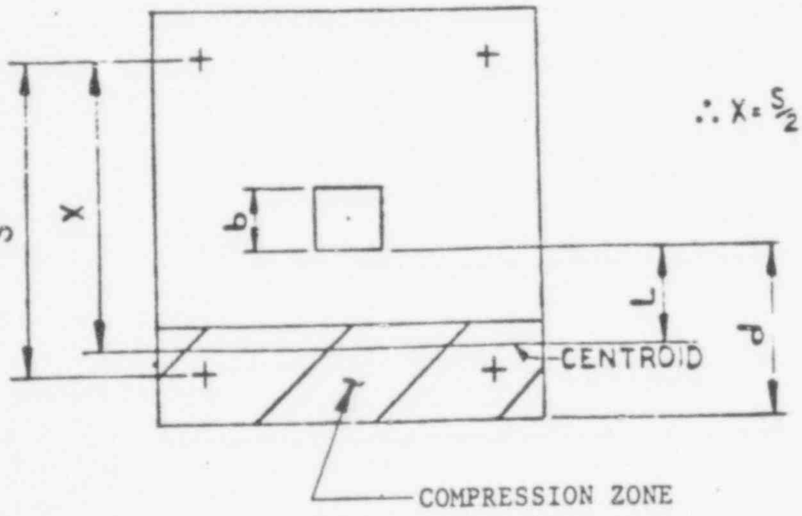
BEAM MODEL:

THE PLATE IS IDEALIZED AS A BEAM SUPPORTED AT THE COMPRESSIVE FORCE RESULTANT AND THE TENSION BOLT. THE DISTANCE "X" IS DETERMINED WHEN THE COMPRESSION CENTROID IS LOCATED AND "T" CAN THEN BE CALCULATED.



$T \cdot X = M$

FOUR BOLT PATTERN LOADED CENTROIDALLY:



$\therefore X = \frac{S}{2} + \frac{b}{2} + L$

503 230

CONCEPTUALLY,

L=FUNCTION (t,d,K_B)

WHERE,

L=DISTANCE FROM EDGE OF ATTACHMENT TO THE CENTER OF COMPRESSION (IN.)

t=PLATE THICKNESS (IN.)

d=DISTANCE FROM EDGE OF ATTACHMENT TO THE EDGE OF THE PLATE (IN.)

K_B=BOLT STIFFNESS (K/IN.)

BASED ON SEVERAL FINITE ELEMENT ANALYSES (i.e. VARYING T,d & K_B), THE FOLLOWING EMPIRICAL RELATIONSHIP WAS DERIVED:

$$L = 3.5 \left[\left(\frac{t}{d}\right)^{\frac{2}{3}} \left(\frac{44}{K_B}\right)^{\frac{1}{3}} \right] (d) \quad (1)$$

WHERE $L \leq d$

FROM L, THE TOTAL TENSION (T) AND BOLT LOAD (F_T) CAN BE FOUND:

$$T = \frac{M}{\frac{s}{2} + \frac{b}{2} + L} \quad (2)$$

$$F_T = \frac{T}{2} = \frac{M}{S + b + 2L} \quad (3)$$

FOR CENTROIDALLY LOADED FOUR-BOLT PATTERNS ONLY

THIS METHOD CAN BE EXTRAPOLATED FOR USE WITH COMBINED LOADING CASES.

503 231

FOR BIAXIAL BENDING:

