TECHNOLOGY ASSESSMENT

PARAMETER STUDIES FOR ENHANCED INTEGRITY OF RECIPROCATING COMPRESSOR FOUNDATION BLOCKS

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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
Continued

LIST OF ILLUSTRATIONS
Continued

LIST OF TABLES

I. INTRODUCTION

Industry relies on a large number of multi-cylinder reciprocating compressors mounted on concrete foundation blocks, resting on concrete mats. Anchor bolts hold the machine frame to the concrete block through a mounting system. The mounting system generally rests on a layer of epoxy grout, which acts as a cap to the concrete block. The grout layer together with the mounting system maintain the machine alignment and help reduce heat transfer from the compressor to the concrete. Besides supporting the compressor's weight, the foundation has to restrain shaking forces which the machine frame transmits from each cylinder through the mounting system.

In recent years, compressor operators have found that a large number of blocks in the range 25 to 40 years old, have developed cracks. Oil seepage into these cracks helps further deteriorate the block. Some recently built units also exhibit such problems. Regrouting and block repair are expensive and often inconvenient. However, reliable operation depends on foundation block integrity and machine mounting system. Loss of foundation integrity can cause excessive frame vibration, misalignment, and if not corrected, main bearing or crankshaft failure.

Several operating companies, foundation repair contractors, and consultants have evolved practices and *"rules of thumb"* for foundation design and repair from years of experience. Such techniques are not uniformly shared across the industry. The need exists for common understanding of how parameters of design or repair influence integrity.

The study reported here continues research on reciprocating compressor foundations, sponsored by PCRC and previously reported[1,2,3]. Earlier reports show the complexity of predicting foundation block behavior. The present (interim) report addresses the impact of anchor bolts, concrete strength, rebar density, etc. on foundation block integrity and shows where additional investigation is needed. It focuses on a particular installation for a large synchronous motor-driven compressor with eight horizontally opposed cylinders. The report acts an *"interim report"* documenting ongoing efforts to improve understanding of how compressor mounting systems and foundation blocks behave and interact with transmitted forces. The research should develop guidelines and solutions which guide design or repair of foundation blocks to achieve prolonged integrity and safe compressor operation. Information in this interim report can help the designers address key issues. The investigations complement past research, supported by the Pipeline Research Committee into stress relationship for crankshafts and the measured influence of foundation thermal distortion[4,5,6] on compressor alignment.

The model development and analyses of reinforced concrete block used the "ANSYS" finite element program[7]. An earlier report[3] presented background information on this finite element approach. Parametric studies identify the influence of key parameters on block integrity, described in terms of concrete stresses and the extent of cracking. These studies have included investigation of:

- Anchor bolt parameters (tension, length, etc.).
- Rebar density.
- Concrete strength.
- Shaking force.

II. FOUNDATION BLOCK DETAILS

The study addresses a baseline block belonging to a PCRC member. This block had developed noticeable cracks in the concrete after three to four years of service. Figure II-1 shows a schematic layout with dimensions (length 41.4, width 10.7, height 10 feet). The flywheel end of the block increases to 13.7 feet wide. This three stage heat pump compressor has eight horizontal cylinders, four on each side. The axes of nominally opposed cylinders on opposite sides of the compressor actually have a small axial offset between them. The machine operates at a constant speed of 327 RPM. The compressor frame is mounted on steel chocks resting on rails. As Figure II-2 shows, the anchor bolts at the chock locations shown in Figure II-1 are 1-1/2 inches in diameter, 3 feet long and pass through the 1-1/4 feet long sleeves at the top of the block. The bolts are anchored into the concrete block with 5 inches wide square plates welded to their ends. The anchor bolts have a specified pretension load of 42,000 lbs. (42 kips), which corresponds to a bolt stress level of 30,000 psi. The crosshead guides are anchored to the block near the edge through steel chocks resting on steel soleplates. All soleplates and rails have a layer of about 4 inches thick epoxy grout underneath and around the edges. Figure II-2 shows typical details of the anchor bolts. The cylinder heads are supported by separate columns, connected to the foundation base mat; we assume these columns offer weight support, but negligible horizontal restraint.

A. <u>Material Properties</u>

The important material properties include elastic modulus and Poisson's ratio for concrete, grout, and rebar materials. Table II-1 gives the values used in the analysis, which are based on data provided for the foundation. The compressive strength of the concrete based on core samples is about 4000 to 4500 psi. We assumed a concrete tensile strength of 270 psi —six to seven percent of compression strength. The tensile strength most directly controls crack initiation in the concrete.

TABLE II-1. MATERIAL PROPERTIES			
Property	**Concrete**	**Grout**	**Steel (Rebar)**
Elastic Modulus	3 x 10^6 psi	3 x 10^6 psi	30 x 10^6
Poisson's Ratio	0.2	0.4	0.3
Compressive Strength	4000 psi	-	-
Tensile Strength	270 psi	-	-

B. Shaking Forces

Table II-2 lists the reciprocating and the rotating weights associated with each cylinder along with the phase angle between the different crank throws. The procedure described in Reference 2 gives maximum unbalanced horizontal and vertical shaking forces and moments acting on the block. Assuming a completely rigid compressor frame, all anchor bolts share the net inertial shaking force equally. The resultant horizontal force from all cylinders of about 4.5 kips would give a force of only 179 lbs. per bolt between the 26 anchor bolts holding down the frame. For large compressor frames, Smalley[8] shows that the rigid frame assumption is unrealistic and unconservative. At the other extreme, if we assume that the frame is fully flexible[3], then the anchor bolts adjacent to a cylinder share the maximum inertial force due to that cylinder. This is naturally a conservative assumption, but more appropriate in the absence of a detailed frame stiffness analysis. Cylinder #1 imposes a peak horizontal load of 96 kips. Sharing this load equally among four anchor bolts, two on the main frame and two on the crosshead guide associated with cylinder #1, gives a horizontal force at each anchor bolt of 24,000 lbs. (24 kips) to be restrained. A previous study on

TABLE II—2. RECIPROCATING AND ROTATING WEIGHTS OF CYLINDERS

Cylinder Number	Rotating Weight (lbs.)	Reciprocating Weight (lbs.)	Phase[1] Angle (deg.)	Cylinder[2] Orientation (deg.)	Crank Radius (in.)	Connecting Rod Lengeth (in.)	Distance on[3] Shaft (in.)
1	1458	2766	0	180	7.5	39	128.75
2	1458	2755	0	0	7.5	39	97.75
3	1458	2762	90	180	7.5	39	53.25
4	1458	2752	90	0	7.5	39	22.25
5	1458	2618	135	180	7.5	39	-22.25
6	1458	2469	135	0	7.5	39	-53.25
7	1458	2617	225	180	7.5	39	-97.75
8	1458	2470	225	0	7.5	39	-128.75

Notes: (1) *Relative phase angles for crank radii of respective cylinders.*
(2) *Orientation angles defined relative to horizontal plane.*
(3) *Distances relative to midpoint of the crankshaft length between cylinders 1 through 8.*

the block performed by the owner had imposed a load of 20 kips at each anchor bolt; since the two forces are close, we decided to use 20 kips as a reference value for the parametric evaluations presented in this report. Note that the study does not address implications of gas loads— simply inertial shaking forces. Ideally, the compressor frame carries the gas loads, which act in one direction on the piston head, and in the other direction on the bearings. A subsequent study should address the effect gas load has upon the block.

C. Anchor Bolt Preload

The anchor bolts, ideally, maintain a normal force at the interface between frame and mount which enables transfer of the shaking force through friction. The parameter studies use the design anchor bolt preload of 42 kips as a reference value. The report addresses the relationship between shaking forces and anchor bolt preload for design analysis in a subsequent section.

III. FINITE ELEMENT MODEL

Several simplifying assumptions helped control the size of the finite element model. At first, the segment of the block which houses the flywheel was excluded, and only the reduced block configuration supporting the eight cylinders was considered for the analysis (Figure III-1). Although the axes of the adjacent cylinders on opposite side of the crankshaft axis are not exactly collinear, we assumed that the block is symmetric about the vertical plane through the crankshaft axis. Figure III-2 shows the finite element model of the half block. In order to reduce further the model size, the half block segment was truncated so as to include the section influenced by the shaking forces imposed by cylinder #1 (Figure III-3). Analysis of this section under the imposed horizontal loading and the anchor bolt preload showed that the lower half section of the block had a very low level of stress, and justified a further reduction in model size by truncating it at a horizontal plane about 56 inches above its bottom. Figure III-4 shows the truncated finite element model.

The reinforced concrete portion in the model used ANSYS SOLID65 element[7]. These elements represent rebar by averaging its properties over the entire element. This nonlinear element can predict concrete cracking or crushing based on principal stresses at the integration points within the element[3,7]. The epoxy and the steel chock/rail models used eight node brick (SOLID45) elements. We modeled steel anchor bolts with spar elements (LINK8). Spar elements support only tensile and compressive loading. For the portion of the anchor bolt embedded in concrete, the spar elements share common nodes with the concrete. This assumes no disbonding between anchor bolt and concrete under load. For the portion of anchor bolt that passes through a sleeve, the spar elements and concrete use disconnected, but coincident, duplicate nodes. While this approach does not model the cavity in the sleeve, it permits movement of the anchor bolt independent of the adjacent concrete elements. Model size constraints required anchoring the bolt at its end, and neglecting details of the anchor plate. In this manner, two types of anchor bolt configurations could be easily adapted in the model. The first one, hereafter called *"embedded bolt (EB)"* represents an anchor bolt configuration as shown in Figure II-2; the top portion of the bolt passes through a sleeve and the lower portion of the bold is embedded in the concrete. The second configuration, hereafter called *"free-standing bolt (FSB),"* represents an anchor bolt disconnected from the concrete over its entire length; a sleeve surrounding the entire length of the bolt, anchored in the block only at the terminal point achieves this arrangement.

Anchor bolt preload is modeled by imposing the required tensile force at the top of the anchor bolt. The resulting compressive loading on the top of the block is modeled by imposing a downward force equal to the anchor bolt preload on the soleplate. The peak horizontal shaking force from the cylinder is also imposed as a point load on the steel soleplate. In reality, both the shaking forces and the anchor preload are transferred to the block as distributed loads. However, with steel much stiffer than epoxy, the above described method should provide a satisfactory means of applying loads.

The nonlinearity of the concrete element requires an iterative solution with incremental load steps. If at any load step, the principal stresses at the integration point satisfy the failure criterion, then a number indicating the status of the integration point at the end of final integration is stored in the results. This status marker is used in the post processing to determine if the concrete cracked at the integration point along any one of the three principal axes. By collecting such cracked elements, the entire cracked region in the concrete block is mapped out. The volume of such cracked regions has been used to quantify the block integrity. A larger volume of the cracked region implies more potential damage to the foundation block.

Figures III-5 through 9 show typical results of the finite element analysis of the truncated block section. In this case, partially embedded anchor bolts as shown in Figure II-2 have been used. The key parameters used in this case are:

- Horizontal Force = 20 kips per Anchor Bolt.
- Anchor Bolt Preload = 42 kips.
- Rebar Density by Volume = 0.2% Along Each Axis.
- Anchor Bolt Configuration - Embedded Bolt (Figure II-2).
- Material Properties shown in Table II-1.

Figure III-5 shows surface contours of the highest principal stress (S1) across the reinforced concrete section in the block. The peak principal (tensile) stress is 288 psi. This is higher than the limiting tensile strength of concrete (270 psi); although the integration point stresses never exceed the tensile strength of concrete, the nodal stresses are interpolated from the integration point stresses which introduces small differences. Figure III-6 shows contours for the stress along the block height (Sz). The coordinate system used to define the model consists of X-axis along the block width, Y-axis along the block length, and Z-axis along the block height. Figure III-7 shows the concrete elements in blue color that cracked at the 5th integration point. By collecting elements that cracked at one or more of the eight integration points, cracked regions of the block are mapped out as shown in Figure III-8. Figure III-9 shows vertical stress contours (Sz) across a section through the second anchor bolt. This figure shows that the region of the block where the anchor bolt passes through the sleeve is in compression, whereas the portion immediately below the sleeve is in tension where the cracking originates.

In this example, the block experiences significant tensile stresses in two distinct regions: the concrete surface near sharp (90°) corners below the compressor's oil pan, and the concrete immediately below the termination of each anchor bolt. Tensile stresses which exceed concrete's relatively low tensile strength tend to cause cracking. Figure III-1 suggests that cracks occurred in both regions of the installation.

IV. PARAMETRIC STUDIES

Studies presented in this report section use the finite element model to show how the following parameters influence tensile stress and crack potential:

- Anchor bolt preload.
- Anchor bolt configuration (embedded versus free-standing).
- Anchor bolt length.
- Rebar density.
- Concrete strength.

