NONLINEAR ANALYSIS OF A BOLTED MARINE RISER CONNECTOR USING NASTRAN SUBSTRUCTURING

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SUMMARY

Results of an investigation of the behavior of a bolted, flange type marine riser connector is reported. The method used to account for the nonlinear effect of connector separation due to bolt preload and axial tension load is described. The automated multilevel substructuring capability of COSMIC/NASTRAN was employed at considerable savings in computer run time. Simplified formulas for computer resources, i.e., computer run times for modules SDCOMP, FBS, and MPYAD, as well as disk storage space, are presented. Actual run time data on a VAX-11/780 is compared with the formulas presented.

INTRODUCTION

A marine riser is the equipment which connects an offshore drilling rig to the subsea wellhead control system on the ocean floor. The riser provides a conduit for various fluids and tools, as well as support for the control lines which run from the rig to wellhead. A riser consists of a series of lengths of pipe with connectors on each end. Axial tension load is applied to the riser by tensioners on the rig to prevent the riser from buckling and to resist ocean current. As offshore drilling depths have increased to over a mile, new riser connector designs have evolved to meet this need.

The analysis reported here is of a bolted, eliptical flange type of connector (HMF) with a rated axial load of 1.5 million pounds. The riser pipe is 18-5/8 inches outside diameter. The connector, shown in Figure 1, is characterized by 4 inch thick flanges and an outside diameter of 38-1/4 inches. The analysis must include the nonlinear effect which is introduced by the fact that the mating surfaces of the connector will support only a compressive type of loading. Bolt preload can cause the connector surface to separate at points remote from the bolt pressure area. The axial tension load will also tend to separate the connector. The solution technique reported here makes use of COSMIC/NASTRAN automated multistage substructuring. This capability provides an economical solution to very large models, such as the one described below

TECHNICAL APPROACH

The calculation of bolt preload stress and alternating stresses caused by cyclic loading of the riser connector requires an accurate understanding of how the pin/box/bolt interfaces behave under these load conditions. A solid (three-dimensional) model of a 22.5 degree section of the connector was developed. The 22.5 degree "pie" section was taken in the region of the choke and kill line, as shown in Figure 2. The flange stiffness is lowest in this area, which provides a conservative assumption.

A practical limit is quickly approached, in terms of computer resources, when very detailed, three-dimensional solid models are required for an analysis. This restriction is relieved to some extent by using a technique called substructuring.

The substructure approach reduces the number of equations to be solved by modeling the structure as separate pieces. Each piece is modeled independently. Using matrix reduction techniques, an equivalent stiffness matrix is formulated with the degrees of freedom only of the boundaries of mating pieces. These reduced matrices are combined in the same manner as finite element stiffness matrices (hence referred to as superelements) to form a set of equations identical in form to the non-substructure case, but consisting of much fewer equations. After solution of the combined structures, the stresses in each of the individual pieces are recovered separately.

In the case of the HMF connector, the pin, box, and bolt each make up a substructure. The boundary interfaces are the pin/box interface, the bolt/shoulder interface, and the bolt thread/box interface.

Mathematical Model Description

Separate finite element models were developed of the pin, box, and bolt. Hidden line plots of the finite element models of the pin, box, and bolt, showing the element boundaries, are presented in Figures 3, 4, and 5, respectively. Table I shows the substructure components along with the related number of elements, degrees of freedom (D.O.F.), and boundary degrees of freedom.

As can be seen from Table I, the use of substructuring reduces the number of degrees of freedom by a factor of 30 (from 23,753 to 789). It is with this reduced structure that the analysis proceeds during Phase II.

Boundary interface behavior is determined through the use of NASTRAN substructure multipoint constraints (MPC's), which is a method to impose constraints on the relative motion of grid points of different substructures. Bolt preload is applied as an equivalent thermal load. Axial load is applied as a pressure normal to box/riser pipe boundary.

Loads, Boundary Conditions, and Constraints

The loads consist of the bolt preload and the axial load applied to the coupling. Boundary conditions define the fixed end of the assembly to react the applied axial load, as well as cyclic symmetry boundary conditions. Constraints refer to the interface boundaries of the pin, box, and bolt. An axial tension load of 1.5 million pounds is applied to the connector. Results are presented for three bolt preloads; equivalent to 1.7, 2.5, and 3.3 million pounds.

Boundary conditions are applied to react the primary axial load and to provide symmetry constraints to the model. The pin/riser pipe interface (i.e., the analogues surface on the pin that the axial load is applied to on the box), is constrained from moving in the axial direction only. Radial motion is allowed.

The symmetry boundary condition, for an axisymmetric load, is achieved by forcing the displacement of grid points lying on the two planes (i.e., 0 degrees and 22.5 degrees) to be zero in the direction normal to the surface. The local coordinate system used on the 22.5 degree boundary is rotated 22.5 degrees from the global coordinate system. This rotation is necessary since NASTRAN can only constrain grids along the local coordinate axes.

The interfaces between the pin, box, and bolt are controlled by substructure multipoint constraints. These constraints are defined in NASTRAN by the following equation:

$$\Sigma A_i U_i = 0 \qquad (1)$$

where,

A_i = coefficient of i^{th} degree of freedom

U_i = displacement of i^{th} degree of freedom

For the case where two grids, numbers 1 and 2, are constrained to move together in the Z direction, equation (1) would be:

$$W_1 - W_2 = 0 \qquad (2)$$

where,

$A_1 = 1$

$A_2 = -1$

W_i = displacement in the Z direction of i^{th} grid

The finite element mesh for pin, box, and bolt are compatible in that the node points of the models along the mating surfaces are coincident in space. Each pair of nodes are coupled according to equation (2).

Solution Procedure

The substructure solution process is divided into three "phases" by NASTRAN; Phase I - Generation of each substructure, Phase II - Combining and reducing any number of times and then solving for the final substructure, and Phase III - Stress recovery of the individual substructures.

Two separate procedures are needed for the Phase II solution:

1. Determine equivalent thermal loads to achieve the desired bolt preload consistent with proper equilibrium forces, and

2. Determine the pin/box interface with both bolt preload and axial load applied consistent with proper equilibrium forces.

Both load conditions, when applied to the pin/bix/bolt assembly, cause certain portions of the surfaces to lose contact. This characteristic creates a nonlinear influence in the solution. An iterative technique is adopted to solve this problem.

For each substructure, at the solution phase (i.e., Phase II of the substructure procedure), equilibrium forces (i.e., substructure single point constraint forces), are calculated by NASTRAN as

$$[F_e^i\} = [K^i][X^i\} - [F^i\} \quad (3)$$

where,

$[F_e^i\}$ = Equilibrium forces for the i^{th} substructure

$[K^i]$ = Stiffness matrix for the i^{th} substructure

$[X^i\}$ = Solution vector for the i^{th} substructure

$[F^i\}$ = Load vector for the i^{th} substructure

The solution for both load cases is started assuming that the mating surfaces are in complete contact and the solution for the combined substructures is obtained. The equilibrium forces are calculated according to equation (3). The equilibrium forces necessary are either tension or compression on the interface surface. Those forces that are tensile in nature are not allowed, so the constraint condition, equation (2), is removed for all degrees of freedom (D.O.F.) associated with the tensile load.

Removal of the constraints changes the stiffness matrix in equation (3). With the constraints removed from the selected D.O.F., a new Phase II solution is obtained. The process is repeated until equilibrium is obtained, i.e., all interface forces are compressive. With equilibrium established in the Phase II solution, stress recovery in Phase III can then be accomplished.