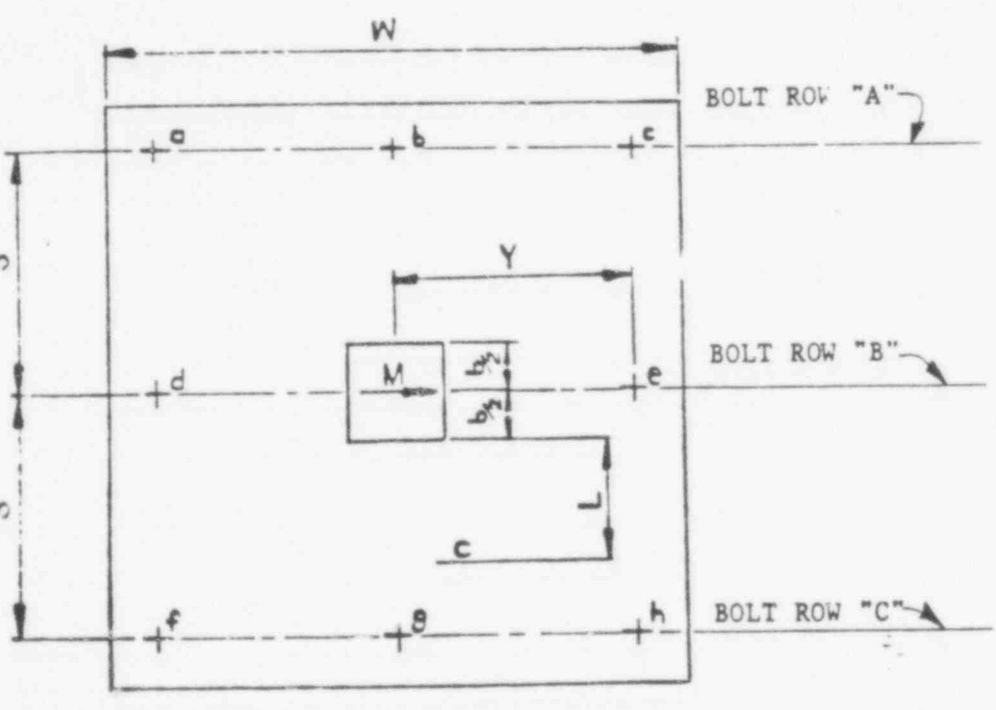
$$\text{CRITICAL } F_T = \frac{M_x}{S_x + b_x + 2L_x} + \frac{M_y}{S_y + b_y + 2L_y} \qquad (4)$$

FOR COMBINED BENDING AND TENSION:

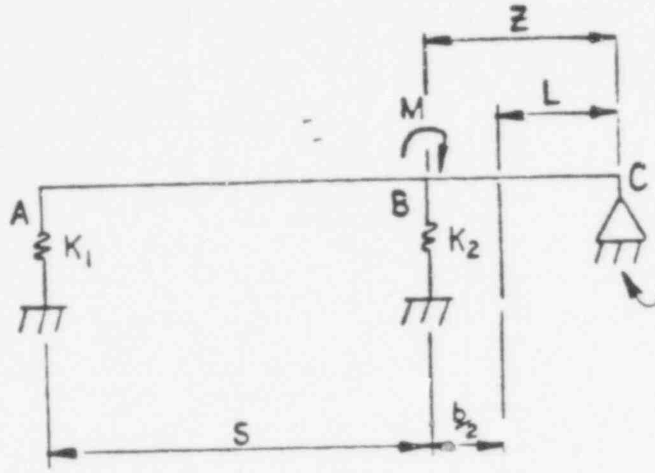
$$\text{CRITICAL } F_T = \frac{M}{S + b + 2L} + \frac{T}{4} \qquad (5)$$

SINCE L VARIES WITH t, d & K, THE METHOD FOR FINDING L CAN BE USED FOR MANY PLATE AND BOLT PATTERNS. ONCE L IS KNOWN THE PLATE CAN BE MODELED AS A BEAM ON SPRINGS. THE BEAM CAN BE SOLVED BY VARIOUS METHODS AND THE TOTAL TENSION FORCE FOR ANY ROW OF BOLTS CAN BE CALCULATED. THIS WILL BE DEMONSTRATED FOR SIX AND EIGHT BOLT PATTERNS IN THE FOLLOWING DETAILS.

II. EIGHT-BOLT PATTERN - MOMENT LOADING CASE



BEAM MODEL:



K_B = BOLT STIFFNESS

$I = \frac{Wt^3}{12}$

THE REACTIONS FOR THIS INDETERMINATE BEAM MODEL CAN BE SOLVED USING THE VIRTUAL WORK PRINCIPLE. THE FOLLOWING EQUATIONS WERE DERIVED FOR EIGHT-BOLT PATTERNS:

$Z = \frac{b}{2} + L$ WHERE L IS DETERMINED FROM EQ (1)

$EI = 2417Wt^3$ (KIP IN^2)

IF REDUNDANTS ARE TAKEN "C":

$$EI\,\delta_{co} = \frac{EIM(K_1+K_2)}{S^2K_1K_2}\left[Z + \left(\frac{K_1}{K_1K_2}\right)S\right] - \frac{MZS}{3} \qquad (6)$$

WHERE δ_{co} IS THE DEFLECTION AT "C" DUE ONLY TO "M":

$$EI\,\delta_{cc} = \frac{EI}{S^2K_1K_2}\left[K_1S^2 + 2K_1ZS + (K_1+K_2)Z^2\right] + \frac{Z^2}{3}\left[Z+S\right] \qquad (7)$$