In general, each case varies one or more parameters about the baseline configuration described in Section III. Each figure defines the pertinent values of the varied parameters.

A. Anchor Bolt Preload

Figures IV-1 through 8 show how varying preload of partially embedded anchor bolts affects stresses and crack severity, with all other parameters held fixed. The rebar density was maintained at 5% by volume along all three block axes in Figures IV-1 through 8. As Section VI discusses, rebar densities fall below 5% by volume, and all subsequent parameter studies reflect more typical rebar densities. However, the predicted sensitivities to anchor bold preload discussed below should remain valid. For an anchor preload of 42 kips at each bolt, Figure IV-1 shows the distribution of principal stresses, and Figure IV-2 shows the map of the cracked elements. Figures IV-3, 4, 5, and 6 show principal stresses and cracked elements with anchor bolt preloads of 63 kips and 84 kips. Increasing anchor bolt preload clearly increases the cracked volume by subjecting more elements surrounding the anchor bolt to the limiting tensile stresses. As previously stated, the model does not include the cavity around the bolt in the sleeve section which in reality may limit how far the cracked region extends. However, the results make clear the potential disadvantages of relying on a highly preloaded bolt, terminated in the concrete, to hold the compressor against shaking forces.

Figures IV-7 and 8 show principal stresses and cracked elements with zero anchor bolt preload. This is a mathematical abstraction of a case where the anchor bolt loses tension due to untorquing of the nut or the breakage of the bolt, but the block must still carry the shaking forces. Figure IV-8 shows that the shaking forces caused the block to develop cracks in the oil pan corner (blue elements), presumably because loose anchor bolts relax the precompression in the concrete. Thus, in addition to holding the compressor, anchor bolt tension can help inhibit cracking under shaking forces. Properly located, post-tensioning bolts which have a separate function from holding down the compressor, would provide a similar tendency to inhibit cracking.

B. <u>Anchor Bolt Length</u>

Figures IV-9 through 12 show the predicted effect of increasing anchor bolt length from the standard 3 feet to 4-1/3 feet. In these figures, the bolt is a free-standing bolt, the anchor bolt preload is 42 kips, horizontal force is 20 kips and the rebar density is assumed to be 0.2%. Figures IV-9 and 10 show the results for a standard bolt length. Figures IV-11 through 13 show results for increased bolt length. Figure IV-13 shows that increasing bolt length shifts the cracked region downwards into the block. The volume of cracked concrete reduces very slightly when longer bolts are used. Figures IV-9 and 11 also show that the maximum principal stress is reduced due to increased bolt length. The small amount of cracking at the top appears to result from shear load imparted by the epoxy layer to the concrete. This local cracking requires more detailed attention to assess its significance and possible methods of control if needed.

Comparing Figures IV-14, 15, and 16, for a 4.33 feet long, partially embedded bolt, to Figures III-5, 7, and 9 (standard length partially embedded bolt), shows that the increase in length has essentially no effect on maximum tensile stress or on the cracked region. For a partially embedded bolt of either length, all predicted failure initiates at the top of the concrete embedded portion of the bolt or where the sleeve begins.

C. <u>Anchor Bolt Configuration</u>

As the preceding section discusses, anchor bolt configuration (partially embedded or a free-standing) has a distinct influence on how and where the block develops cracks. Comparing Figures III-5 and 8, and Figures IV-9 and 10, shows that for the embedded bolt, cracking starts at the point where the bolt emerges from the concrete and the sleeve section starts. This section experiences the maximum tensile loading. A cracked region closer to the block top suggests increased susceptibility to oil seepage, and the potential for further block degradation. In contrast, for a free-standing bolt, the cracked region originates at the anchor point on the bottom of the bolt. Moving the cracked region further down into the block should reduce potential for oil intrusion. Hence, although the analysis predicts cracking in both cases, the crack location for the free-standing bolt appears preferable.

Figures IV-17 and 18 show the result of extending the free-standing anchor bolts all the way through the block, and imposing 63 kips preload. This “tie-rod” configuration imposes compressive loading on the entire block height The resulting maximum principal stress is also reduced. A minimal cracked region occurs at the top, which apparently results from shear loading between epoxy and concrete. The model with full length bolt predicts no cracking in the pan region. These results imply that increasing anchor bolt preload only has benefits with anchor bolts extended all the way into the concrete mat. This "*tie-rod*" anchor bolt configuration appears to offer an attractive solution. Methods to control the predicted shear load cracking near the top deserve further investigation.

D. Rebar Density

Figures IV-19 through 28, for free-standing bolts with 42 kips preload, present stresses and cracking extent for various rebar densities in the range 0 to 20%. Increasing rebar density from 0 to 0.2% reduces the number of cracked elements from 52 to 36, but further increases in rebar density, to 1.0% and above, do not cause further reductions. The rebar density has some influence on maximum tensile stress, but the data offers no clear trend. The sensitivity of cracking extent to more detailed variation in rebar densities in the range 0 to 1.0%, or a little higher deserves further investigation.

E. Concrete Strength

Concrete can fail by cracking when tensile stress exceeds the tensile strength or by crushing when compressive stress exceeds the concrete compressive strength. This investigation predicts no compressive stresses which approach the compressive strength suggesting that only tensile strength influences block integrity for reciprocating compressors. Yet foundation specifications seem to specify the minimum compressive strength of the concrete mix, without explicit specification of tensile strength.

Figures IV-29 and 30 show results of a block analyzed with the basic parameters defined earlier, but with tensile strength increased to 500 psi and compressive strength increased to 6000 psi. The rebar density is 0.2%, and anchor bolts are free-standing. Comparing with Figures IV-19 and 20 reveals a reduced region of cracking (20 cracked elements versus 36). Figures IV-31 and 32 show for a tensile strength of 1000 psi and compressive strength of 6000 psi, that the cracked region reduces further to only four elements. With new concrete mixes available (for example, using steel fiber reinforced concrete—reference[9]) to provide tensile strengths above 500 psi, the results presented here make a case for seeking and using higher tensile strength concrete for reciprocating compressor foundations.

F. <u>Shaking Forces</u>

Comparing Figures IV-33 and 34 with a shaking force of 5 kips per bolt to Figures IV-19 and 20 with 20 kips per bolt shows no change in the cracked region extent. This implies that anchor bolt preload load controls the cracked region extent, because the bolt preload has already reached the level necessary to control pan area cracking even with 20 kips shaking force.

V. INTERACTION OF ANCHOR BOLT PRELOAD AND SHAKING FORCES

The preceding evaluations have explored sensitivity of block stress and cracking to anchor bolt preload, and shaking force, as independent quantities. However, design analysis for a specific application should more specifically relate anchor bolt preload to shaking forces.

The anchor bolt holds the compressor base against the mount with a normal force controlled by anchor bolt tension. The compressor's weight is distributed over the tie-downs and adds to anchor bolt tension. Frictional resistance parallel to the interface resists sliding motion of the compressor under the action of shaking forces. The anchor bolt must therefore ensure sufficient friction force to withstand the highest expected shaking force. The following offers preliminary guidelines:

A flexible frame analysis provides a conservative value for the shaking forces. Typically, determine the individual shaking force for each throw of the crankshaft, and share this force between the anchor bolts adjacent to this throw. This flexible frame approach may require restraint of a shaking force substantially higher than a rigid frame assumption (which requires the anchor bolts to carry a share of the net total shaking forces and moments for the unit).

Use a coefficient of friction appropriate for the interface materials (e.g., 0.2).

Design anchor bolt preload to exceed the maximum per bolt shaking force divided by the coefficient of friction, minus the per bolt share of the compressor's weight.

Choose anchor bolt diameter; the bolt holes in the frame often set this diameter. Calculate the bolt stress resulting from the preload. Choose an anchor bolt material which can carry this stress; this may require a high strength steel.

Based on the preceding studies, select a bolt configuration to avoid cracking within the block—a through-to-the-mat configuration appears to come close to this requirement.

Select anchor bolt torquing specifications to ensure providing the full required preload.

It is noted, for the compressor installation addressed in the preceding parametric evaluations, that the shaking force of 20,000 lbs. divided by a 0.2 coefficient of friction minus a 26 bolt share of the 436,000 lbs. compressor weight (100,000 lbs. - 17,000 lbs.), would have called for a preload of 83,000 lbs., as opposed to the 42,000 lbs. specified.

VI. DISCUSSION OF RESULTS

The flexible frame assumption leads to a need for high anchor bolt preload in many cases. The finite element studies have shown that providing such a preload with the bolt terminating in the concrete can cause substantial internal cracking in the concrete.

With partially embedded bolts, predictions show some cracking near the top of the embedment. A free-standing (sleeved) anchor bolt seems to force bolt induced cracking down nearer the point of termination. Hopefully, this can lessen the potential for oil penetrating these cracks.

The *"through-to-the-mat"* sleeved anchor bolt configuration offers a solution which makes the achievable tie-down force a function of steel tensile strength rather than concrete tensile strength.

Since the predictions show cracking to start around individual bolts, and do not show a tendency for cracks to join up horizontally, the studies do not provide strong arguments for or against the relatively common practice of staggering anchor bolt termination points. The studies do not address long term effects of working cracks, whose long term advance may be inhibited by staggering the bolt length. However, it seems clear that the initiation of cracks cannot be inhibited by this practice. Perhaps future design analysis should focus on practices which have the best chance of avoiding cracking altogether.

Some predictions show cracking at the interface between epoxy and concrete with the free-standing anchor bolt configuration. This should be controllable with appropriate mount design and may simply result from interface assumptions in the model. With the otherwise promising results of free-standing anchor bolt analysis, this aspect deserves further study.

The shaking forces transmitted to the block can cause cracking in the area of the pan. Observed cracks on the subject foundation confirm this potential. The tendency appears localized to sharp corners at interfaces between vertical and horizontal concrete surfaces. The use of sloping surfaces and large radii offer potential to control this tendency (even though they may be more complicated to construct). This geometrical design detail deserves further study.

The precompression of the concrete induced by adjacent anchor bolts tends to reduce pan area cracking, emphasizing that tight anchor bolts may play a more substantial role than strictly tying down the compressor frame—they may also assist with maintaining the integrity of the concrete. Specifically designed post-tensioning bolts can also reduce the tendency to crack, and the above observation provides argument for the use of such devices—which separate the functions of tying down the frame from inhibiting tension-induced cracking.

The use of rebar tends to control or reduce the extent of cracking, but not avoid it. There is a distinct decrease in the number of cracked elements as rebar is added, but there seems to be some limit to the benefits obtained by adding more rebar. The need exists to investigate more closely the effects of rebar densities in the range of 0.1 to 2%, and the influence of density on cracking severity and maximum tensile stress. Use of #8 rebar (1-inch diameter) on 8-inch centers, which some contractors for reciprocating compressors recommend, yields 1.25% area density, so 2% probably represents an appropriate upper bound to use in further studies.

The studies of high tensile strength concrete certainly focus attention on the potential benefits of such concretes. The developing art of modified concretes with built-in tensile strength enhancers deserves monitoring. It will be useful to gather test data on tensile strength and long-term operating experience under dynamic loads.

The studies reported have not yet addressed a number of important questions, in addition to those identified above:

- To what extent, and under what circumstances can gas loads be transmitted to the block as a result of frame stretching?
- What role do vertical engine loads play?
- How does a realistic analysis of frame flexibility reduce transmitted loads?
- How are foundation deflections imposed on the bearings and shaft, and how should their severity be assessed?

VII. SUMMARY

1. Holding maximum shaking force based on a flexible frame assumption with a bolt which terminates in the block is likely to cause internal cracking of the concrete.

2. The use of free-standing bolts appears to have advantages over embedded bolts, and shifts the cracked region downwards; lengthening the bolts appears to have benefit.

3. Through-the-mat free-standing bolts seem to offer a chance of eliminating internal cracking.

4. With free-standing through-to-the-mat bolts, the holding force can be governed by steel tensile strength rather than concrete tensile strength; high strength steel may be needed to give the required preload.

5. The parameter studies show some tendency for cracking around the interface between epoxy and concrete immediately under the mount with free-standing bolts. This may result from modeling assumptions and needs further investigation.

6. The shaking forces transmitted to the block tend to cause high tensile stress and cracking under the pan.

7. The tendency for cracking under the pan seems to be associated with sharp interfaces between vertical and horizontal surfaces, and could probably be

reduced with appropriate detail design to increase radii and use sloped rather than vertical surfaces. This topic deserves further investigation.

8. The concrete precompression induced by adjacent anchor bolt tension seems to help inhibit the pan area cracking tendency.

9. The use of independent post-tensioning bolts specifically to control tensile stresses seems to be supported by these observations.