Results of Analysis

The results of the Phase II solution illustrate the nonlinear characteristics of the solution. The stress recovery in Phase III is straight forward and not included in this paper.

The equilibrium condition for bolt preload of 1.7, 2.5, and 3.3 million pounds resulted in the same contact surface of the bolt. The contact surface is shown as the shaded area in Figure 6. The effective diameter, as calculated in accordance with equations presented in Reference 1, are shown for comparison. Figure 6 graphically illustrates the effect of the proximity of the choke and kill lines. The flange stiffness, which is proportional to contact area, is less than predicted by the classical method. However, the actual alternating stresses in any of the bolts will be less than that calculated by the finite element model. This is due to the modeling assumptions. The four bolts that are next to the choke and kill lines have a stiffer flange than the model, because the model symmetry implies a choke and kill line on both sides of the bolt. The remaining four bolts have flange stiffnesses even higher since these lie between hydraulic lines which are smaller in diameter than the choke and kill lines.

The applied axial load of 1.5 million pounds is applied to the box while the pin was restrained. Due to the eccentric nature of the load, the head of the bolt bends and some contact is lost between the pin and the box. The solution procedure, as in the bolt-up load condition, is iterative due to this nonlinearity.

The contact areas for bolt preloads of 1.7, 2.5, and 3.3 million pounds are shown in Figures 7, 8, and 9, respectively. Note that as the bolt preload increases, the contact area increases and moves inward. This causes an increase in the effective flange stiffness and reduces the amount of bending in the bolt. Both of these effects reduce the alternating peak stress in the bolt caused by the axial load as bolt preload is increased.

RESOURCE ESTIMATES

In order to determine the most cost effective substructure method, it is necessary to calculate computer resource requirements; computer run time and disk storage. The documentation available, References 2 and 3, provide some guidance in this area. However, the timing equations presented in these documents are complex, and is some cases, are apparently in error. Simplified timing equations are presented for the operations which, in the analysis presented, Static Analysis (Solution 1), Phase I, II and III substructuring comprise the overwhelming majority of computer run time.

Computer run time, using a VAX-11/780 with a floating point accelerator (FPA), was used for the analysis. The timing equations should prove to be quite general since the TIMETEST module in NASTRAN was used to provide the timing constants. The operations discussed below are symmetric decomposition (SDCOMP module), forward-backward substitution (FBS module), and matrix multiply and add (MPYAD module).

Symmetric Decomposition

Symmetric decomposition time can be significant in both Phase I and Phase II. In Phase I, the calculation of the substructure stiffness matrix, K_{aa}, requires the decomposition of K_{oo},

$$K_{aa} = \overline{K}_{aa} + K_{oa}^{T} G_{oa} \tag{4}$$

where the Guyan transformation matrix, G_{oa};

$$G_{oa} = K_{oo}^{-1} K_{oa} \tag{5}$$

is formed by forward-backward substitution. This process is also performed if multipoint constraints are called for in case control.

Similar reductions are available in Phase II. The matrices are smaller, but very dense. For these calculations the average bandwidth, C, is essentially equal to N/2. The BANDIT program, Reference 4, can be used as an effective means to find C in Phase I. A more costly method is to use a small value on the TIME card that will cause NASTRAN to abort the decomposition process after SDCOMP time is calculated. A time estimate will be printed out and the solution terminated.

Time estimates for symmetric decomposition, assuming that no spill occurs, is (Reference 3, Section 14):

$$T_{sdc} = .5T_m \, NC^2 + T_b \, NC \quad \text{(sec)} \tag{6}$$

where,

T_b = Time/word to pack and write elements of a matrix (sec/word)

T_m = Medium loop multiply, an average of loose loop and tight loop multiply (sec/ele)

N = Order of the matrix (degrees of freedom) K_{oo}

C = Average bandwidth of matrix K_{oo}

The first item is multiplication time, usually double precision; the second item is I/O time.

Forward-Backward Substitution

Immediately after decomposition of K_{oo}, the forward-backward substitution process, (FBS), is initiated to form the G_{oa} transformation matrix. No timing checks are made by NASTRAN on this operation, however, the time involved can be substantial. The time for symmetric FBS is estimated as (Reference 3, Section 14):

$$T_{fbs} = 2T_m \, PNC + T_b N(2C + P/2) \quad \text{sec.} \tag{7}$$

where,

P = degrees of freedom in the "A" set, i.e., the order of K_{aa}

The first item is multiply time (two operations forward and backward) and the second item is I/O (P is read only once, but N*C is written twice).

Matrix Multiply

Time estimates for matrix multiply and add (MPYAD) is most troublesome for a number of reasons:

1. NASTRAN will automatically pick one of three very different methods depending on the characteristics of the matrices.

2. I/O time is strongly dependent on matrix characteristics but is considered completely described by the matrix trailers. In particular, the matrix density is used to calculate how many columns must be processed; a very rough approximation. I/O time can be the dominant factor in MPYAD.

3. Each of the three matrix processing routines are quite complex. Some require multiple passes if a matrix does not fit in core. It is common for a matrix not to fit even in the very large virtual core than the VAX can provide.

In spite of these difficulties a simplified approximation is offered here. Assume that the matrix multiply and add is described by

$$[A][B] + [C] = [D] \quad (8)$$

Use the Method 1 time estimated provided in Reference 2, Section 3.5.12.4:

$$\begin{aligned} T_{mpy} = \; & \rho_a R_a C_a C_b \quad T_m && \text{(multiply time)} \\ & N_p(\rho_a R_a + 5)C_a \; T_i && \text{(interpretive unpack A)} \\ & .5(1 + \rho_b)R_b C_b \; T_u && \text{(unpack B)} \\ & .5(1 + \rho_d)R_a C_b \; T_p && \text{(pack D)} \\ & .5(1 + \rho_c)R_a C_b \; T_u && \text{(unpack C - if present)} \end{aligned} \quad (9)$$

where,

R_i, C_i = number of rows or columns in matrix "i"

T_i = interpretive unpack sec/word

T_u = unpack sec/word

T_p = pack sec/word

T_m = multiply time sec/operation

N_p = number of passes to interpretive unpack B

and:

$$N_p \cong \frac{(R_a + C_a) * C_b}{\text{OPEN CORE/WORDS PER ELEMENT}} \quad (10)$$

where open core is the number of words in open core (set diagnostic no. 13 in the executive control deck to find this number) and words per element are 1 and 2 for single precision and double precision, respectively.

Repeat the calculation for the transpose of equation (9) by interchanging R_a and C_b, C_a, and R_b, ρ_a and ρ_b pick the smallest of the two times.

The reader is cautioned that equation (9) will only provide an order of magnitude due to the complexities of the operation.

Disk Storage Space

Disk storage space, including the substructure operating file (SOF) is dominated by the G_{oa} matrix since the matrix density is 100% and the boundary D.O.F. are usually numerous. It is worthwhile to calculate ahead of time this space for planning purposes. For example, up to ten physical files may be used for the single SOF logical file. One may wish to limit each physical file such that a single tape or mountable disk pack would be adequate for back-up storage.

The G_{oa} size is simply

$$W_{Goa} = 2*N*P \quad \text{words}$$

where double precision has been assumed.

COMPUTER TIME COMPARISONS

Computer time estimates are based on data obtained from the TIMETEST module with the outer loop, N, equal to 100 and the inner loop, M, equal to 1,000. The timing parameters, shown in Table II, are those which NASTRAN uses and is found in NTMXBD data block. A VAX-11/780 with a floating point accelerator (FPA) was used.