WHERE δ_{cc} IS THE DEFLECTION DUE TO A 1^k FORCE APPLIED AT "C":

$$\text{REACTION AT } C = R_c = -\frac{EI\,\delta_{co}}{EI\,\delta_{cc}} \qquad (8)$$

$$\therefore R_A = \frac{[M - Z(R_c)]}{S}\,;\ R_B = R_c - R_A \qquad (9)$$

503 233

AS THE PLATE GETS WIDER AND z BECOMES SMALL COMPARED TO Y, THE TWO MIDDLE BOLTS CANNOT BE LUMPED TOGETHER AS ONE SUPPORT WITH $K_2=2K_B$. K_2 WILL BE SOMEWHAT LESS THAN $2K_B$. THE FOLLOWING EXPRESSION FOR K_2 YIELDED RESULTS WHICH WERE CONSISTENT WITH THE RESULTS FROM THE FINITE ELEMENT ANALYSIS.

$$K_2 = 2K_B\left(\frac{z}{Y}\right)^2 \leq 2K_B \tag{10}$$

FOR PLATE SIZES GENERALLY USED IN PIPE SUPPORTS, THIS WIDTH EFFECT WILL HAVE NEGLIGIBLE EFECT ON ROW "A" (i.e. THE STIFFNESSES OF THE THREE BOLTS CAN STILL BE LUMPED TOGETHER IN THE BEAM MODEL).

THE REACTIONS IN THE BEAM MODEL ARE NOW KNOWN. THE REACTION AT ANY ONE SUPPORT IS THE TOTAL TENSION IN THAT ROW OF BOLTS. TO DISTRIBUTE THE LOAD TO THE BOLTS:

FOR ROW "B" FROM SYMMETRY, (11)

TENSION PER BOLT $= F_{Td} = F_{Te} = \frac{R_B}{2}$

FOR ROW "A", THE RELATIVE STIFFNESS OF THE PLATE AND THE BOLTS AND THE BOLT DISTANCE FROM THE ATTACHMENT WILL AFFECT THE LOAD DISTRIBUTION BETWEEN THE MIDDLE AND THE CORNER BOLTS. THE BOLT CLOSEST TO THE ATTACHMENT WILL CARRY MORE LOAD AND IF THE ATTACHMENT SIZE IS SMALL, BOLT TO ATTACHMENT DISTANCE MAY BE SUBSTITUTED BY THE DISTANCE OF THE BOLT TO THE CENTER LINE OF THE PLATE. THUS TENSION IN THE MIDDLE BOLT "b":

$$F_{Tb} = \alpha\left[f\left(\frac{K_B}{\frac{EI}{\ell_1^3}}\right)\right]\left[\frac{\frac{1}{L_m}}{\frac{1}{L_m}+\frac{2}{L_c}}\right](R_A) \tag{12}$$

WHERE: L_m = DISTANCE FROM PLATE CENTER TO BOLT "b"

L_c = DISTANCE FROM PLATE CENTER TO BOLTS "a" & "c"

$\ell_1 = S + z$

α = CONSTANT

503 234

BASED ON SEVERAL FINITE ELEMENT ANALYSES, THE FOLLOWING EXPRESSION OF F_{TB} WAS DERIVED:

$$F_{TB} = \lambda (R_A) = \frac{2}{3}\left[\frac{K_B}{EI/\ell_1^3}\right]^{1/4} \left[\frac{1/L_m}{1/L_m + 2/L_c}\right](R_A) \qquad (13)$$

WITH THE LIMITS $0.333 < \lambda < 1.0$ CORRESPONDING TO VERY RIGID AND VERY FLEXIBLE PLATES.