10. Rebar appears to control, rather than inhibit cracking.

11. The addition of rebar is predicted to reduce the cracked extent considerably.

12. There appears to be a limit to the extent to which cracking is controlled by increase in rebar density, but there is a need for more detailed evaluation of this limit and its relationship to practical limits for packing rebar into the foundation design.

13. Predictions show high tensile strength concrete has significant impact on block integrity, in addition to high compressive strength.

14. The ability to achieve over 1000 psi tensile strength would have substantial benefits in reducing or eliminating the likelihood of cracking. This appears to represent a substantial challenge to developers of advanced concrete mixes.

15. There is a need for further investigations including:

- Rebar density.

- Cracking tendencies near the top of free-standing bolts.

- Inhibiting pan area cracks.

- Load sharing by the frame and how it affects transmitted shaking forces.

- Stretching of the frame under gas load, and how it might influence block cracking.

- The influence of block and frame deflections on the bearings and crankshaft.

- Thermally-induced stresses.

VIII. RECOMMENDATIONS

As operating companies and engineering companies encounter the need to repair existing foundations and to design new ones, they should bear the results of this report in mind. The trends and preliminary guidelines reported should help the process of specification, design, analysis, and planning. In particular, the use of high strength, through-to-the-mat bolts should be seriously considered, together with a combination of post-tensioning rods and detailed design in the pan area to avoid high local tensile stresses.

The user of this report should also take note that the results focus on one foundation configuration for one compressor, and that the discussion and summary add some judgment to these results. While the trends observed appear generic enough for applicability to other configurations, care should be exercised when extrapolating the results. The prudent user of these results, if they influence critical decision will seek confirmatory analysis or confirmatory test for the specific application under consideration. The user should also note the subjects not yet addressed by the reported studies.

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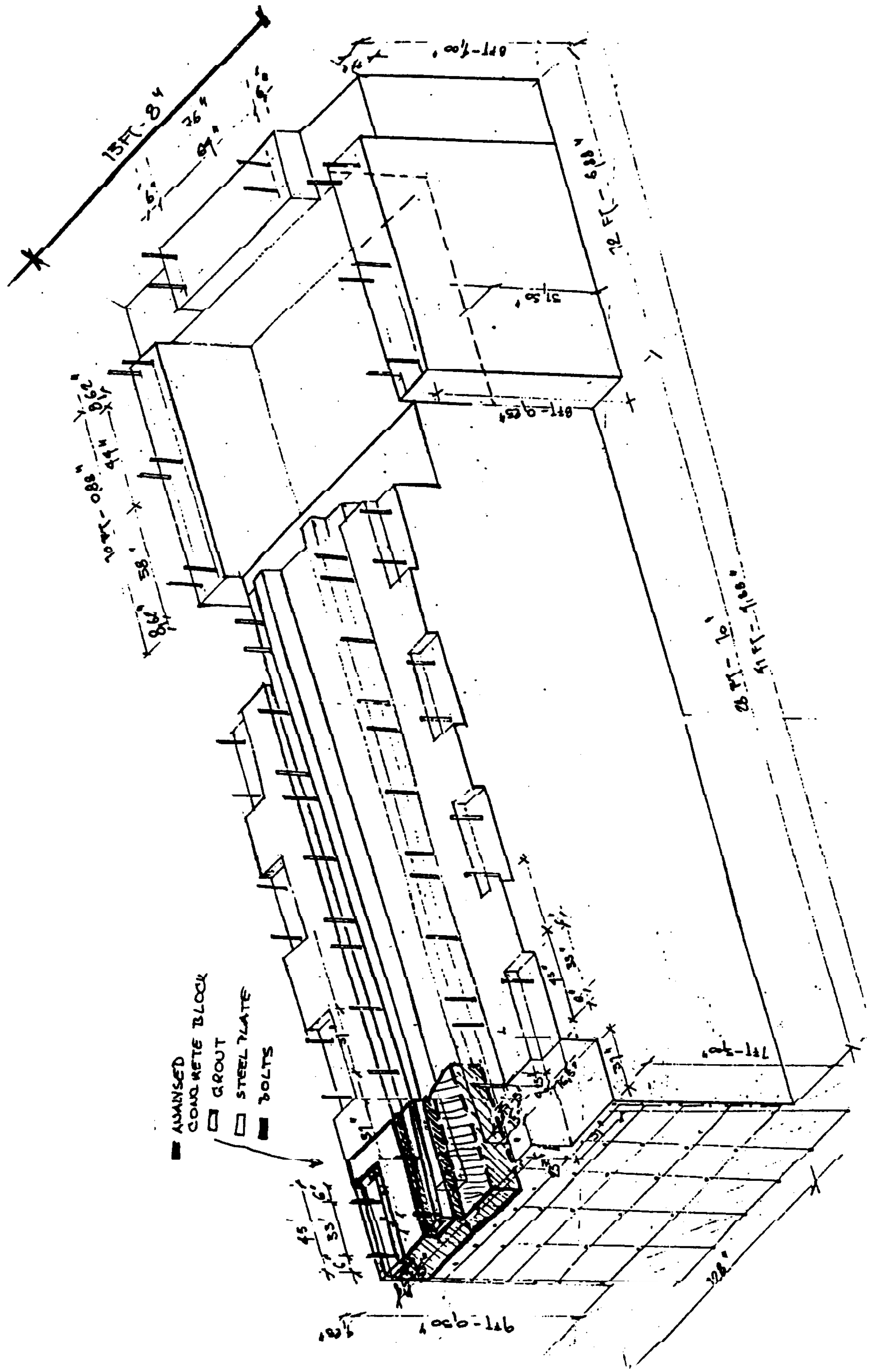
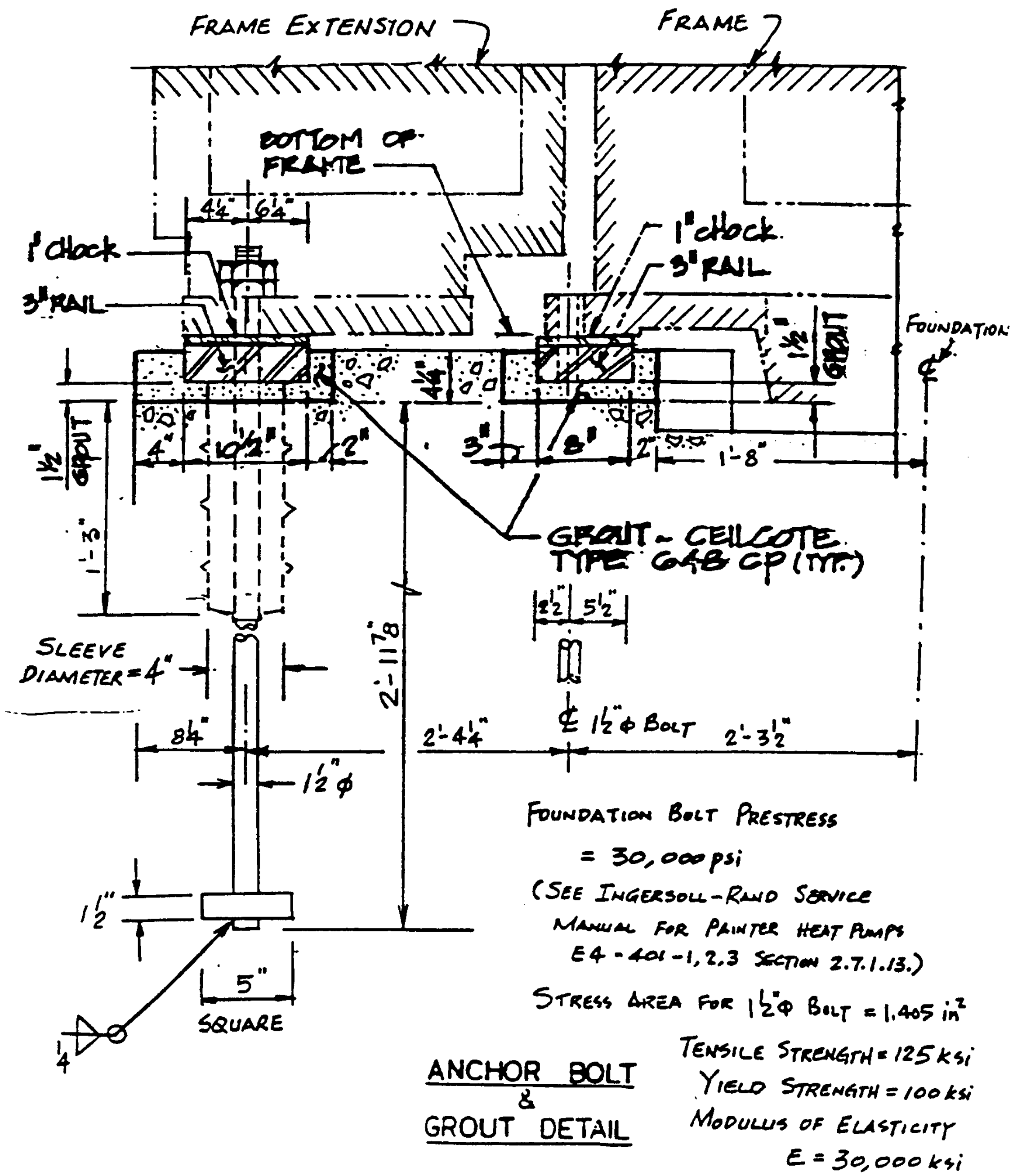


FIGURE II-1. FOUNDATION BLOCK ISOMETRIC VIEW—COMPLETE INSTALLATION



ANCHOR BOLT NOTES:

1. FDN. BOLT MTL. SHALL BE SAE 4140 ANNEALED BAR, HEAT TREATED TO ASTM. A193, GR. 7 SPECS. ANC. BOLT NUTS TO MEET ASTM A-194, GR. I SPECIFICATION.