SDCOMP Module

Table III gives a comparison of actual time expended in the SDCOMP module vs. that calculated by equation (4) for various size matrices. Note that as the time increases so does the error in the estimate. This may indicate a stronger dependence on C than was assumed. To be conservative one should add 50% to the estimated time.

FBS Module

Table IV gives a comparison of actual time in the FBS module vs. that calculated by equation (7) for various size matrices. Again, to be conservative, one should add 20% to the estimated time. If NASTRAN finds that all the time has been expended in FBS and SDCOMP, she terminates without checkpointing first; the time is lost.

MPYAD Module

Table V compares both estimated times (remember to pick the smallest) for the MPYAD module vs. actual times. The examples given are characteristic of Phase I, II, and III operations and include all five possible NASTRAN MPYAD options. An educated guess must be made at the densities of the matrices involved. The following densities are suggested:

Phase I: $G_{oa} = 1.0$

$\bar{K}_{aa} \cong 0.1 - 0.25$

$K_{oa} \cong 0.005 - 0.05$

Phase II: $K_{aa} = 1.0$

$H \cong R_b$ / Number of rows in H = order of K

where,

R_b = Substructure DOF / Combined DOF

Phase III: $G_{oa} = 1.0$

$U_a = 1.0$

$P_o = 0 - 1.0$

It is assumed that a program like BANDIT, Reference 4, has been used. NASTRAN internal BANDIT was not used in this analysis.

The matrix multiply times generally are within a factor of two; indicating that one would want to double the time estimate to be safe. The sole exception is

Case No. 3, which is off by nearly an order of magnitude. Comparing this time to Case No. 4, it is possible that if Method 2 had been used the time would match more closely. All five possible methods are included for comparison; Method 3 is only available for the transpose case. Table VI provides a breakdown of the preferred time estimate into the five components. Note that I/O time is often significant. Table VII provides the matrix characteristics and typical operations for the three phases.

CONCLUDING REMARKS

Use of substructure multipoint constraints provides an effective means to model contacting surfaces of separate substructures. The single point constraint forces let the analyst check for proper equilibrium conditions. Nonlinear effects can be accounted for by repeated analysis until equilibrium is satisfied. The method used converged reasonably quickly, requiring about 8 iterations for each of the 4 solutions; the bolt preload condition, 3 bolt preloads plus axial load.

The number of iterations required for each solution was 8, a total of 32 for the entire analysis. Without substructuring, approximately 30 hours per iteration or 900 hours of computing time would have been required. By using substructuring, the computer time was reduced to less than 90 hours, a factor of ten in cost reduction. This calculation assumes that SDCOMP will not use spill logic for decomposition of the combined model. Numerical error is also a concern; with a 64 bit word length, matrices over about 10,000 D.O.F. are risky (Reference 5).

It is imperative that a small model be analyzed, start to finish, and checked for correctness, not just completion. Subcase structures in particular must be compatible. With thermal loads, it was found that in Phase II, additional subcases could be added that are linear combinations of Phase I loads. In Phase III, new loads and temperature subcases, corresponding exactly to those in Phase II, must be used. This will cause NASTRAN to re-generate the proper thermal loads but not decompose the stiffness matrix. Do not change the loads in subcases defined in Phase I, NASTRAN will not re-calculate the thermal loads. The solution will complete normally but the answers will be incorrect!

The FBS module is the dominant factor in computer run time for substructuring, assuming that there is no core spill in the SDCOMP module. It is recommended that the substructures be small enough to avoid spill logic in SDCOMP since, if not - according to Reference 3, quantum increases in computer time will result.

It appears that a large number of small substructures is most cost efficient from a computer run time standpoint. This must be traded off against the loss in labor and clock time efficiency caused by additional bulk data generation and bookkeeping. For example, each substructure must have a specified boundary and, it multiple stages are used, boundary sets for each stage may be specified.

REFERENCES

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4. Everstine, Gordan C., The BANDIT Computer Program for the Reduction of Matrix Bandwidth for NASTRAN®, Naval Ship Research and Development Center, Bethesda, Maryland, Report 3827, March 1972.

5. MacNeal, R., et al., The NASTRAN® Theoretical Manual, National Aeronautics and Space Administration, Washington, D.C., Publication NASA SP-221(06), January 1981.

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TABLE I

CHARACTERISTICS OF THE THREE BASIC SUBSTRUCTURES

NAME	D.O.F.*	ELEMENTS	BOUNDARY D.O.F.
Pin	10,923	4,474	235
Box	6,407	1,824	359
Bolt	6,423	1,920	159
Total	23,753	8,218	789

*After removal of symmetry boundary D.O.F.

TABLE II

VAX-11/780 TIMING CONSTANTS

ITEM*	TIME (micro-sec)	DESCRIPTION	
1	15.6	Average of Read, Write, and Backward Read/Word	
2 (T_b)	1200	Pack and Write elements of a column	
3 (T_i)	1277	Read and Unpack elements of a column	
4 (T_p)	49.5	Pack and Write entire column	
5 (T_u)	112	Read and Unpack entire column	
6	31	Read a string from buffer	
7	31	Write a string to buffer	
8	8	Real Single Precision (RSP)	Tight Loop Multiply (T_t)
9	13.5	Real Double Precision (RDP)	Tight Loop Multiply (T_t)
10	23	Complex Single Precision (CSP)	Tight Loop Multiply (T_t)
11	42	Complex Double Precision (CDP)	Tight Loop Multiply (T_t)
12	10	RSP	Loose Loop Multiply (T_ℓ)
13	16.5	RDP	Loose Loop Multiply (T_ℓ)
14	26.5	CSP	Loose Loop Multiply (T_ℓ)
15	44	CDP	Loose Loop Multiply (T_ℓ)

* Position in NTMXBD data block; $T_m = \frac{1}{2}(T_t + T_\ell)$

TABLE III

COMPARISON OF SDCOMP TIMES
(VAX-11/780 with FPA)

N	C†	TIME (MINUTES)			
		ARITH*	I/O*	TOTAL*	ACTUAL
250	125	0.48	0.62	1.10	0.92
291	131	0.62	0.76	1.38	1.85
3139	299	35.1	18.8	53.9	54.5
3268	274	30.7	17.9	48.6	51.8
4159	372	71.9	31.0	102.9	133.1
4202	422	93.5	35.5	129.0	192.4
6270	289	65.5	36.2	101.7	100.4
9662	494	294.7	95.5	390.2	589.1

* Calculated with T_m = 15E-6, T_b = 1200 E-6;

† C is average bandwidth from NASTRAN message 3023

TABLE IV

COMPARISON OF FBS TIMES

(VAX-11/780 with FPA)

N	C †	P	TIME (MINUTES)			
			ARITH*	I/O*	TOTAL*	ACTUAL
250	125	4	0.06	1.26	1.32	0.12
291	131	248	4.72	2.24	6.96	6.08
3139	299	294	138.0	46.8	184.8	154.7
3268	274	323	144.6	46.4	191.0	160.8
4159	372	841	650.6	96.9	747.5	769.5
4202	422	814	721.7	105.1	826.8	868.8
6270	289	153	138.6	82.1	220.7	154.6
9662	494	235	560.8	213.6	774.4	617.5

* Calculated with T_m = 15E-6, T_b = 1200 E-6;

† C is average bandwidth from NASTRAN message 3023

TABLE V

COMPARISON OF MPYAD TIMES (Seconds)
(VAX-11/780 with FPA)

CASE	TIME EST.		METHOD* USED	ACTUAL TIME
	$AB + C$	$B^T A^T + C^T$		
1	1305	154	3-T	143
2	1267	149	1-NT	289
3	20	465	1-T	135
4	699	26	2-NT	22
5	167	3303	2-T	262
6	1292	151	3-T	145

* See References 2 and 3 for a description of the methods; T means that the A matrix is to transposed; times are in seconds.