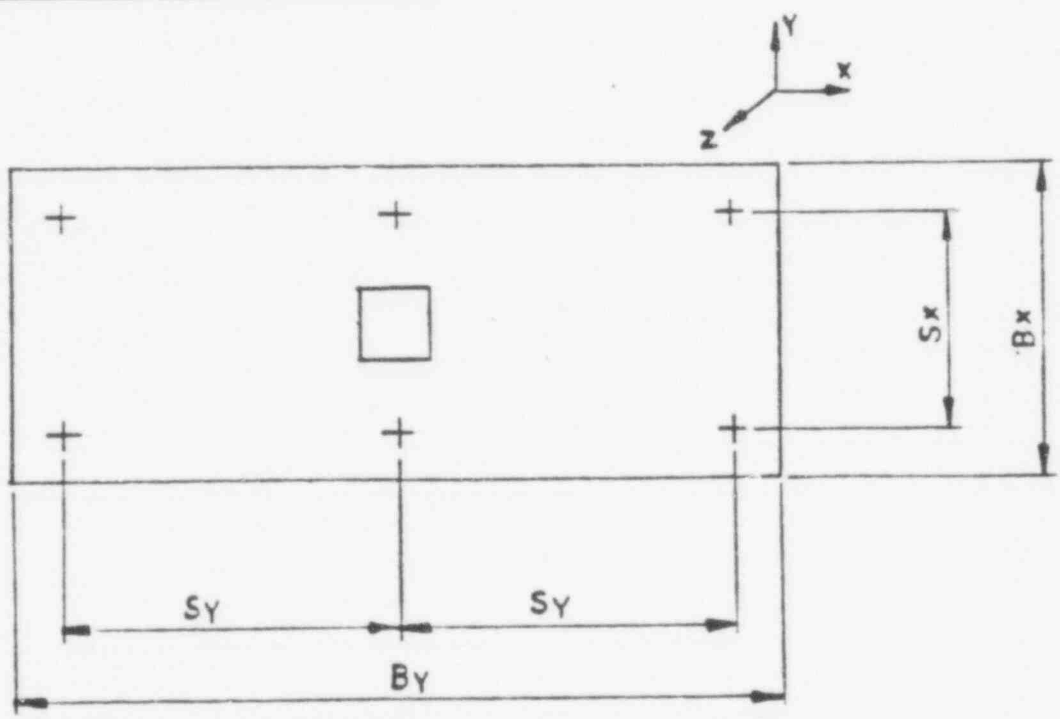
TENSION IN THE CORNER BOLTS IS GIVEN BY:

$$F_{Ta} = F_{Tc} = \frac{R_A - F_{Tb}}{2} \qquad (14)$$

$$\text{AND} \quad F_{Tf} = F_{Tg} = F_{Th} = 0 \qquad (15)$$

FOR BIAXIAL BENDING, THE RESULTANT BOLT FORCES WILL BE DETERMINED BY SUPERPOSITION.

III. SIX-BOLT PATTERN - MOMENT LOADING CASE



THE SIX-BOLT PATTERN CAN BE SOLVED BY USING A COMBINATION OF THE EQUATIONS FOR FOUR-BOLT AND EIGHT-BOLT PATTERNS.

503 235

FOR MOMENT ABOUT THE X-X AXIS:

(A) USE EQUATIONS (1) AND (2) TO SOLVE FOR TOTAL TENSION

(B) USE THE 8-BOLT DISTRIBUTION EQUATIONS (13) AND (14) FOR SOLVING THE BOLT LOADS WITH $\ell_1 = \frac{S_X}{2} + Z$ & $EI = 2417 B_Y t^3$

FOR MOMENT ABOUT THE Y-Y AXIS:

(A) USE EQUATIONS (6), (7) AND (8) TO SOLVE FOR REACTIONS WITH

$$K_2 = 2K_6\left(\frac{Z}{Y}\right)^2;\ S = S_Y;\ Y = \frac{S_Y}{2};\ EI = 2417 B_X t^3$$

(B) DIVIDE THE REACTIONS CORRESPONDING TO EACH BOLT ROW BY 2 TO OBTAIN INDIVIDUAL BOLT LOADS.

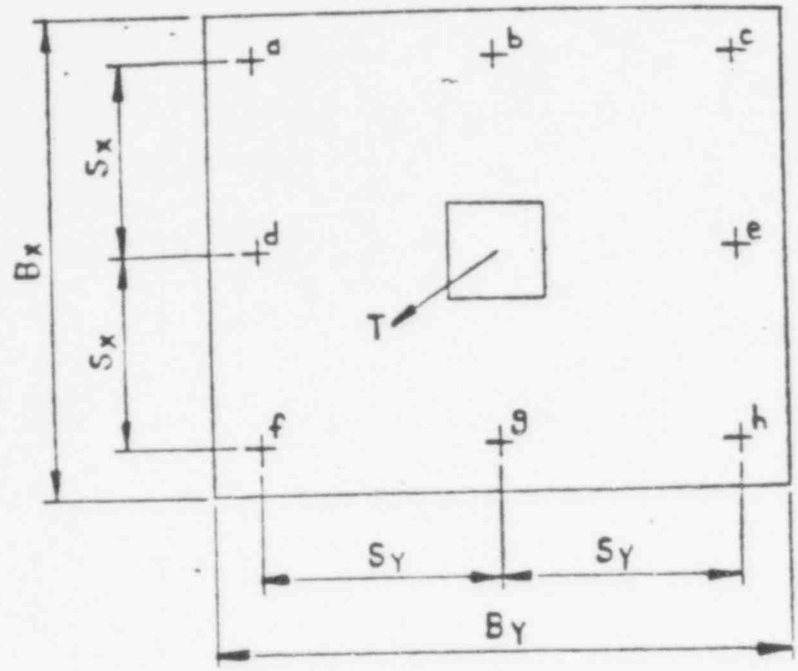
IV. SIX AND EIGHT-BOLT PATTERNS - TENSION LOADING CASES:

