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BOLT IN BORE BOUNDARIES

by
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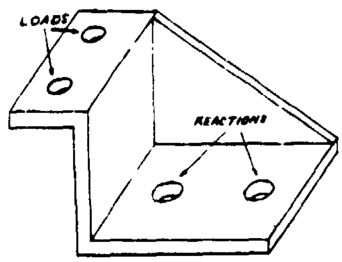
BUTLER ANALYSES

INTRODUCTION

This paper discusses the factors that must be taken into consideration when applying NASTRAN's linear analysis to structures whose principle boundaries are formed by bolting, and for which localized stress peaking is important. The determination of what portion of the bolt boundary is active for a given loading is a nonlinear problem. Once the active boundaries are established for a given load, the determination of the resulting stresses is a linear problem. Does this mean that every analysis whose principle boundaries are formed by bolting are wrong if they are not treated in a nonlinear fashion? Not at all! The importance of this nonlinear condition rears its head only when the finite element mesh is so fine that the bore is no longer represented as a point. Then the particulars of the macro behavior of the bolt in the bore become important. There are two approaches to this problem: Either the employment of a set of nonlinear scalar springs at the boundaries to determine the active region for a given loading followed by a detailed linear analysis under the active bounding locales; or the pursuit of a series of boundary approximations using linear analysis, only, until admissible conditions are found. This paper deals with the second approach. An illustration of these methods is given in an application to a mounting bracket.

OPERATION

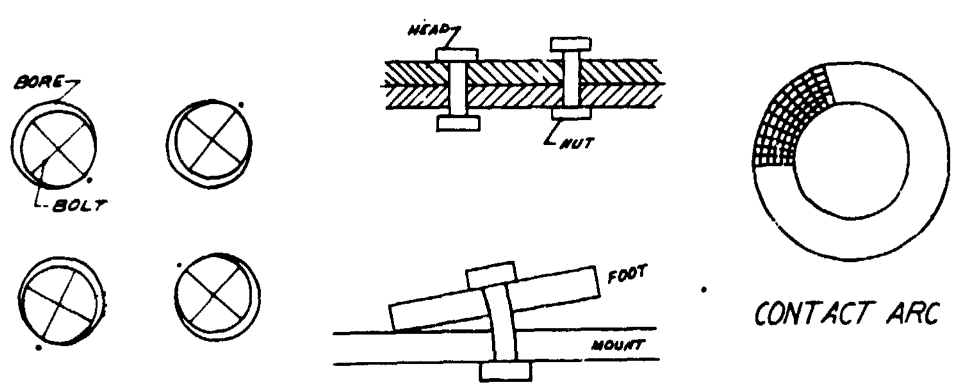
Loads applied simultaneously in 3 coordinate directions involve 3 kinds of boundaries and cause variations depending on the magnitudes of the load components. Unfortunately, it is not possible to apply a set of individual nominal loads then scale them and combine them to get a final result, because linear superposition does not work at all in this highly nonlinear problem. Changing loads causes the hold down bolts to bear on the bore surface in different locations; they cause either the bolt head or not to make contact in different locations; they cause different edges of the bolted foot to bear on the mounting surface. In the application under consideration, there are two bolts through a single rectangular foot.



In the actual case there is a multi-fold infinity of possible bounding contacts. In the finite element case of a fine meshed model there is a high finite number of possible bounding combinations. To reduce the problem of finding admissible combinations to a manageable set, it was decided to limit the trial locations to the following:

TYPE OF BOUNDARY	DETAILS OF REPRESENTATION
Bolt Shank Against Bore Surface	Three Pairs of Points At Each Cardinal Location For Each Of Two Bores
Bolt Head Against Upper Surface Annulus	Circle Of Points About Each Of Two Bores
Bolt Nut Against Lower Surface Annulus	Circle Of Points About Each Of Two Bores
Foot Side Edge Against Mount Surface	Set Of Three Points At Each Of Two Sides Of Each Of Two Points
Foot End Edge Against Mount Surface	Set Of Points Along Entire Edge Of End Nearest Load

Sketches of these boudaries as they might behave under load are shown here.