TABLE VI

TIME ESTIMATE COMPONENTS FOR BEST CASE (Seconds)

TERM	CASE					
	1	2	3	4	5	6
1-Multiply time	4.3	38.8	0.67	1.89	9.71	2.12
2-Interpritive Unpack Matrix A (B^T)	42.7	1.6	2.24	2.24	46.04	41.35
3-Unpack B (A^T)	107.4	107.4	9.68	12.87	107.4	107.4
4-Pack D	0.02	0.93	7.1	9.44	1.16	0.02
5-Unpack C	0.00	0	0.0	0.0	2.62	0
TOTAL	154	149	19.7	26.45	167	151

TABLE VII

MATRIX OPERATIONS AND MATRIX CHARACTERISTICS

MPYAD MODULE

PHASE	CASE	OPERATION*	R_a	C_a	ρ_a	R_b	C_b	ρ_b	ρ_c
III	1	$G_{oa}^T P_o + \bar{P}_a$	153	6270	1.000	6270	3	0.11	1.000
	2	$G_{oa} U_a + \bar{U}_o$	6270	153	1.000	153	3	1.000	1.000
II	3	$H^T K_{aa}$	488	294	0.002	294	294	1.000	0
	4	$(H^T K_{aa}) H$	488	294	0.602	294	488	0.002	0
I	5	$K_{oa}^T G_{oa} + \bar{K}_{aa}$	153	6270	0.005	6270	153	1.000	0.100
	6	$G_{oa}^T P_o + P_a$	153	6270	1.000	6270	2	0.082	1.000

* See Reference 6 for a description of the matrix operation.