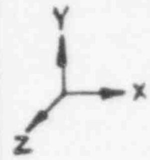
UNLIKE THE FOUR-BOLT PATTERN, FOR THE SIX AND EIGHT-BOLT CASES THE CENTRALLY APPLIED TENSION CANNOT BE DISTRIBUTED EQUALLY TO ALL THE BOLTS DUE TO THE INTERPLAY OF BOLT AND PLATE STIFFNESSES, AND THE RELATIVE DISTANCES OF THE BOLTS FROM THE POINT OF APPLICATION OF THE LOAD.

BASED ON THE MOMENT CASE IT WILL BE ASSUMED THAT THE PARAMETRIC VARIABLES AFFECTING THE LOAD DISTRIBUTION WILL BE OF THE SAME FORM AS IN THE MOMENT CASE. THE CONSTANT 8/9 FOR THE DISTRIBUTION FACTORS DFM_x AND DFM_y WAS OBTAINED FROM FINITE ELEMENT ANALYSIS RESULTS.

503 236

EIGHT-BOLT PATTERNS - TENSION LOADING CASE:





T = TENSION LOAD
F_T = LOAD PER BOLT

CALCULATE:

$EI_1 = 2417\, B_X t^3$

$EI_2 = 2417\, B_Y t^3$

$K_X = \dfrac{EI_1}{2S_Y}$

$K_Y = \dfrac{EI_2}{2S_X}$

$$T_X = \left[\frac{K_X}{K_X + K_Y}\right] T \quad ; \quad T_Y = T - T_X$$

$$L_c = \left[(S_X)^2 + (S_Y)^2\right]^{1/2}$$

$$DFM_X = \frac{8}{9}\left[\frac{K_B(2S_Y)^3}{EI_1}\right]^{1/4}\left[\frac{1/S_Y}{1/S_Y + 2/L_c}\right] \quad ; \quad 4/7 \le DFM_X \le 1.00$$

$$DFM_Y = \frac{8}{9}\left[\frac{K_B(2S_X)^3}{EI_2}\right]^{1/4}\left[\frac{1/S_X}{1/S_X + 2/L_c}\right] \quad ; \quad 4/7 \le DFM_Y \le 1.00$$

NOTE: FOR PLATE STIFFNESS VARING FROM INFINITELY RIGID TO EXTREMELY FLEXIBLE:

$$\frac{4}{8} \le DFM \le 1$$

SINCE A "RIGID" PLATE DOES NOT EXIST, 4/7 IS USED AS A LIMIT

503 237

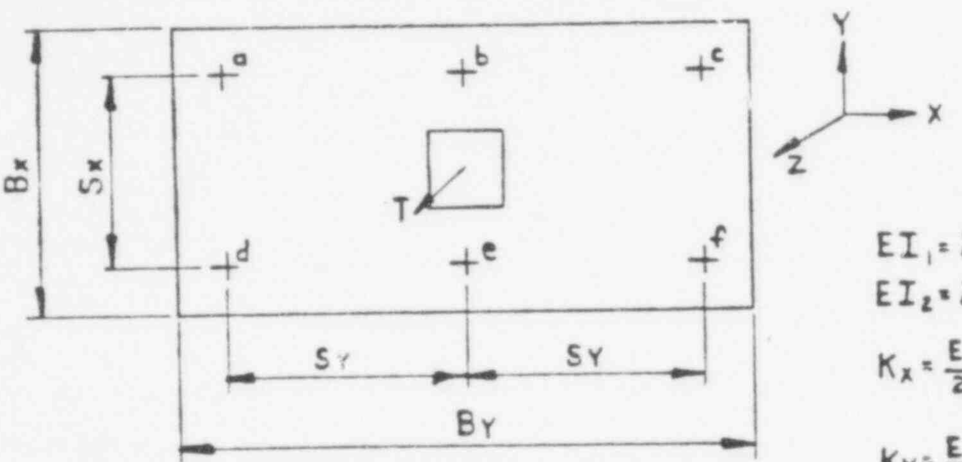
$$F_{Tb} = F_{Tg} = \left[DFM_Y\right]\left[\frac{T_Y}{2}\right]$$

$$F_{Td} = F_{Te} = \left[DFM_X\right]\left[\frac{T_X}{2}\right]$$

$$F_{Ta} = F_{Tc} = F_{Tf} = F_{Th} = \left[\frac{T - 2(F_{Tb} + F_{Td})}{4}\right]$$