2. USE WILSON ANCHOR BOLT SLEEVES. (KEEP SLEEVES FREE OF WATER) △1 **DO NOT FILL SLEEVE WITH GROUT.**

FIGURE II-2. FOUNDATION BLOCK SECTION THROUGH BOLTS

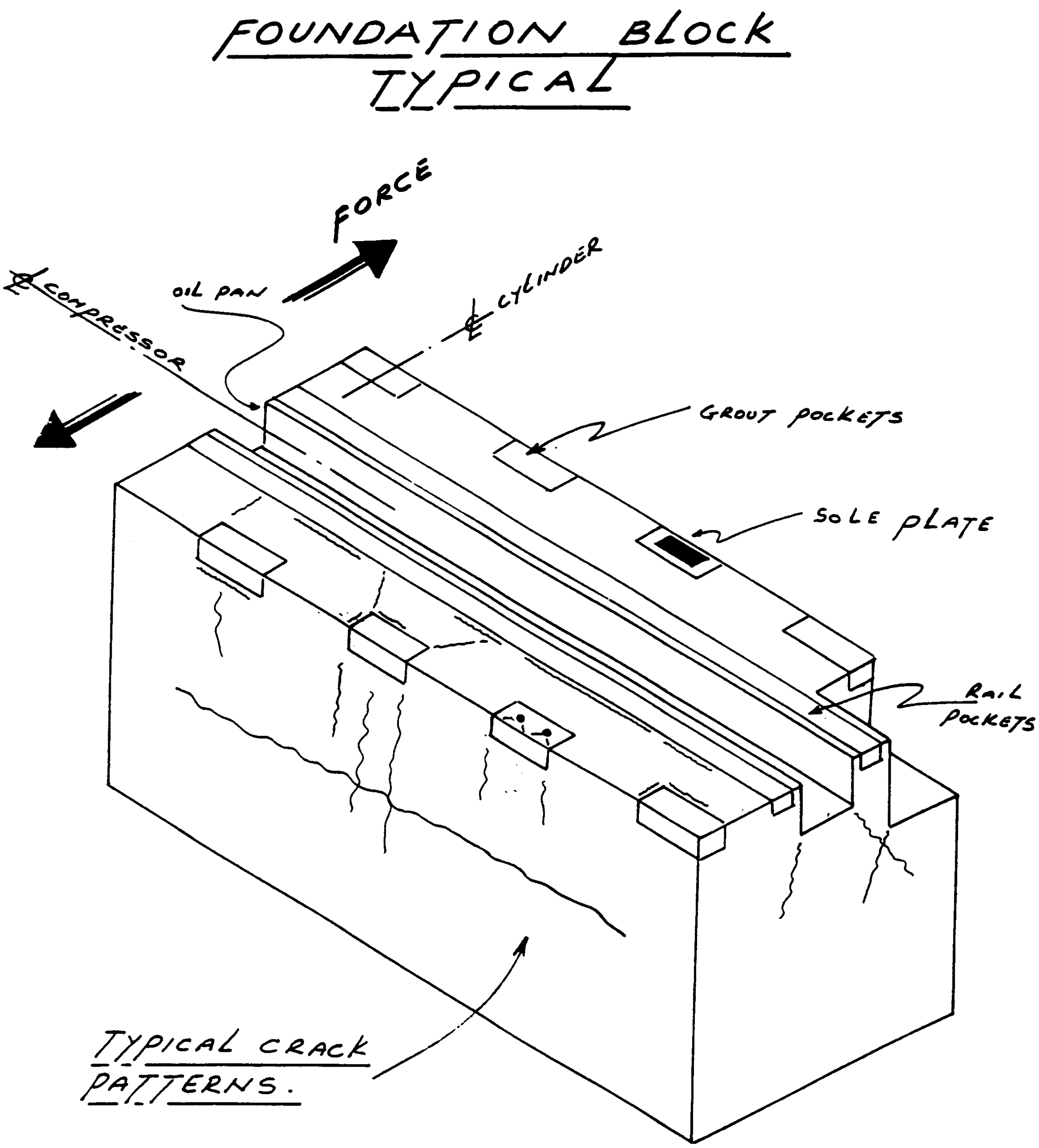


FIGURE III-1. FOUNDATION BLOCK ISOMETRIC VIEW—COMPRESSOR AREA SHOWING GROUT POCKET AND SOLE PLATES

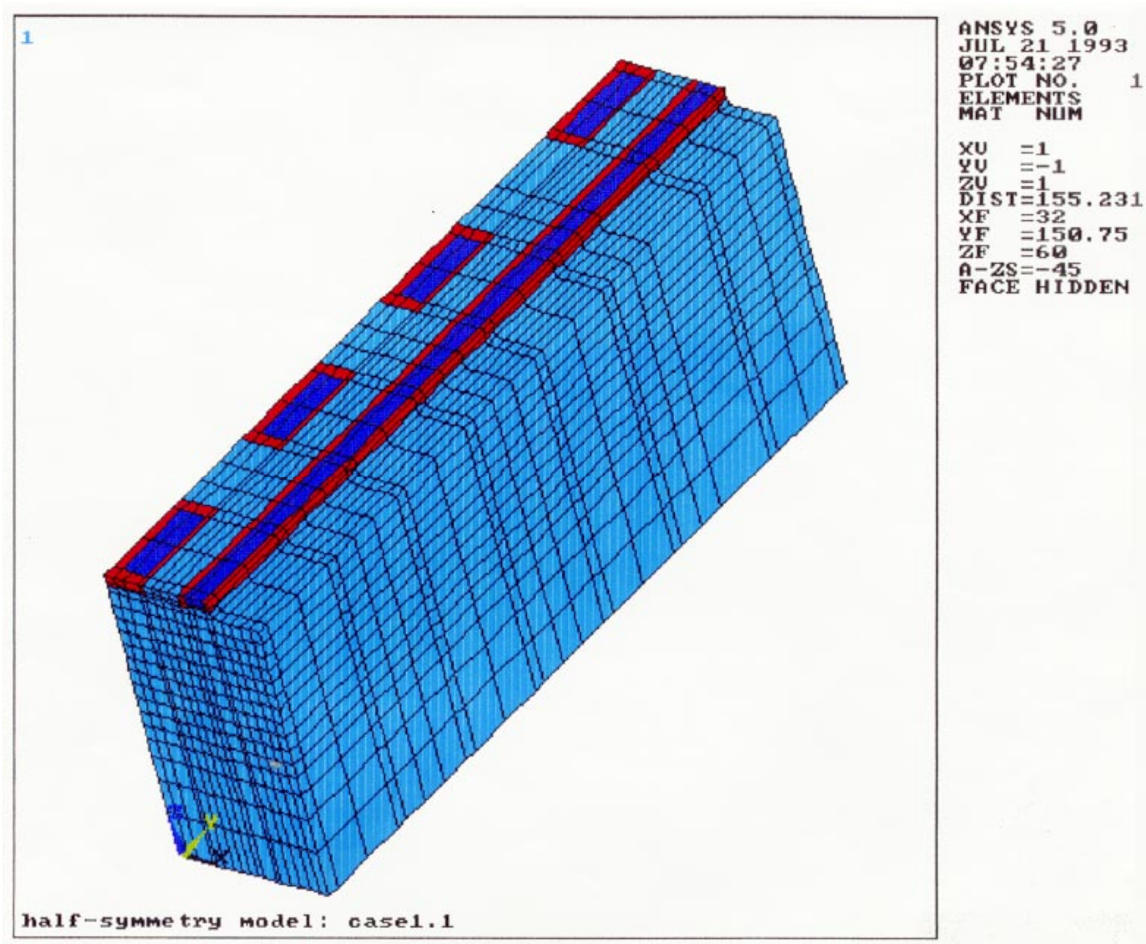


FIGURE III-2. HALF SYMMETRY FINITE ELEMENT MODEL—FOR 4 CYLINDERS

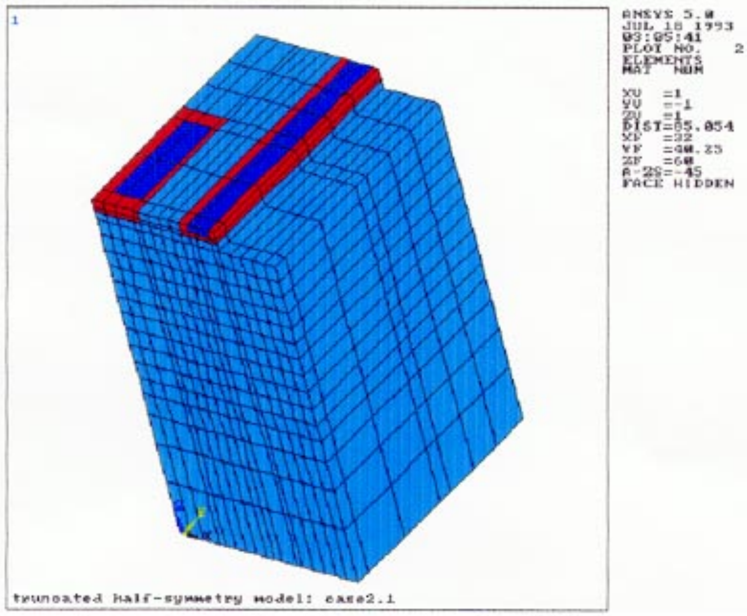


FIGURE III-3. TRUNCATED HALF SYMMETRY MODEL—FOR 1 CYLINDER

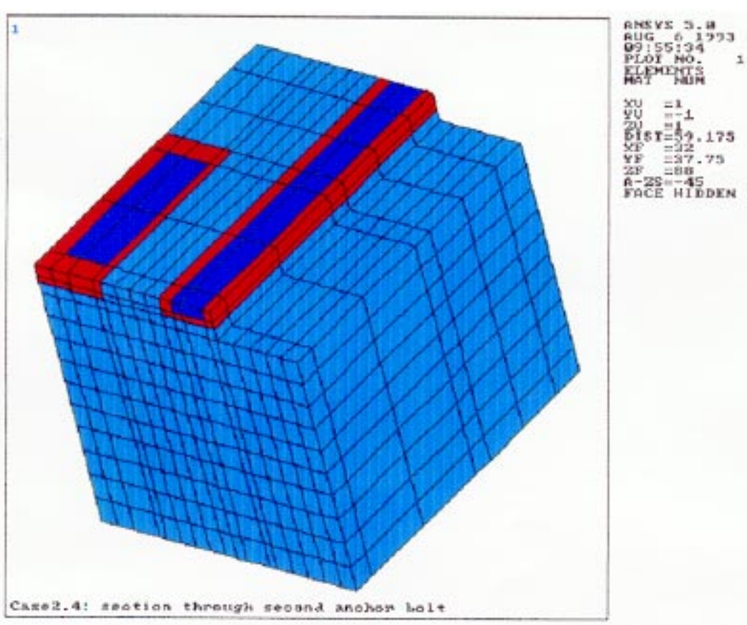


FIGURE III-4. TRUNCATED HALF SYMMETRY MODEL—REDUCED HEIGHT

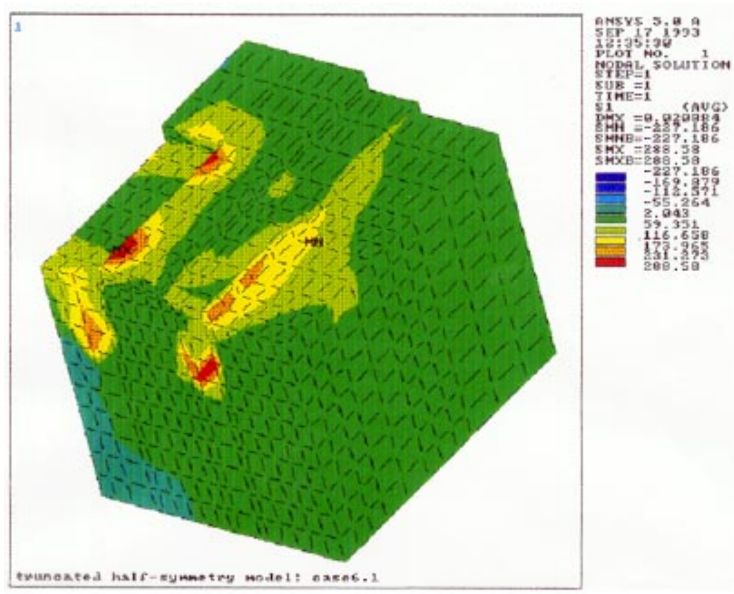


FIGURE III-5. CONTOURS OF PRINCIPAL STRESS (S1)—REFERENCE CASE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

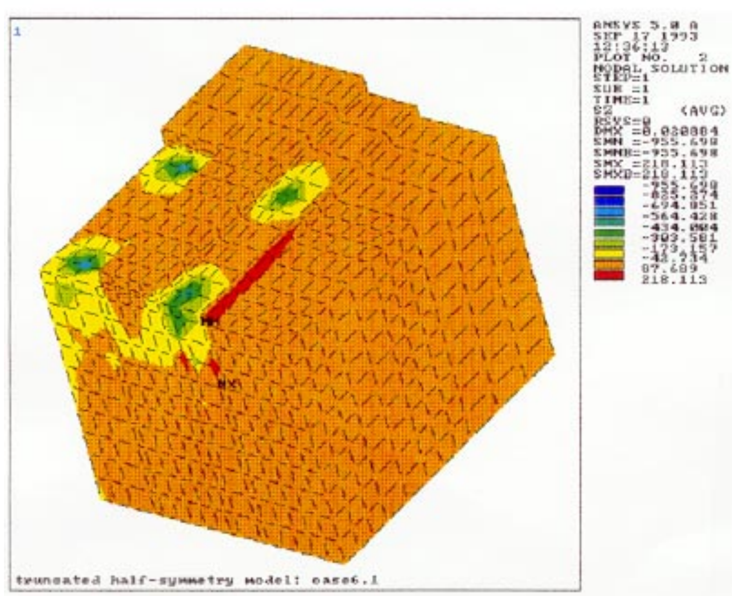


FIGURE III-6. VERTICAL AXIS STRESS—REFERENCE CASE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

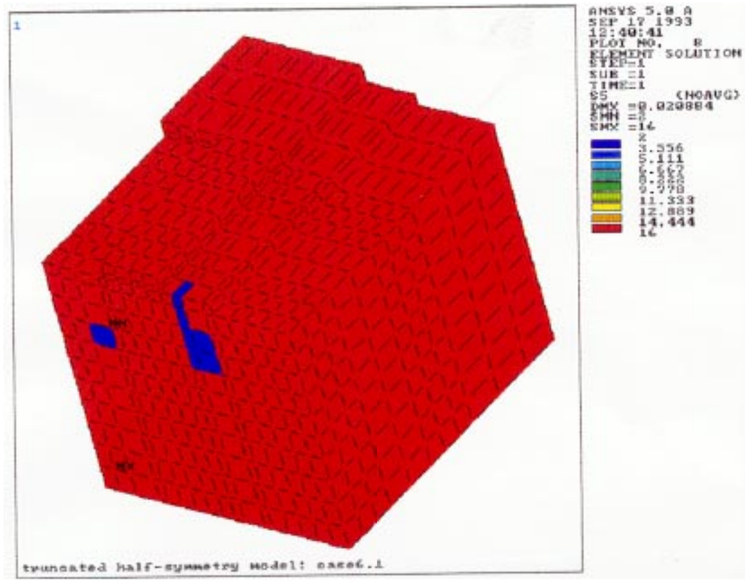


FIGURE III-8. MAP OF CRACKED ELEMENTS—REFERENCE CASE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

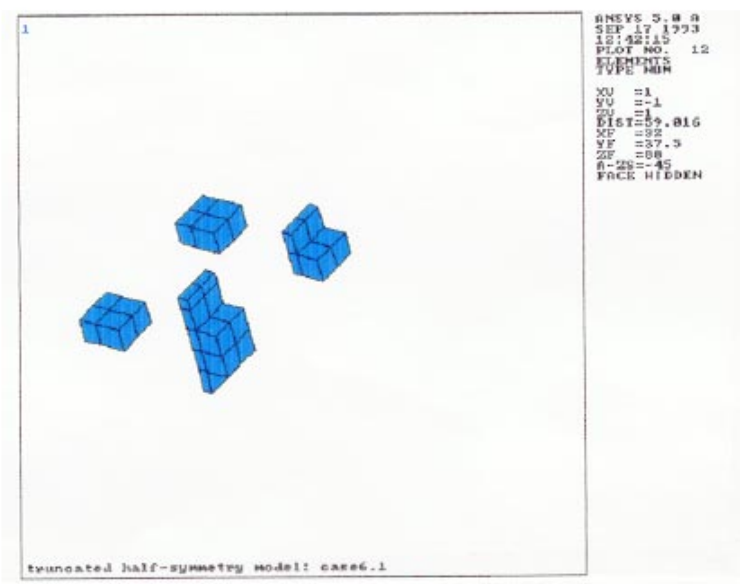


FIGURE III-8. MAP OF CRACKED ELEMENTS—REFERENCE CASE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

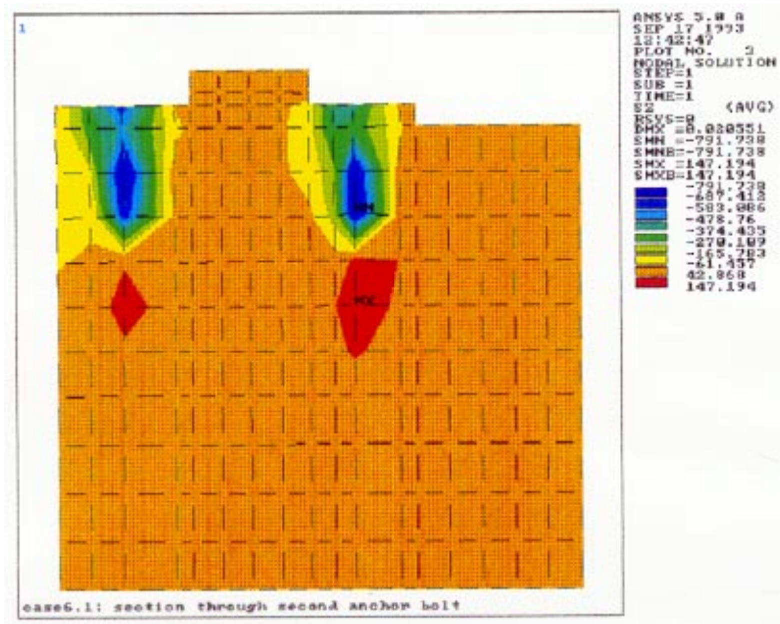