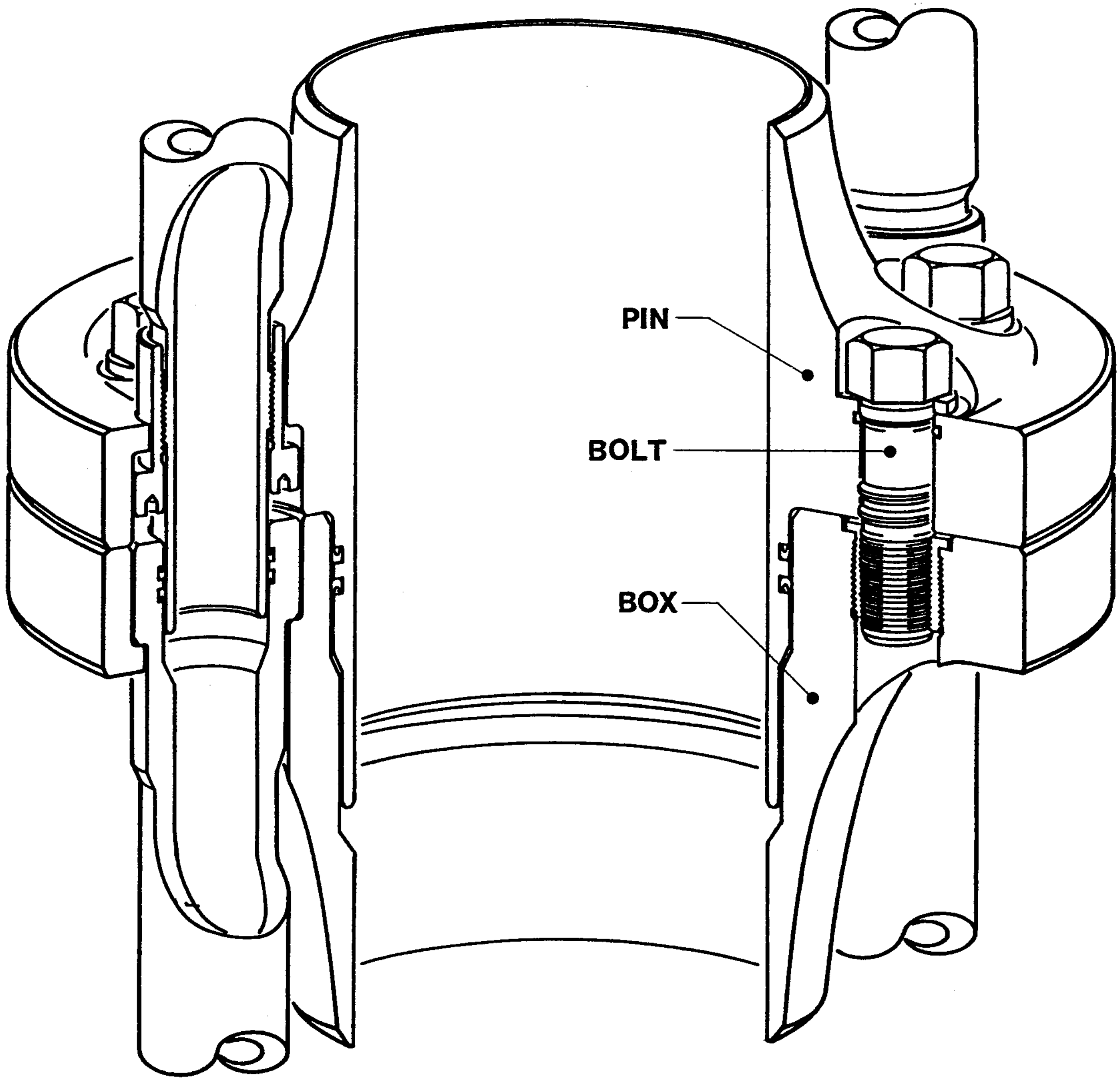

FIGURE 1 - HMF RISER CONNECTOR

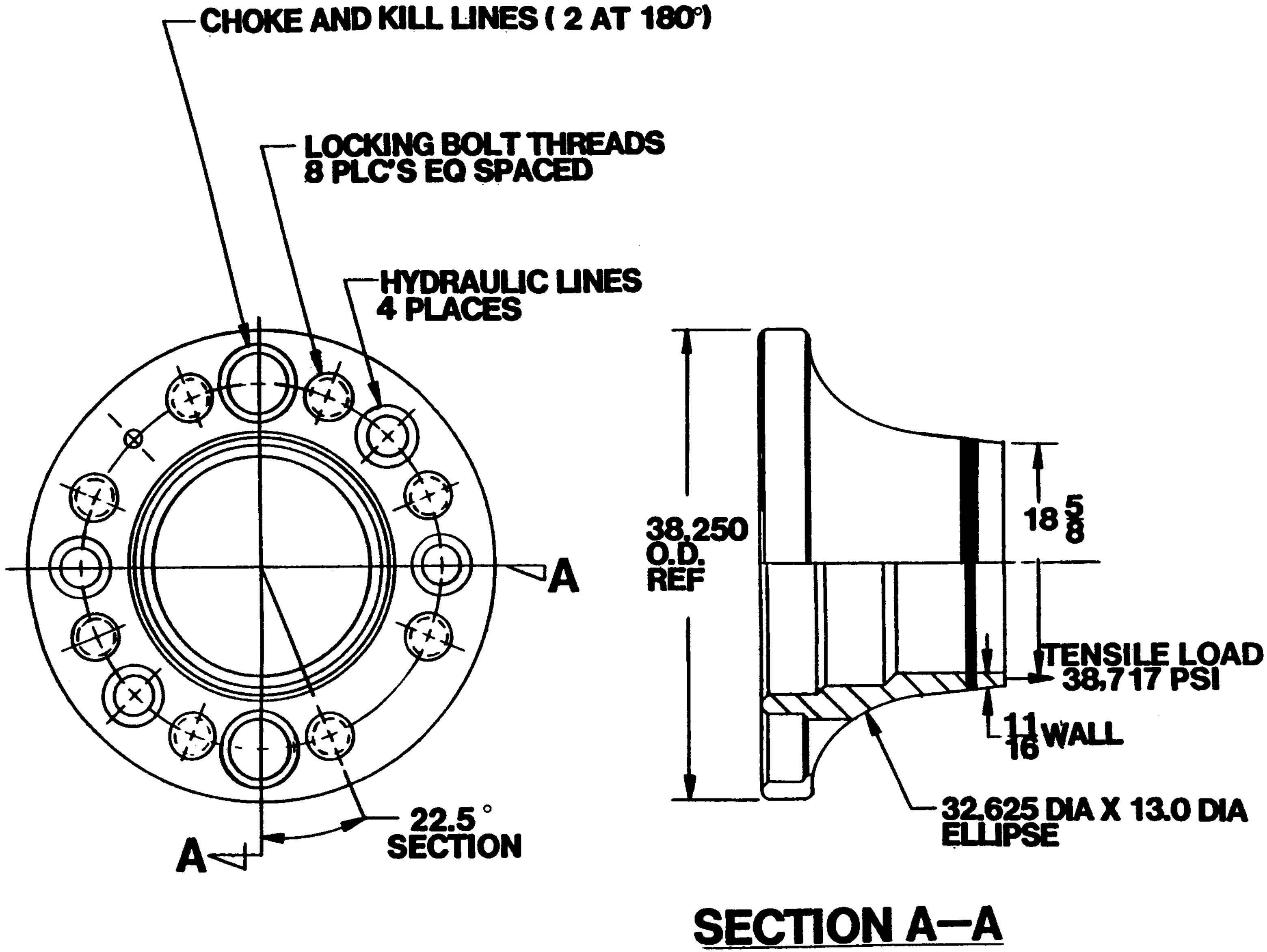

FIGURE 2 - CROSS SECTION OF HMF RISER CONNECTOR

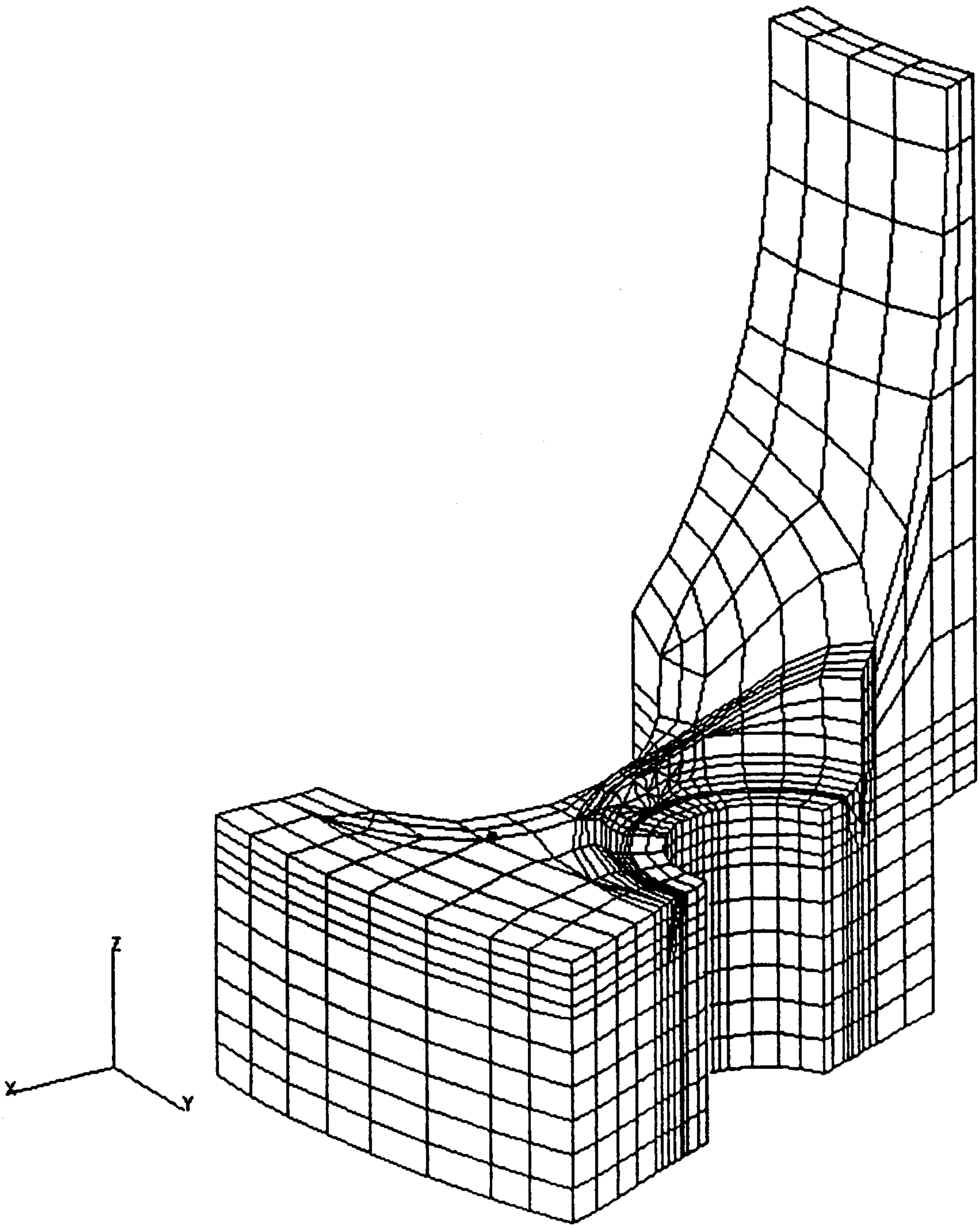