IF BY ABOVE EQUATIONS $F_{Td} < F_{Ta}$ OR $F_{Tb} < F_{Ta}$, SET $F_{Td} = F_{Ta}$ OR $F_{Tb} = F_{Ta}$ AS LIMITING VALUES OR RECTANGULAR PLATES

SIX-BOLT PATTERN - TENSION LOADING CASE:



$$EI_1 = 2417 B_X t^3$$

$$EI_2 = 2417 B_Y t^3$$

$$K_X = \frac{EI_1}{2S_Y}$$

$$K_Y = \frac{EI_2}{S_X}$$

$$T_Y = \left[\frac{K_Y}{K_X + K_Y}\right] T$$

$$DFM_Y = \frac{8}{9}\left[\frac{K_B (S_X)^3}{EI_2}\right]^{\frac{1}{4}}\left[\frac{3/S_X}{3/S_X + 2/L_C}\right] \geq 4/7 \text{ AND} \leq 1.00$$

WHERE $L_C = \left[\left(\frac{S_X}{2}\right)^2 + \left(\frac{S_Y}{2}\right)^2\right]^{\frac{1}{2}}$

$$F_{Tb} = F_{Te} = \left[DFM_Y\right]\left[\frac{T_Y}{2}\right]$$

$$F_{Ta} = F_{Tc} = F_{Td} = F_{Tf} = \left[\frac{T - 2(F_{Tb})}{4}\right]$$

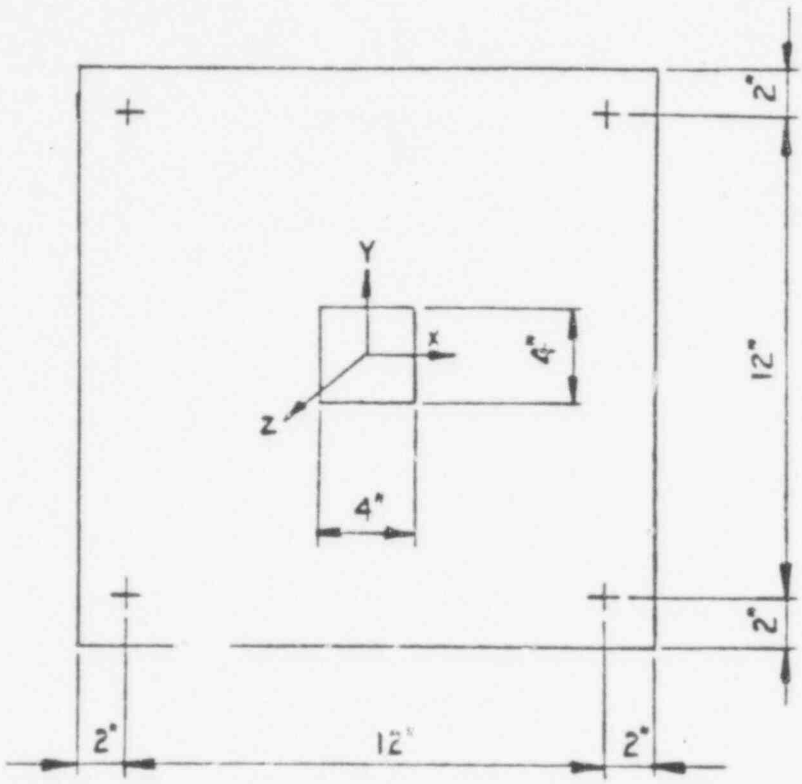
BASED ON THE ABOVE EQUATION, IF $F_{Ta} (= F_{Tc} = F_{Td} = F_{Tf}) > F_{Tb} (= F_{Te})$,

AS MAY BE THE CASE WHERE $S_X \geq 2S_Y$, THEN $F_{Ta} = F_{Tc} = F_{Td} = F_{Tf} = F_{Tb} = F_{Te} = \frac{T}{6}$