FIGURE III-9. VERTICAL STRESS CONTOURS—REFERENCE CASE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

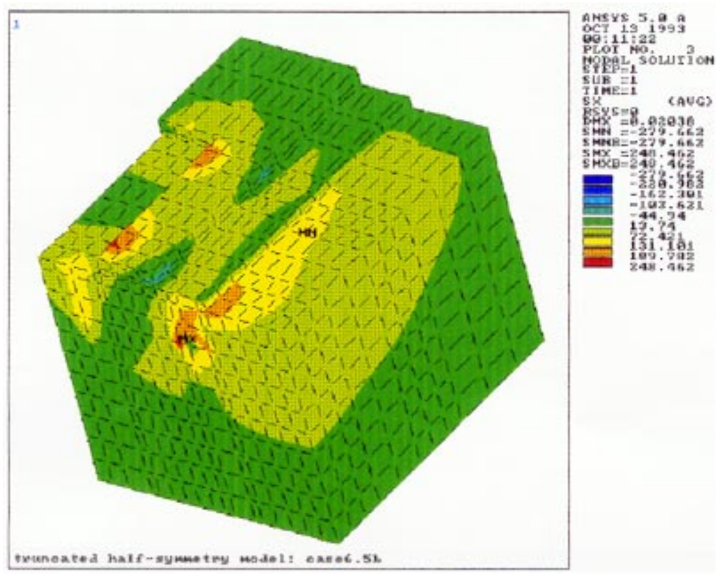


FIGURE IV-1. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

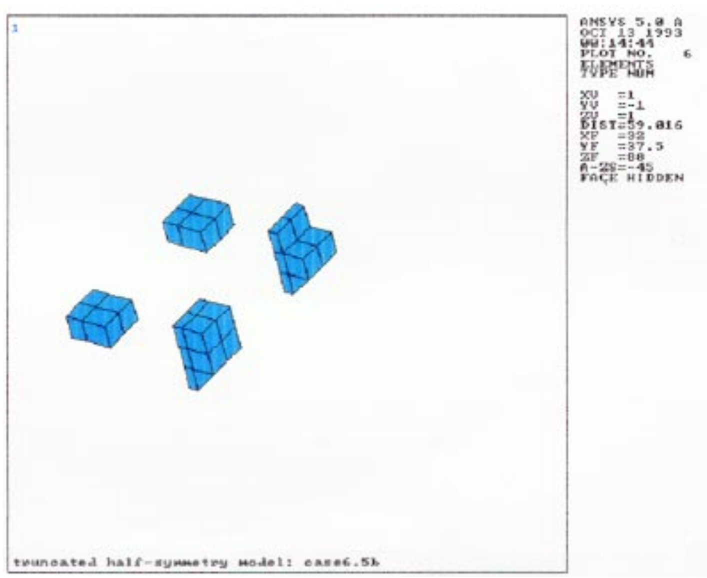


FIGURE IV-2. MAP OF CRACKED ELEMENTS—EFFECT OF PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

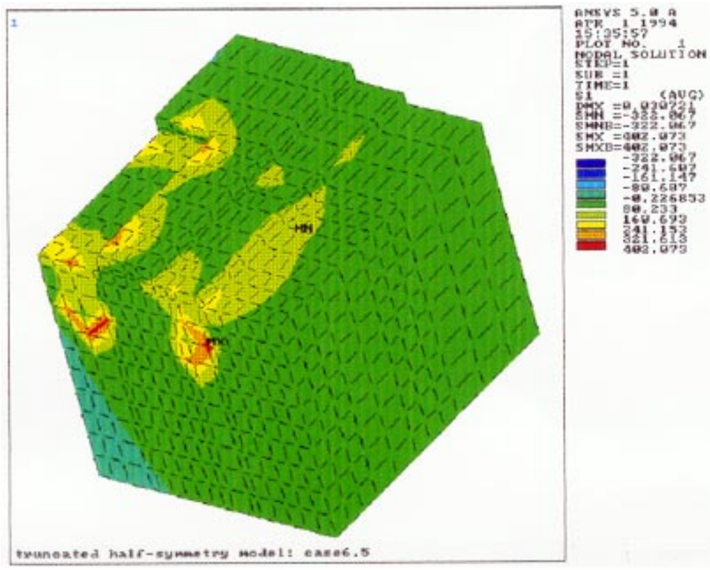


FIGURE IV-3. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 63,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

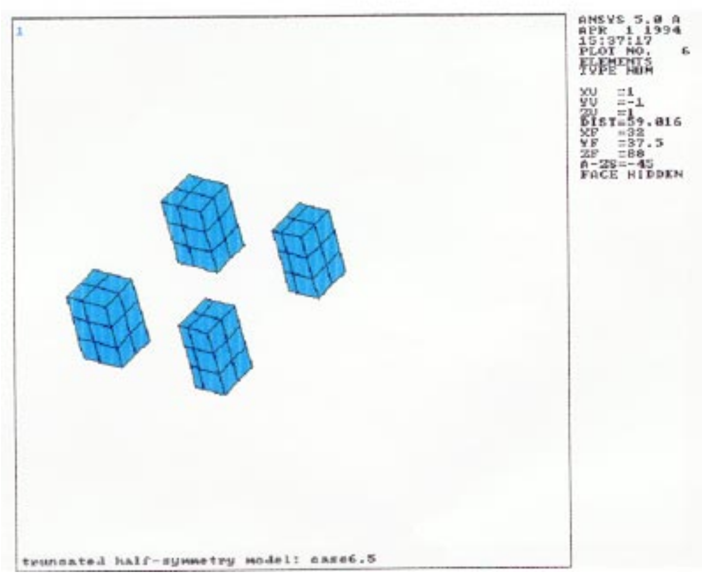


FIGURE IV-4. MAP OF CRACKED ELEMENTS—EFFECT OF PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 63,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

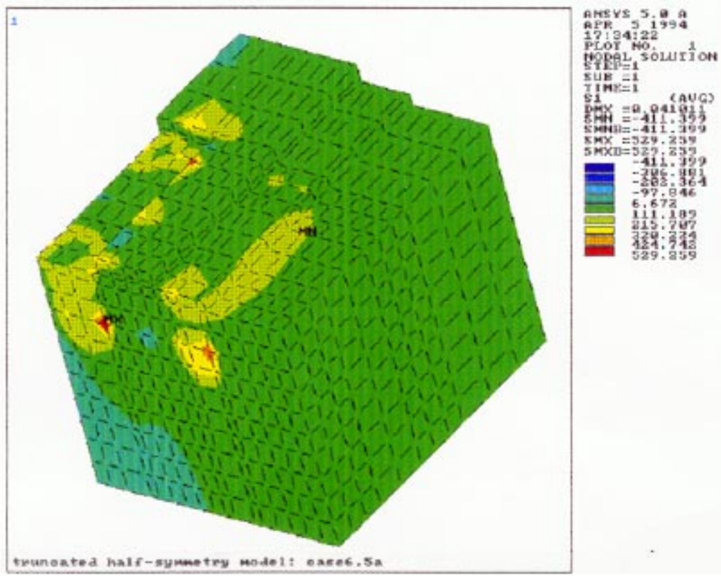


FIGURE IV-5. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 84,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

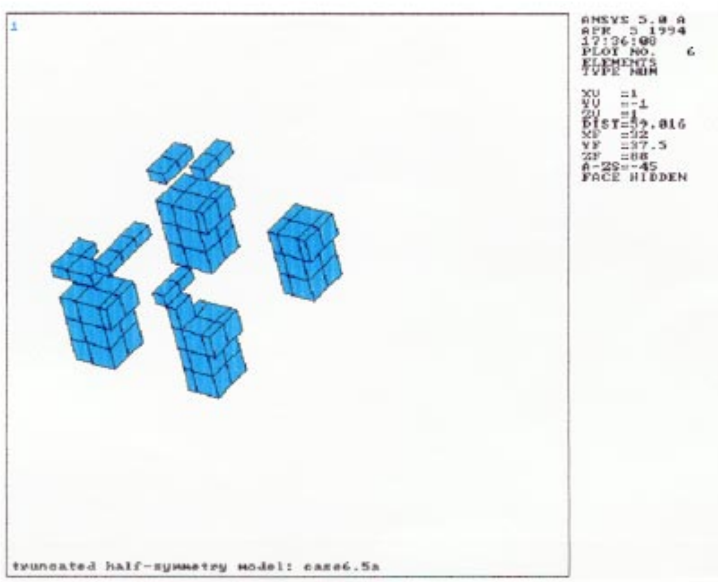


FIGURE IV-6. MAP OF CRACKED ELEMENTS—EFFECT OF PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 84,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

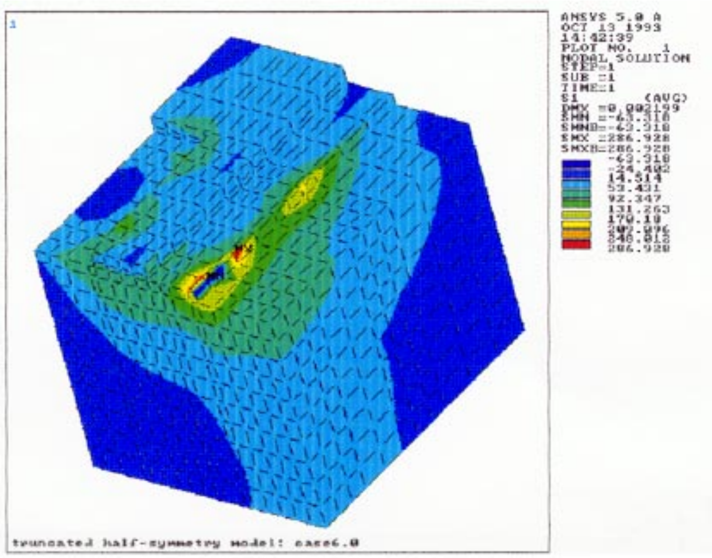


FIGURE IV-7. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF ZERO PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = .0%
SHAKING FORCE = 20,000 LBS.