FIGURE 3 - HIDDEN LINE VIEW OF HMF PIN, 22.5° PIE SECTION

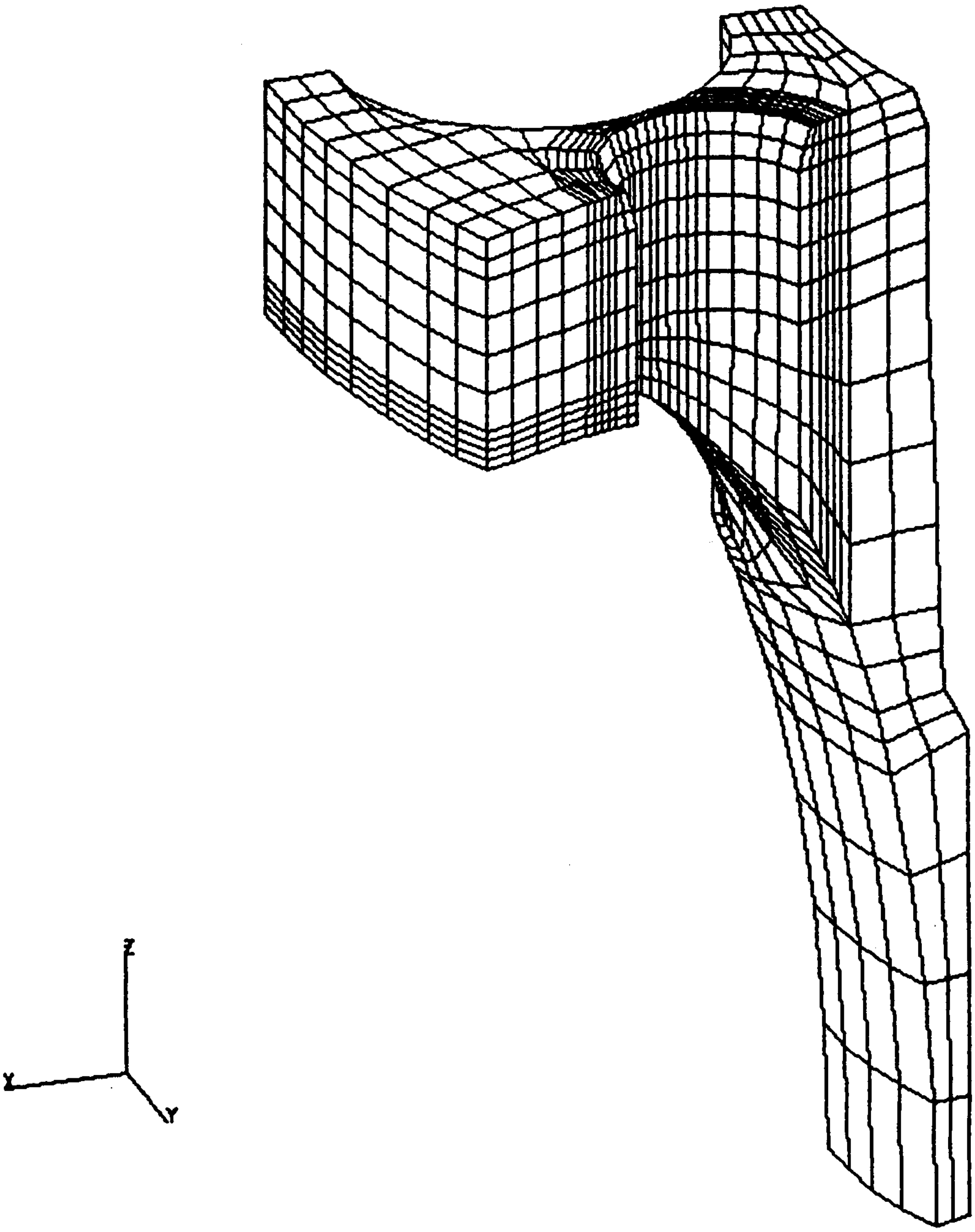

FIGURE 4 - HIDDEN LINE VIEW OF HMF BOX, 22.5° PIE SECTION

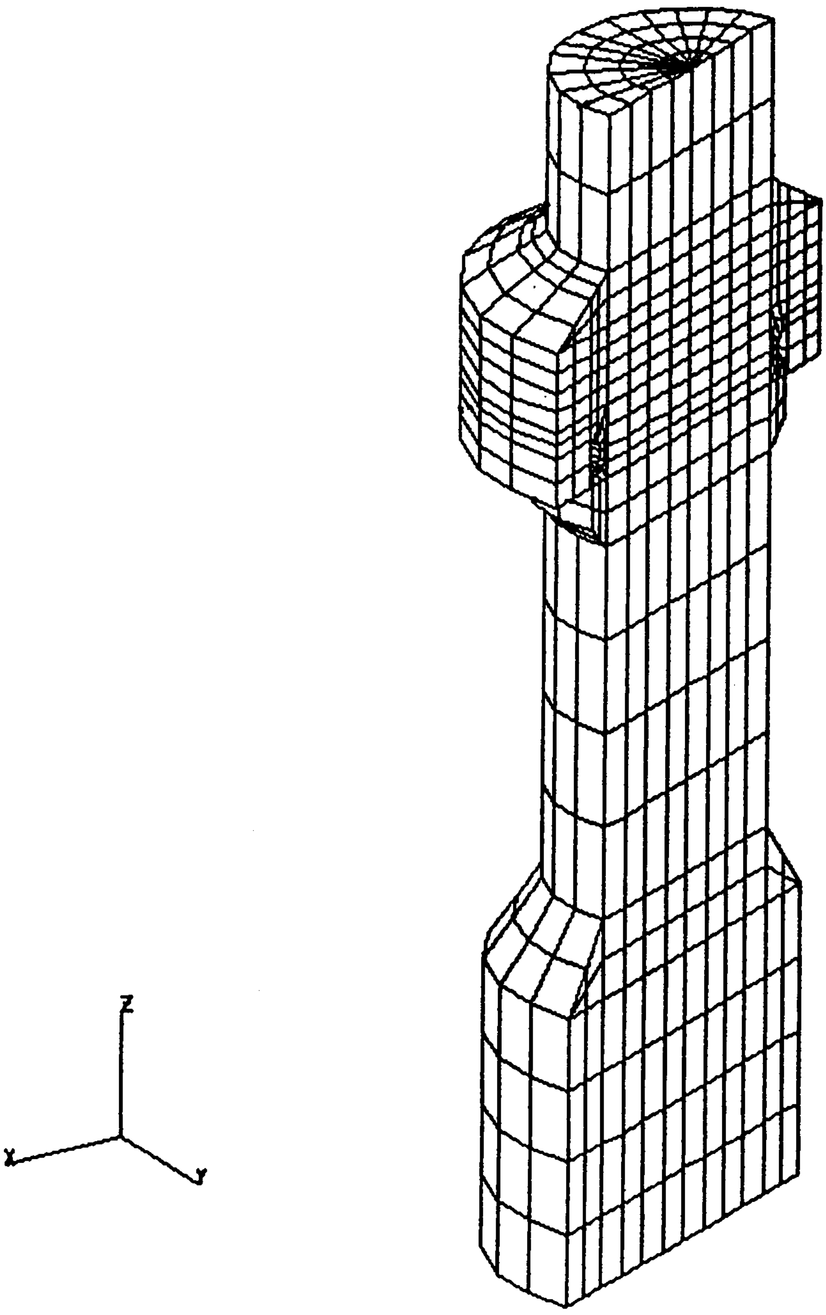

FIGURE 5 - HIDDEN LINE VIEW OF HMF BOLT, 22.5° PIE SECTION