V. COMPARISON OF RESULTS:

FINITE ELEMENT METHOD COMPARED TO THE QUASI-ANALYTICAL METHOD

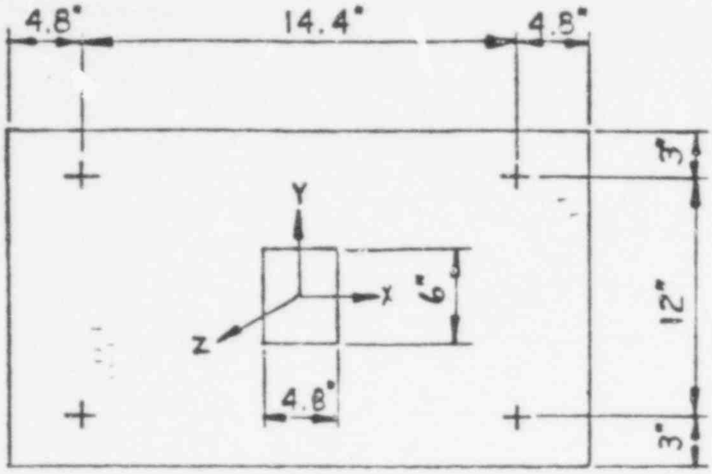
(A) FOUR-BOLT PATTERN



PL	t	K_B	LOADING
1	1/2"	44	Mx = 18K"
2	1/2"	44	Mx = 18K", My = 36K"
3	1/2"	44	Mx = 18K", Fz = 4K"
4	3/4"	44	Mx = 18K"
5	3/4"	150	Mx = 16K"
6	3/4"	300	Mx = 18K"

K_B = BOLT STIFFNESS (K/IN)

t = PLATE THICKNESS



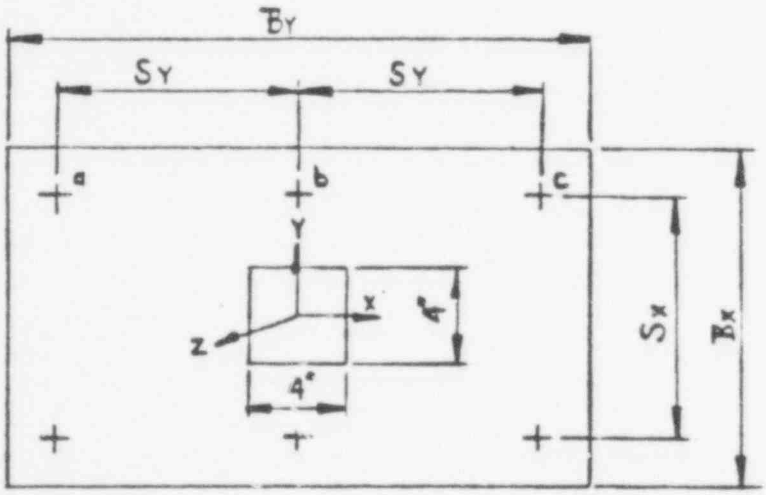
K_B = BOLT STIFFNESS (K/IN)

t = PLATE THICKNESS

[FROM TELEDYNE ENGINEERING REPORT (REFERENCE - 2)]

PL	t	K_B	LOADING
7	3/8"	44	M_Y=247.5K"
8	2"	44	M_Y=247.5K"
9	1/2"	44	M_Y=247.5K" M_X=247.5K"

(B) <u>SIX-BOLT PATTERN</u>:

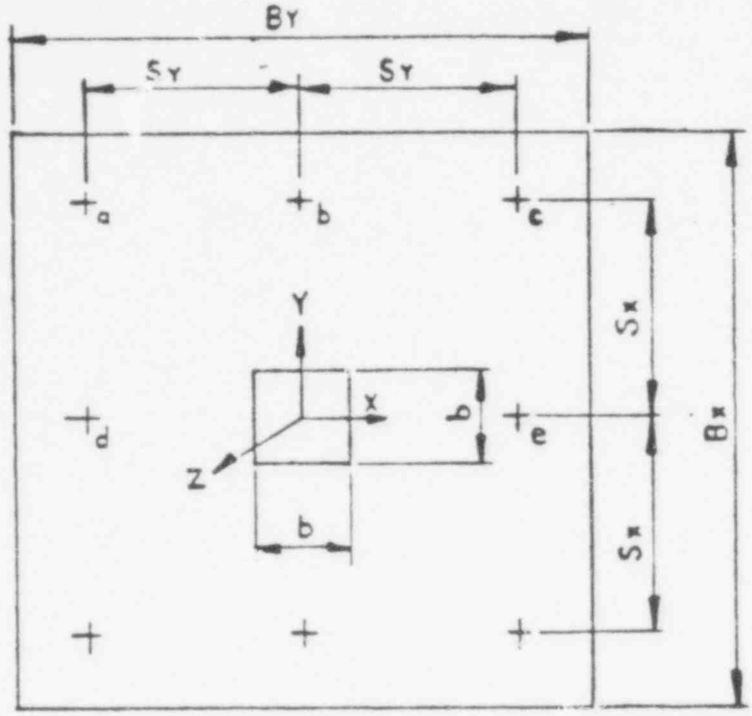


K_B = BOLT STIFFNESS (K/IN)