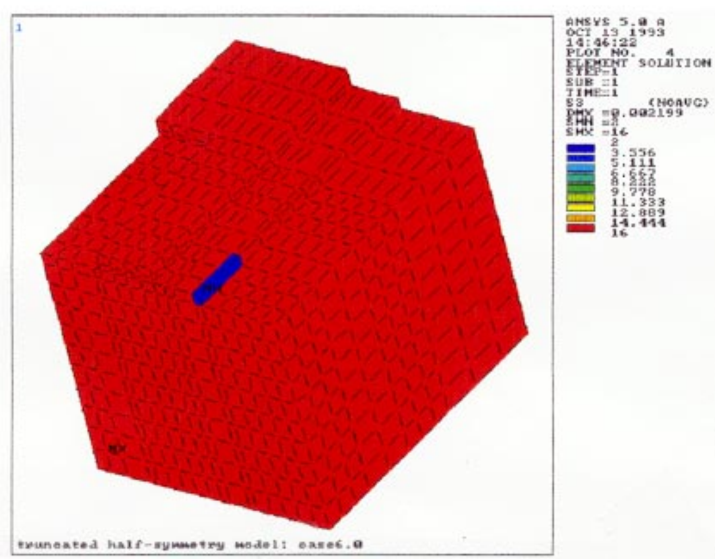


FIGURE IV-8. MAP OF CRACKED ELEMENTS—EFFECT OF ZERO PRELOAD

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 5.0%
SHAKING FORCE = 20,000 LBS.

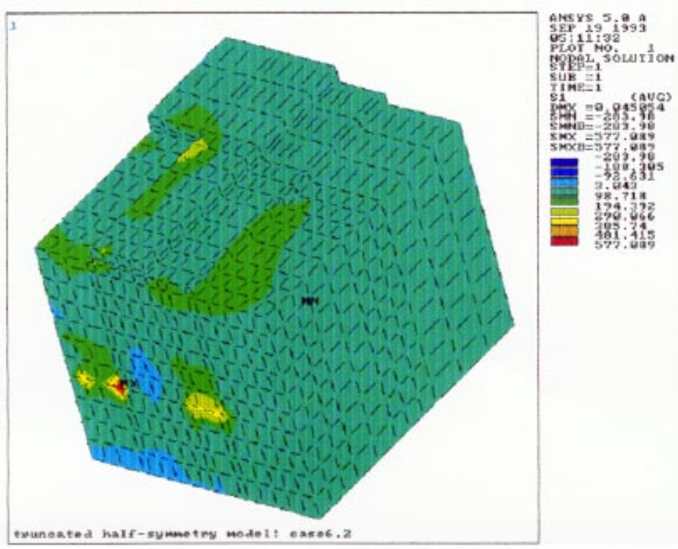


FIGURE IV-9. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF FREE STANDING ANCHOR BOLT LENGTH

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

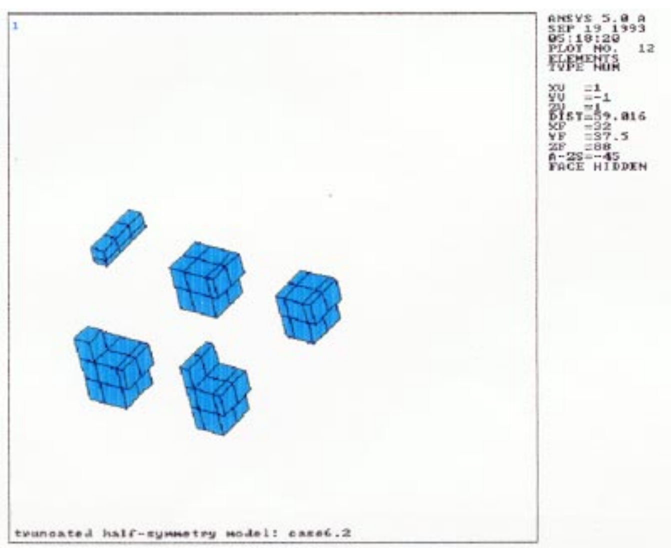


FIGURE IV-10. MAP OF CRACKED ELEMENTS—EFFECT OF FREE STANDING ANCHOR BOLT LENGTH

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

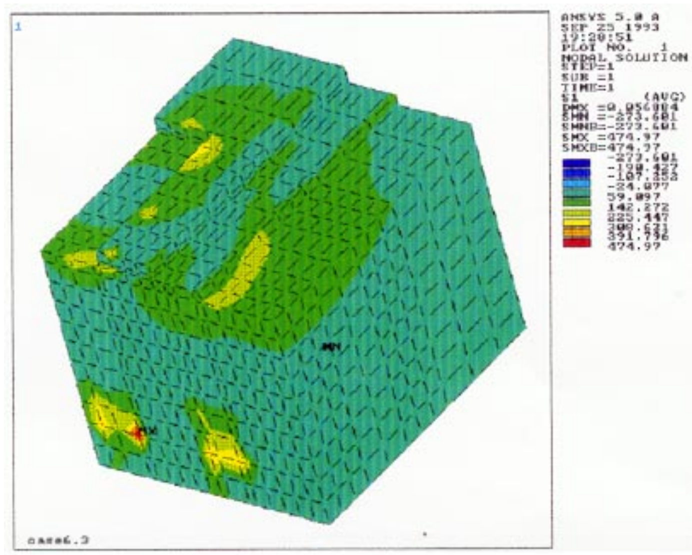


FIGURE IV-11. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF FREE STANDING ANCHOR BOLT LENGTH

ANCHOR BOLT LENGTH = 4.3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

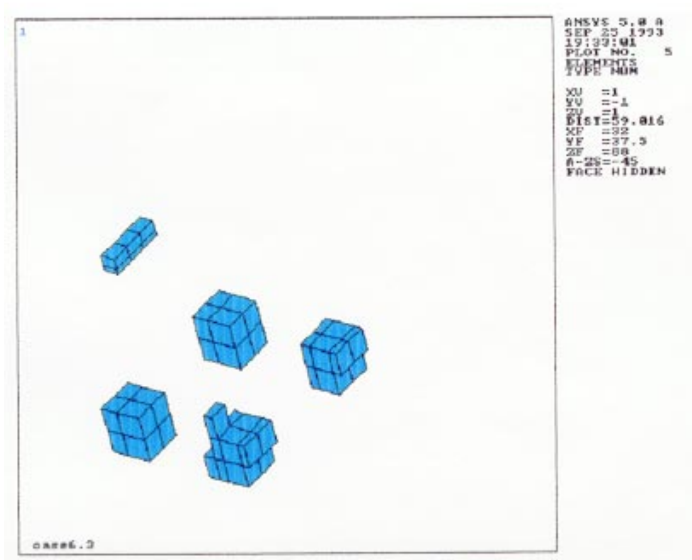


FIGURE IV-12. MAP OF CRACKED ELEMENTS—EFFECT OF FREE STANDING ANCHOR BOLT LENGTH

ANCHOR BOLT LENGTH = 4.3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

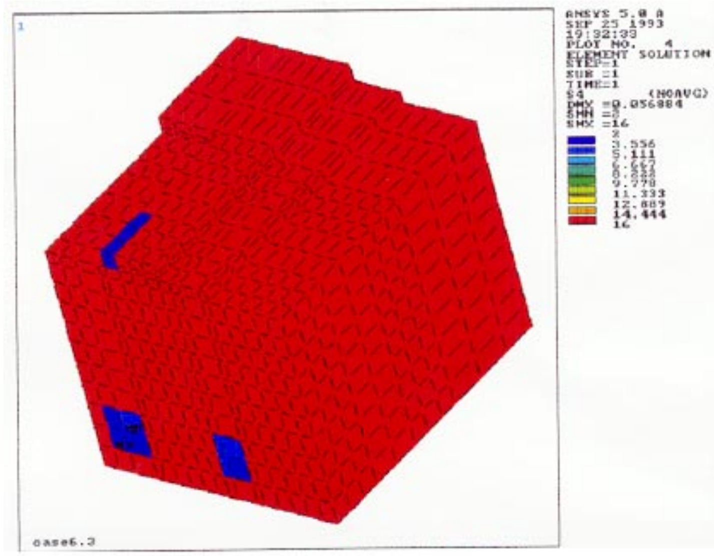


FIGURE IV-13. ELEMENTS CRACKED AT 5TH INTEGRATION—POINT—EFFECT OF FREE STANDING ANCHOR BOLT LENGTH

ANCHOR BOLT LENGTH = 4.3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

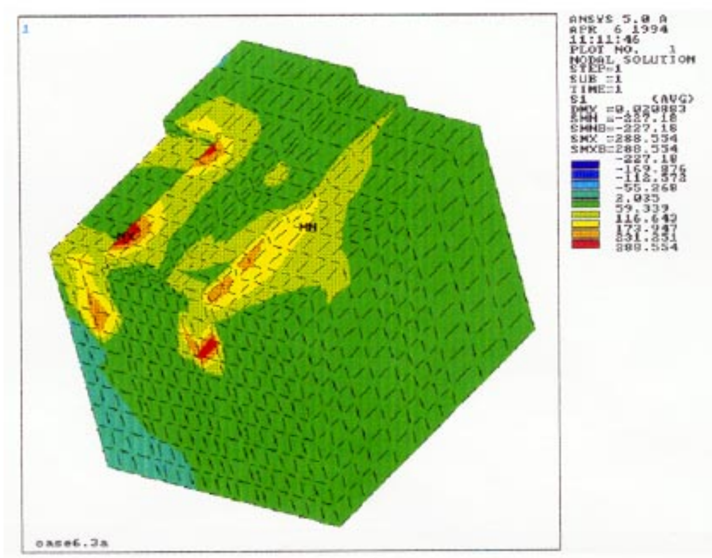


FIGURE IV-14. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF PARTIALLY EMBEDDED LENGTH

ANCHOR BOLT LENGTH = 4.3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

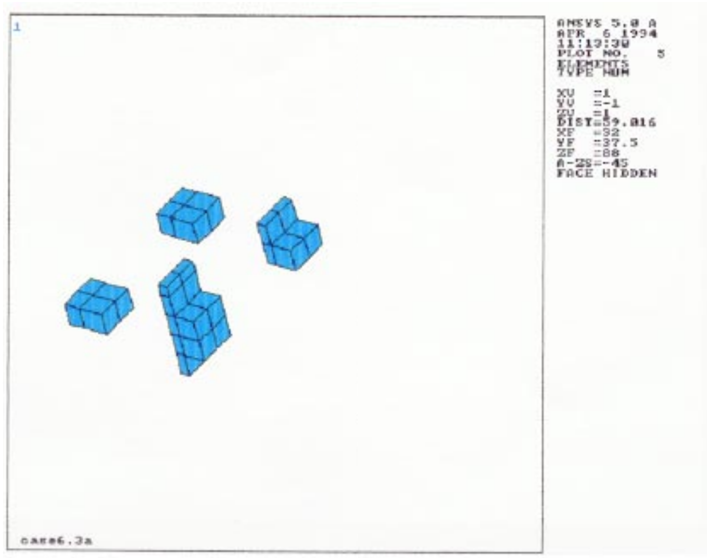


FIGURE IV-15. MAP OF CRACKED ELEMENTS—EFFECT OF PARTIALLY EMBEDDED LENGTH

ANCHOR BOLT LENGTH = 4.3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

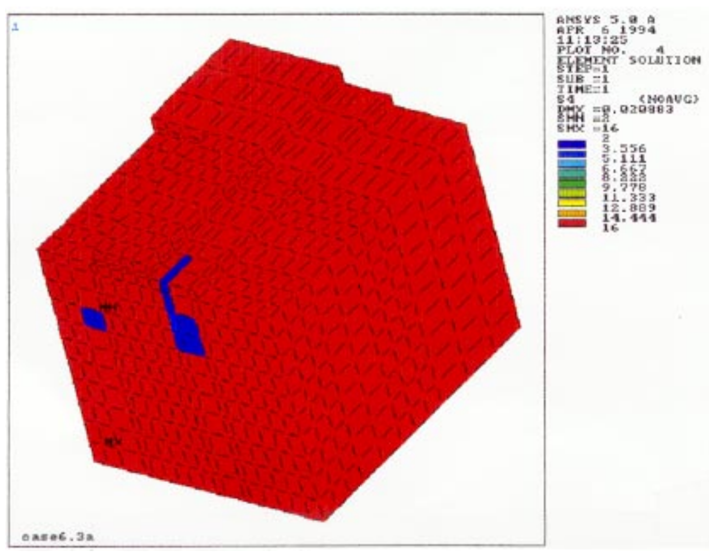


FIGURE IV-16. ELEMENTS CRACKED AT 5TH INTEGRATION POINT—EFFECT OF PARTIALLY EMBEDDED LENGTH

ANCHOR BOLT LENGTH = 4.3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = PARTIALLY EMBEDDED
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