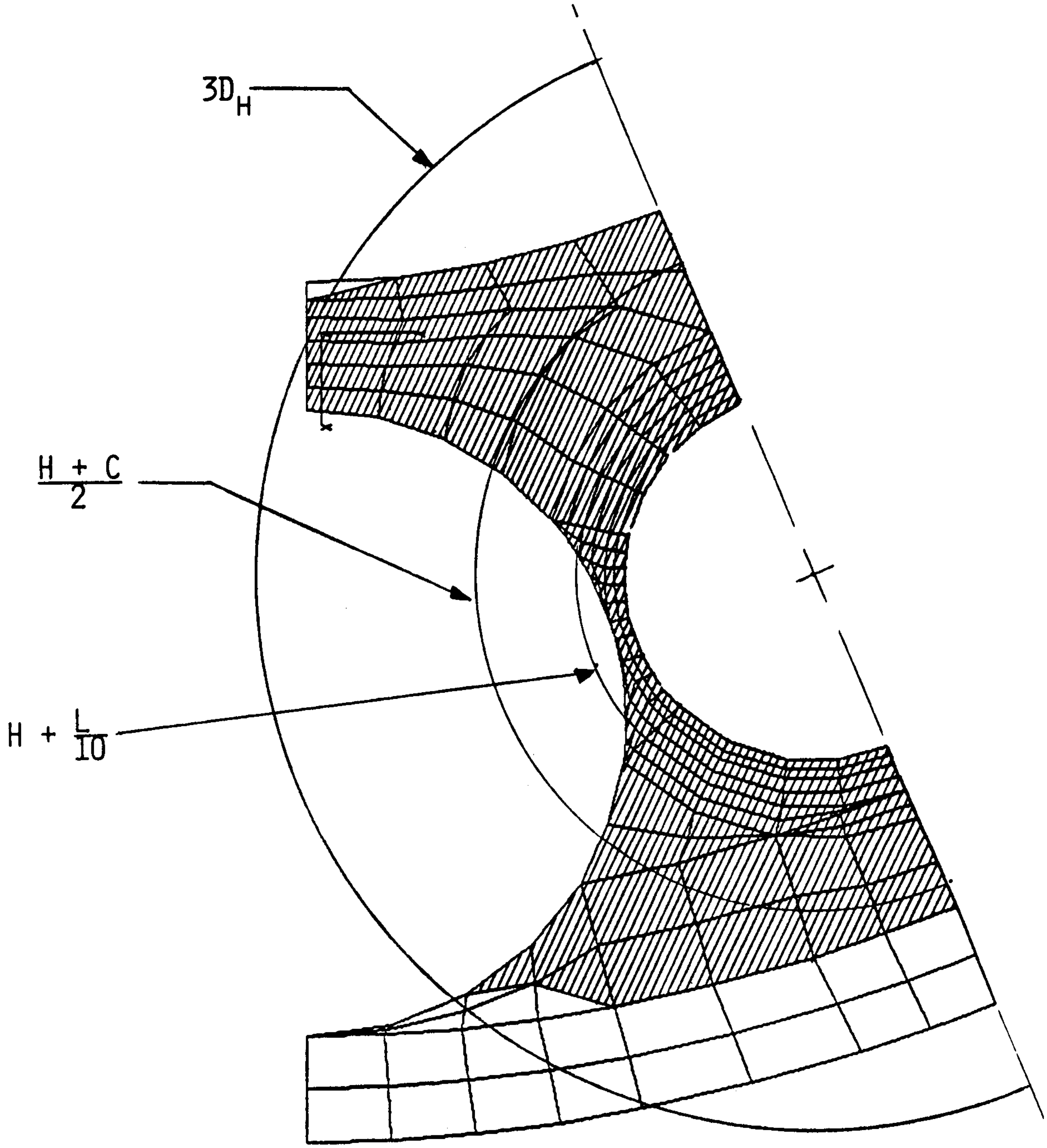

FIGURE 6 - PIN/BOX CONTACT WITH BOLT PRELOAD ONLY

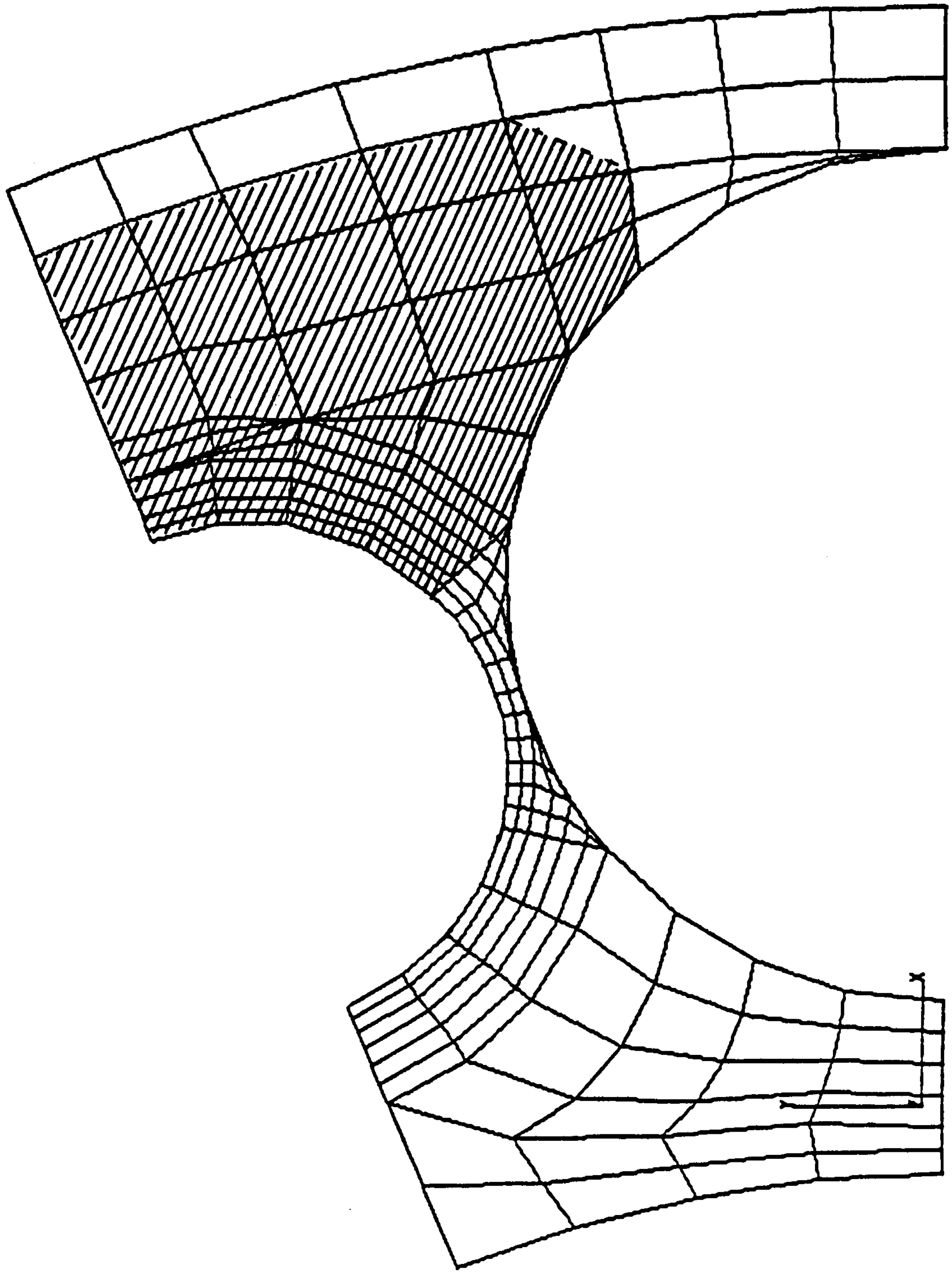

FIGURE 7 - CONTACT AREA FOR 1.7 M LBS. BOLT PRELOAD AND 1.5 M LBS. AXIAL LOAD