t = PLATE THICKNESS

PL	t	K_B	S_X	S_Y	B_X	B_Y	LOADING
1	1/2"	44	12	8	16	20	M_X=36K"
2	1"	440	12	8	16	20	M_X=36K"
3	1"	44	22.5	4	25.5	12	F_Z=10K
4	2"	44	22.5	4	25.5	12	F_Z=10K
5	3/4"	44	12	6	16	16	F_Z=10K
6	1"	44	12	6	16	16	F_Z=9K

(C) EIGHT-BOLT PATTERN:



℄	t	K_B	S_X	S_Y	B_X	B_Y	b	LOADING
1	1¼"	44	12	12	28	28	6	$M_X = 180^{K''}$
2	1¼"	440	12	12	28	28	6	$M_X = 180^{K''}$
3	1"	300	8	8	20	20	4	$M_X = 90^{K''}$
4	1¼"	150	12	12	28	28	6	$F_Z = 16^K$
5	1¼"	44	12	12	28	28	6	$F_Z = 8^K$
6	1"	44	6	10	16	24		$F_Z = 10^K$

K_B = BOLT STIFFNESS (KIP/IN)

t = PLATE THICKNESS

503 241

TABULATED RESULTS:

FOUR-BOLT PATTERN:

PLATE \ ANALYSIS METHOD	LOAD PER BOLT (K) FINITE ELEMENT	LOAD PER BOLT (K) QUASI-ANALYTICAL MODEL	% DIFFERENCE
A - (1)	0.75	0.75	0
A (2)	2.08	2.25	+8.2
A (3)	1.71	1.75	+2.3
A (4)	0.64	0.68	+6.3
A (5)	0.75	0.78	+4.0
A (6)	0.78	0.84	+7.7
A (7)	9.12	9.19	+0.8
A (8)	6.12	6.45	+5.4
A (9)	16.61	18.17	+9.4

SIX-BOLT PATTERN:

	TENSILE LOAD PER BOLT (K)				% DIFFERENCE	
	BOLTS a & c	BOLT b	BOLTS a & c	BOLT b		
PLATE \ ANALYSIS METHOD	FINITE ELEMENT		QUASI-ANALYTICAL MODEL		BOLTS a & c	BOLT b
B (1)	0.65	1.84	0.64	1.72	-1.5	-6.5
B (2)	0.61	1.96	0.72	1.86	+18.0	-5.1
B (3)	1.68	1.64	1.67	1.67	-0.7	+1.5
B (4)	1.67	1.66	1.67	1.67	0	+0.2
B (5)	1.55	1.89	1.67	1.67	+7.2	-13.5
B (6)	1.45	1.59	1.5	1.5	+3.2	-6.1

503 242

EIGHT-BOLT PATTERN:

ANALYSIS METHOD / PLATE	TENSILE LOAD PER BOLT (K)						% DIFFERENCE		
	BOLT a	BOLT b	BOLT c	BOLT a	BOLT b	BOLT d			
	FINITE ELEMENT			QUASI-ANALYTICAL MODEL			BOLT a	BOLT b	BOLT d
C (1)	1.89	2.64	0.75	1.94	2.70	0.92	+2.69	+2.3	+17.0
C (2)	1.55	5.26	1.46	1.58	5.14	1.47	+1.9	-2.3	+0.7
C (3)	1.22	3.32	0.88	1.32	3.23	0.85	+8.2	-2.6	-3.0
C (4)	1.08	2.92	1.46	1.06	2.92	1.46	0	0	0
C (5)	0.83	1.17	0.59	0.86	1.14	0.57	+3.6	-2.6	-3.5
C (6)	0.99	1.95	1.06	0.96	2.04	1.01	-3.1	+4.4	-5.2

503 243

REFERENCES

1. SWANSON ANALYSIS SYSTEM, INC. "ANSYS" ENGINEERING ANALYSIS SYSTEM

2. DILUNA, L. J. AND FLAHERTY, J. A., "AN ASSESSMENT OF THE EFFECT OF PLATE FLEXIBILITY ON THE DESIGN OF MOMENT-RESISTANT BASE PLATES", TELEDYNE ENGINEERING SERVICES (SUBMITTED TO ASME FOR PUBLICATION)