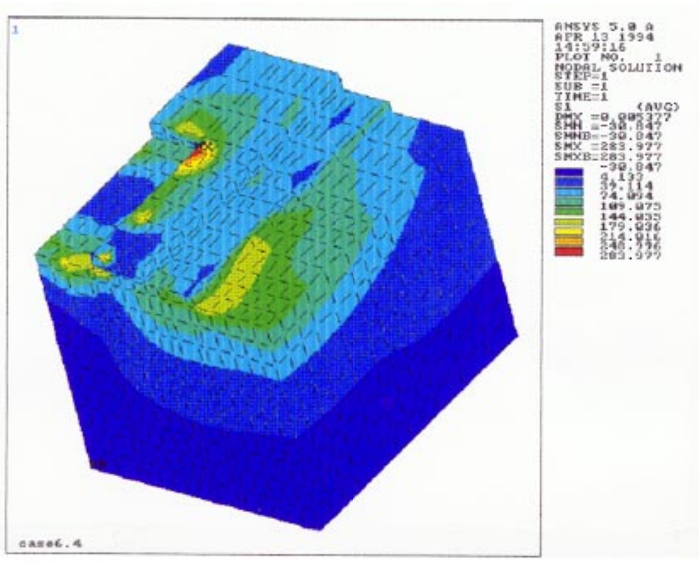


FIGURE IV-17. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF FREE STANDING ANCHOR BOLT THROUGH-TO-THE-MAT

ANCHOR BOLT LENGTH = 10 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

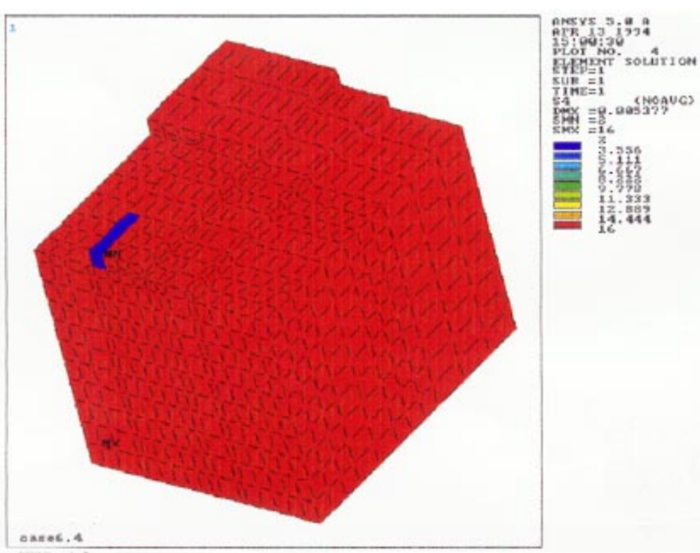


FIGURE IV-18. ELEMENTS CRACKED AT 5TH INTEGRATION POINT—EFFECT OF FREE STANDING ANCHOR BOLT THROUGH-TO-THE-MAT

ANCHOR BOLT LENGTH = 10 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

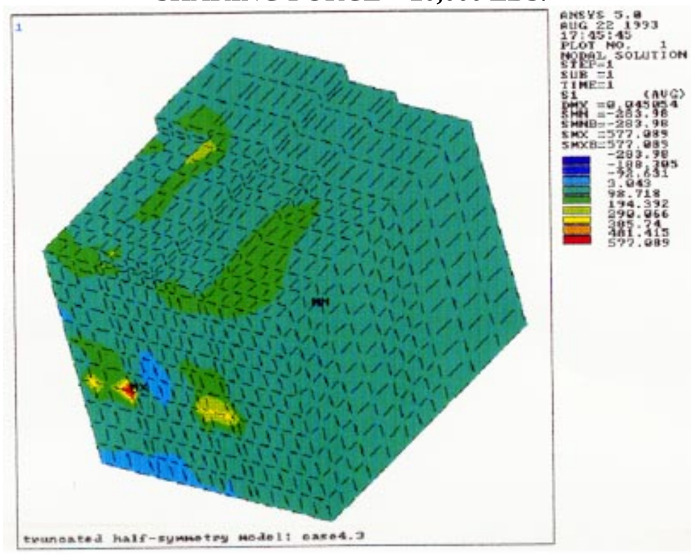


FIGURE IV-19. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

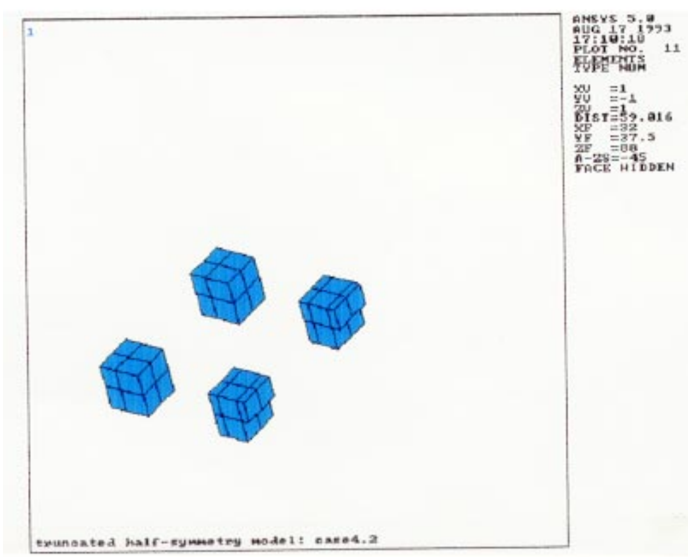


FIGURE IV-20. MAP OF CRACKED ELEMENTS—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

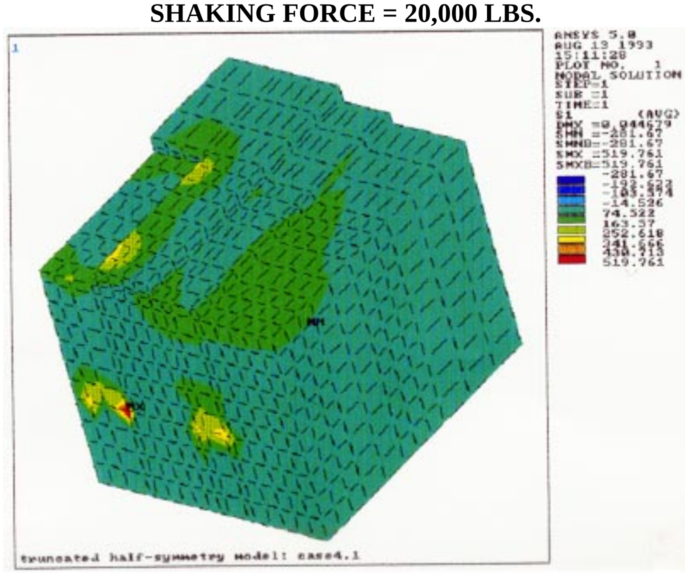


FIGURE IV-21. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 1.0%
SHAKING FORCE = 20,000 LBS.

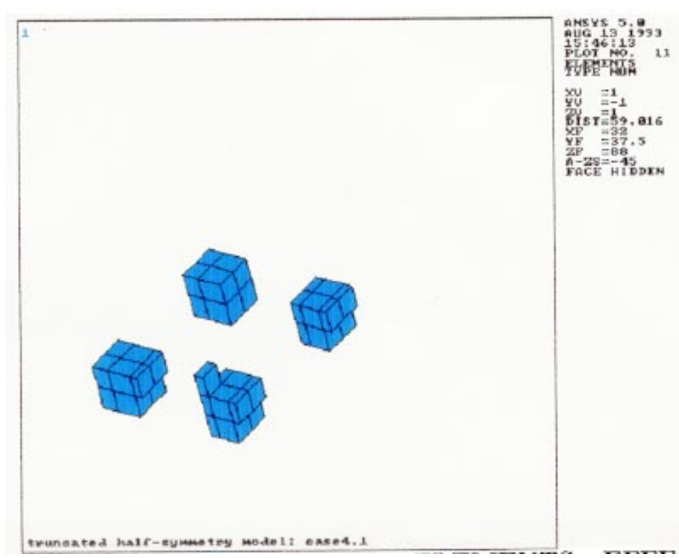


FIGURE IV-22. MAP OF CRACKED ELEMENTS—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 1.0%
SHAKING FORCE = 20,000 LBS.

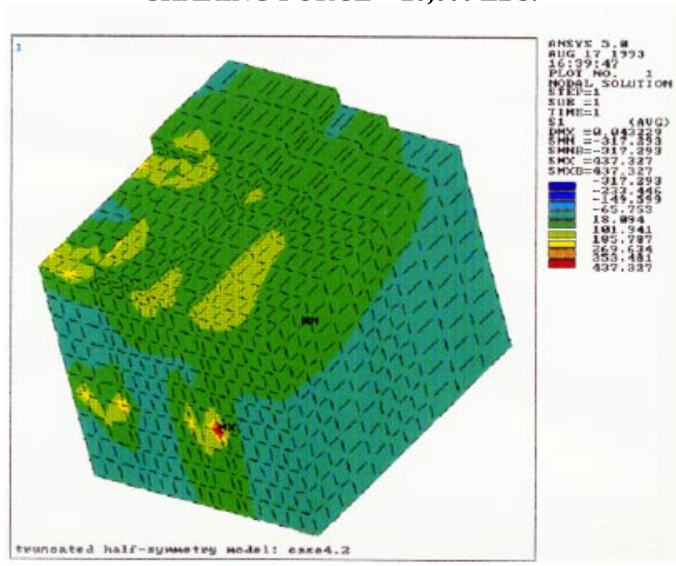


FIGURE IV-23. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 10.0%
SHAKING FORCE = 20,000 LBS.

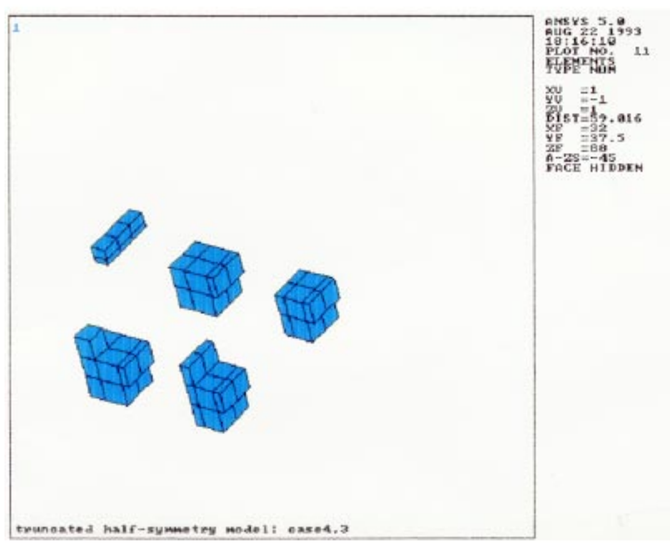


FIGURE IV-24. MAP OF CRACKED ELEMENTS—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 10.0%
SHAKING FORCE = 20,000 LBS.

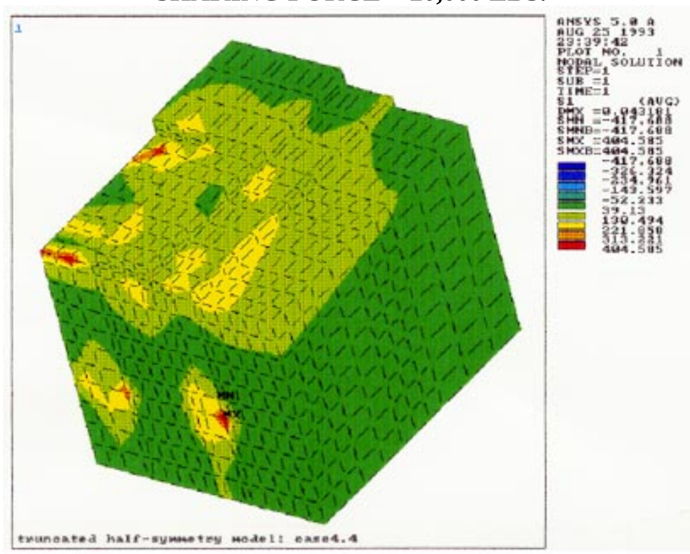


FIGURE IV-25. CONTOURS OF PRINCIPAL STRESS (S1)—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 20.0%
SHAKING FORCE = 20,000 LBS.