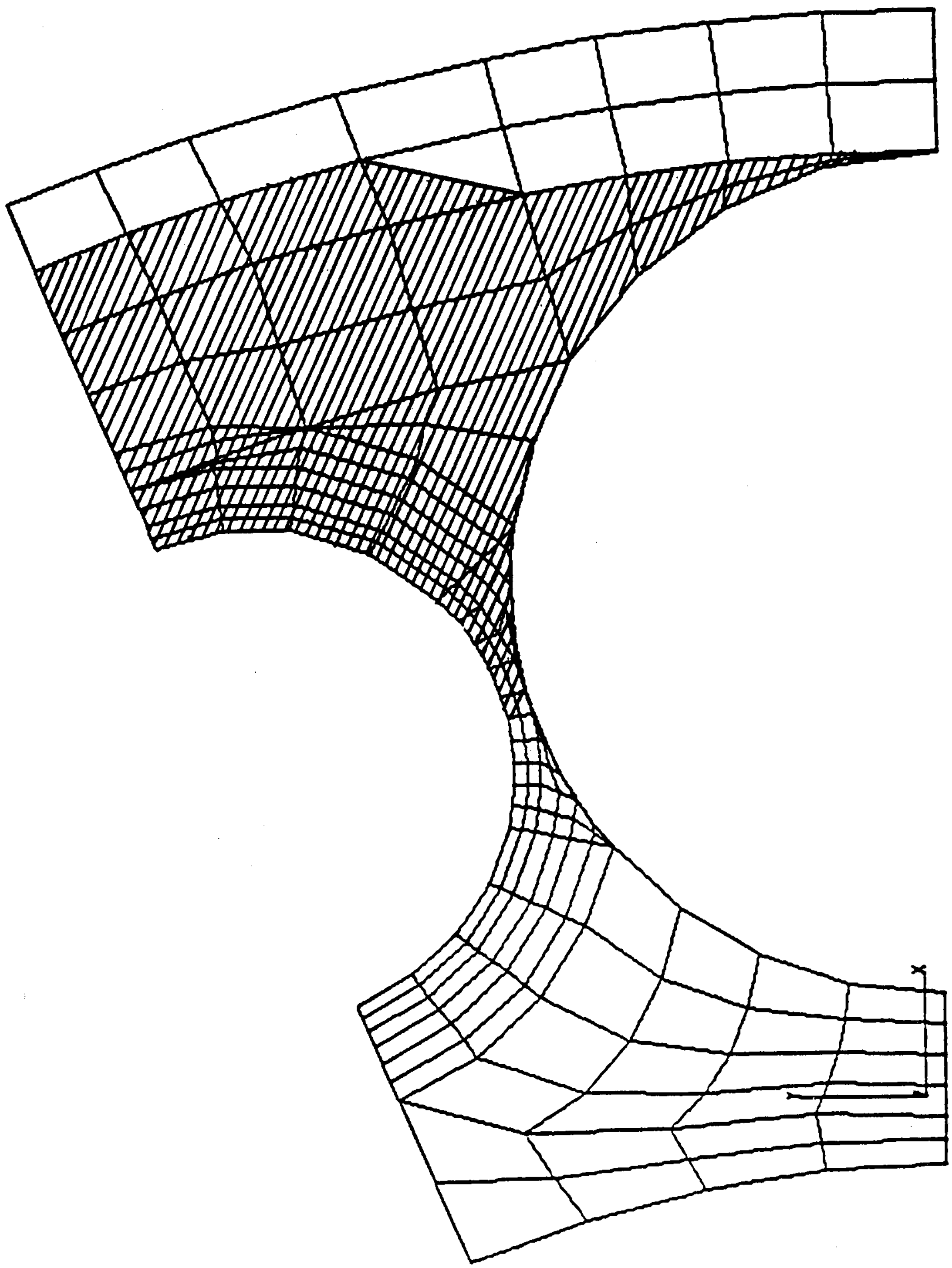

FIGURE 8 - CONTACT AREA FOR 2.5 M LBS. BOLT PRELOAD AND 1.5 M LBS. AXIAL LOAD

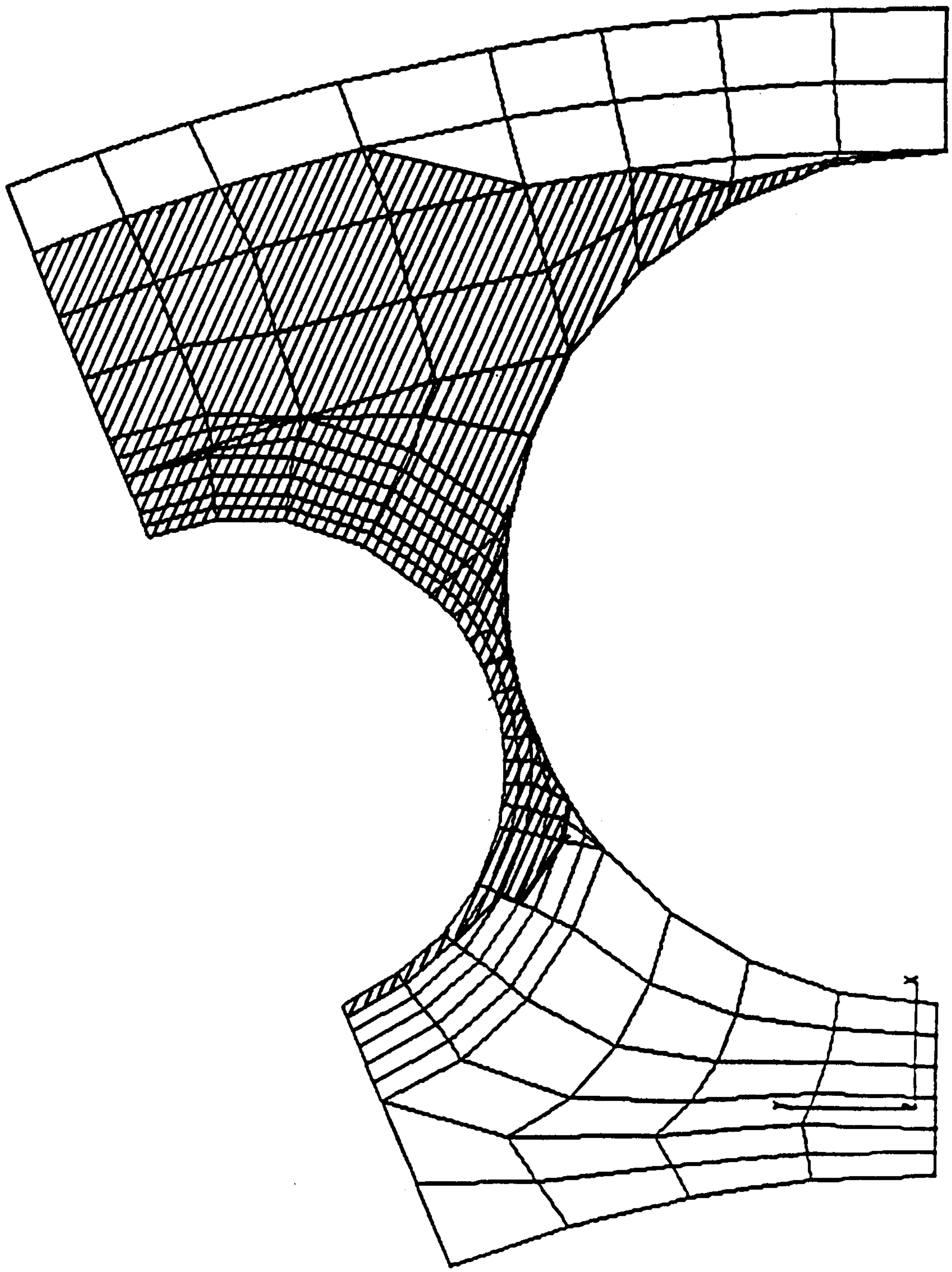

FIGURE 9 - CONTACT AREA FOR 3.3 M LBS. BOLT PRELOAD
AND 1.5 M LBS. AXIAL LOAD