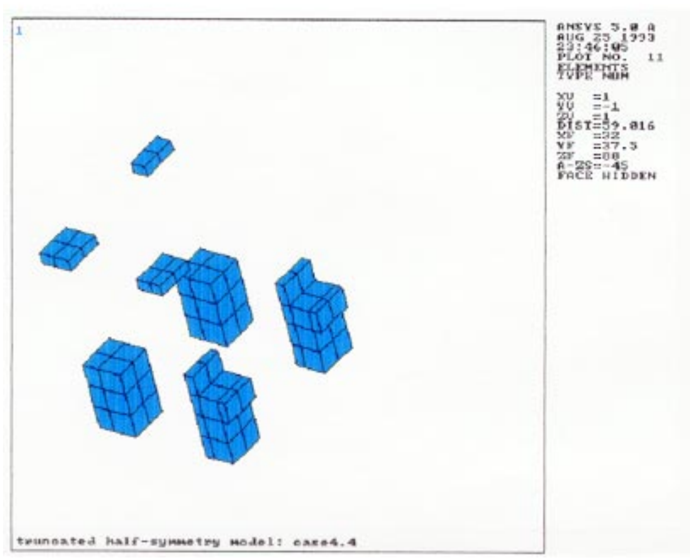


FIGURE IV-26. MAP OF CRACKED ELEMENTS—EFFECT OF REBAR DENSITY

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 20.0%
SHAKING FORCE = 20,000 LBS.

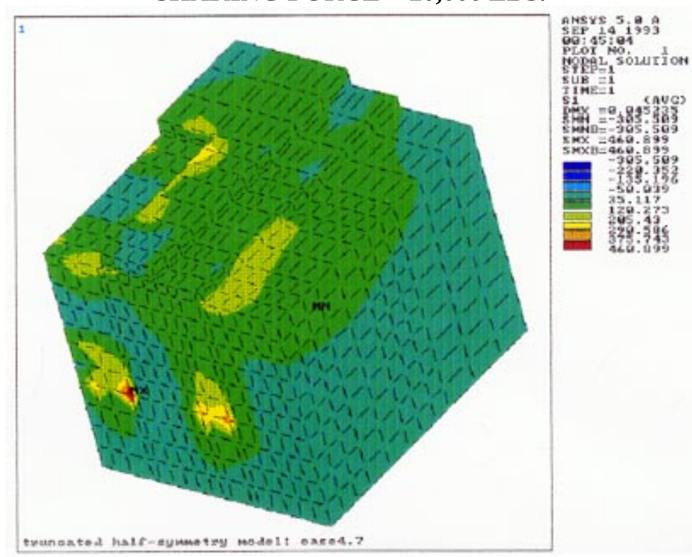


FIGURE IV-27. CONTOURS OF PRINCIPAL STRESS (S1)—NO REBAR

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.0%
SHAKING FORCE = 20,000 LBS.

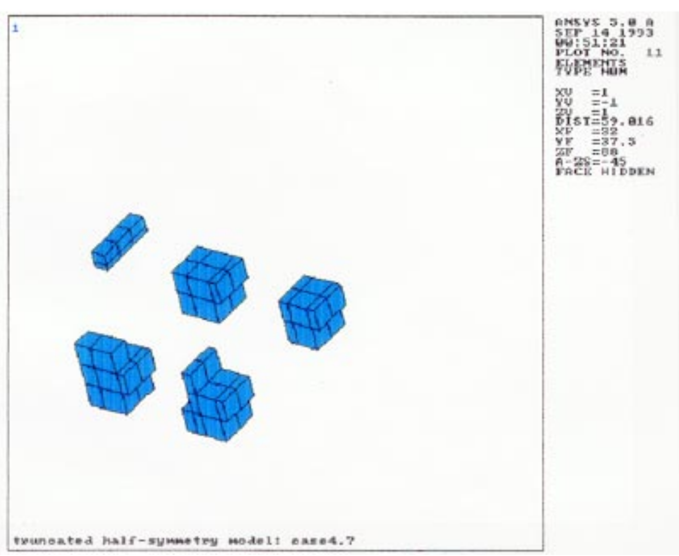


FIGURE IV-28. MAP OF CRACKED ELEMENTS—NO REBAR

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 0.0%
SHAKING FORCE = 20,000 LBS.

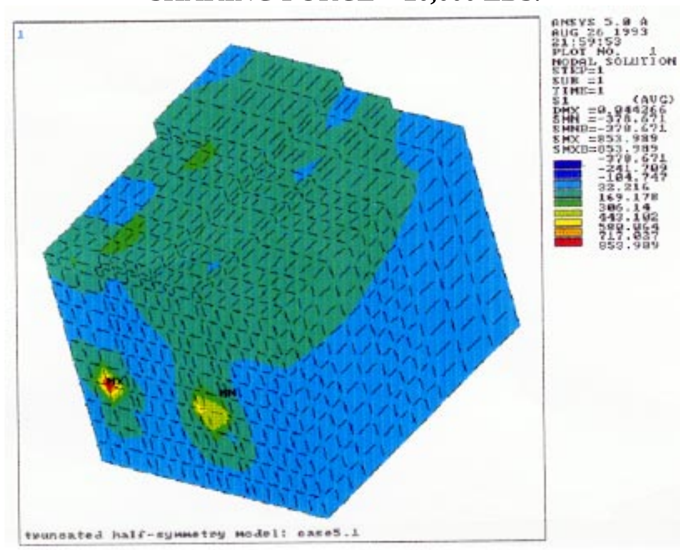


FIGURE IV-29. CONTOURS OF PRINCIPAL STRESS (S1)—INCREASED TENSILE STRENGTH

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

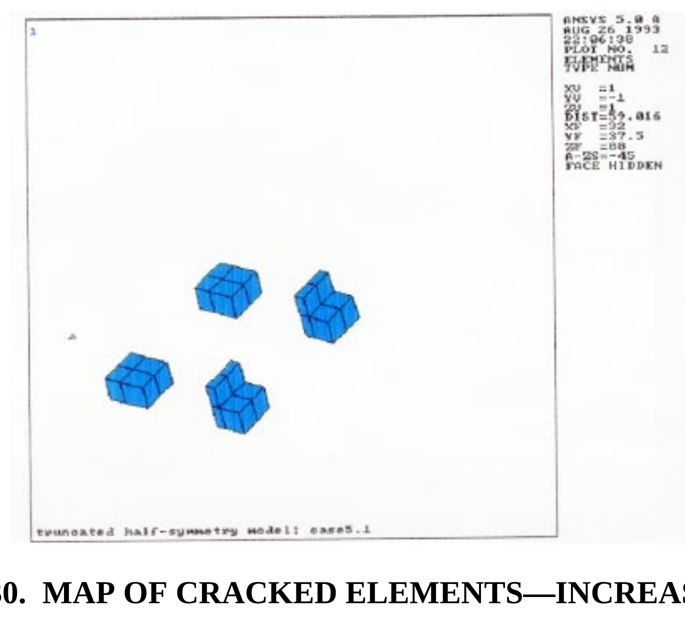


FIGURE IV-30. MAP OF CRACKED ELEMENTS—INCREASED TENSILE STRENGTH

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

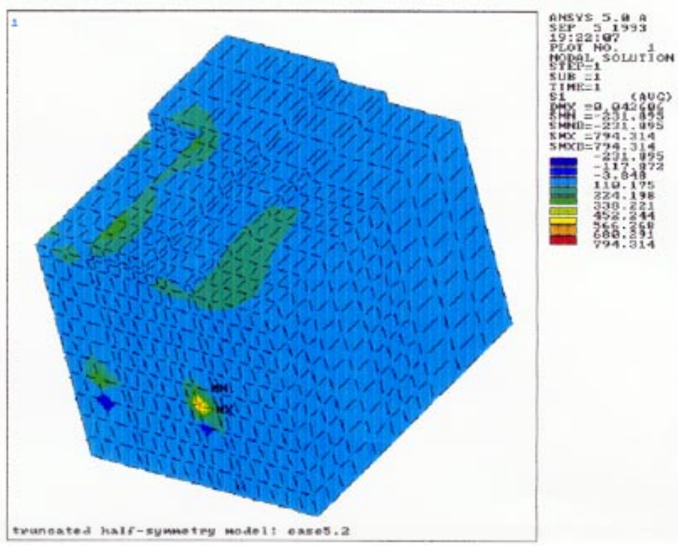


FIGURE IV-31. CONTOURS OF PRINCIPAL STRESS (S1)—INCREASED TENSILE STRENGTH

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

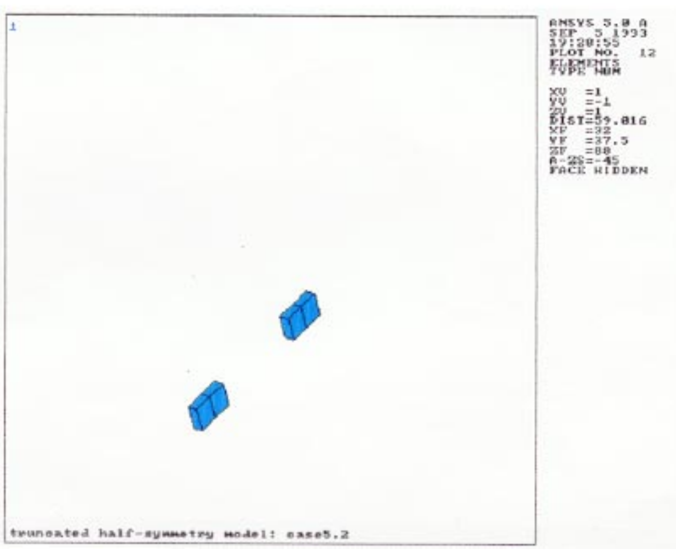


FIGURE IV-32. MAP OF CRACKED ELEMENTS—INCREASED TENSILE STRENGTH

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING

REBAR DENSITY = 0.2%
SHAKING FORCE = 20,000 LBS.

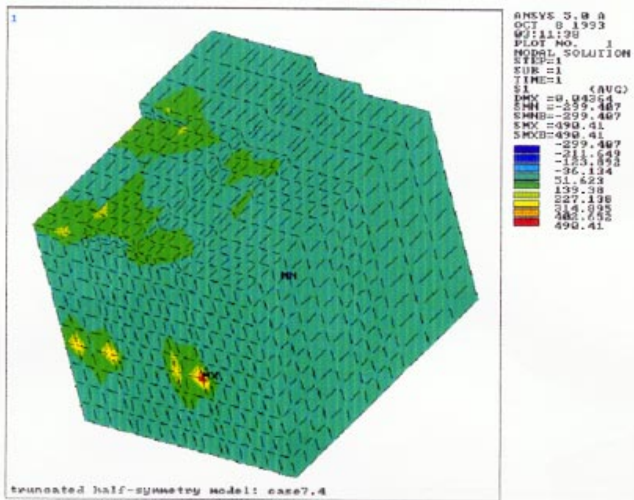


FIGURE IV-33. CONTOURS OF PRINCIPAL STRESS (S1)—REDUCED SHAKING FORCE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 5,000 LBS.

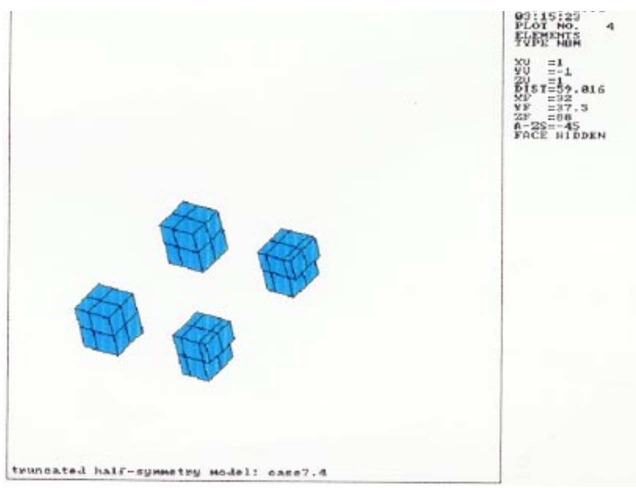


FIGURE IV-34. MAP OF CRACKED ELEMENTS—REDUCED SHAKING FORCE

ANCHOR BOLT LENGTH = 3 FT.
ANCHOR BOLT PRELOAD = 42,000 LBS.
ANCHOR BOLT CONFIGURATION = FREE STANDING
REBAR DENSITY = 0.2%
SHAKING FORCE = 5,000 LBS.