METHOD

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Fools rush in where angles fear to tread. Based on the logic of rigid body actions it appeared quite reasonable to expect that one could make initial predictions that could be modified slightly, after initial reactions were reviewed, to a set that would be admissible. Notice that mealy-mouthed language is already being used: reasonable -- admissible; not correct or precise. If the load were applied in the +X,+Y,+Z directions, one would expect the foot to move over to contact the bolts on the -X sides of the bores, the -Y sides of the bores, and to engage the bolt head rather than the bolt nut for both bolts. It was these rigid body notions that were dashed by the elastic reality of the case. Actions at one bore were different than actions at the other. Loads were offset from the foot and the loading surface was canted to the plane of the foot. These produced moments that were reacted at the bolts. Rigid body calculations were made for each load to help decide on the initial boundary assignments in the first trial of each run. This approach has logical appeal, but it often was considerably off the mark.

In order to improve the first trial, a small pilot model with a coarse mesh was assembled from plate elements and had each bore represented by a point. Readings from the bore points and boundary edge points helped to improve the initial SPC assignments in the solid model.

This analysis used solid elements entirely for the whole model which contributed to a complication in satisfying moments. Pairs of points are needed to create couples when using solid elements, while if plate bending elements were used instead, any bending requirements could be met at a single point rather than over a pair of points. The tendencies of pairs of points to form couples proved troublesome at boundaries. To explain this it will be helpful to redefine some terms.

First of all "boundary" is defined to be that set of points wherein a subset of whose components are constrained to zero displacement. This is a particularly severe condition in view of the inevitible redundancy of constraints. An admissible boundary is one that pushes only and does not pull on the mating boundary strucuture. This restriction makes an ideal argument for using unidirectional nonlinear boundary springs. The nonlinear supports will allow nonzero displacements and still produce a push force. Exploring such a case would be an attractive venture, but this paper concentrates only on the linear trial method. The measure used to discriminate for admissibility of boundary candidates was the sign of the SPCForces at the boundaries. If any boundary components were found to pull, it necessitated redefining the boundary constraints to avoid this pulling condition. Quite often it was not enougn to just eliminate the offending component, because the pulling behavior often moved to the neighboring retained point. Another suprise occurred at the bolt heads. It seemed representative for bolt head constraints to be modeled as an annulus of a double circle of points. As it turned out, pairs of inner and outer radial points acted as couples with opposite signs which is inadmissible, because opposite signs means one is pulling while the other is pushing. Consequently, bolt head and bolt nut reactions were modeled as a single circle of points. Even restricting bolt constraints to single circles was most often not sufficiently curtailed to eliminate all pulling. Trial with only arcs of a circle in various positions and different spans were made before sometimes, an admissible head or nut representation was found.

At times during this analysis, I wanted to say, "What does it matter if there is some pulling?" Severe high stresses occurred in regions where high constraint forces of opposite signs were present. Good answer.

The canted, offset position of the loading produced a tendency for the foot to tilt with respect to the mounting surface in every loading case. A triplet of points on an edge transversely opposite a bore in one direction constituted the candidate boundary set at each of 4 locations. As trials were made it was found that sometimes the triplet had to be reduced to a pair or a single point before it became admissible. In the case of fore and aft edges, it was found that sometimes contact was made at the edge nearest the load but tilting towards the far end was taken up elastically before reaching the far end so that the far edge never became a boundary constraint. The distribution of constraints on the near edge was found to vary from the entire edge to a biased partial set.

Absence of pulling is not the only criterion for admissibility. Over-constraining must be guarded against when trying to trace critical stresses. It is possible to have excessive constraints even though they are all pushing. The requirement used for an admissible quantity of constraints is that the opposing equilibrating elastic constraints be of the same order of magnitude as the opposing forces for rigid body equilibrium. An average of six trial runs per load case were needed to find an admissible set of constraints. Results were considered to be on the

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conservative side, because the contact area broadens as defurmation takes place in the actual case. Broadening of the contact area was not taken into account in this analysis. As a result this analysis should show stresses slightly higher than actual.

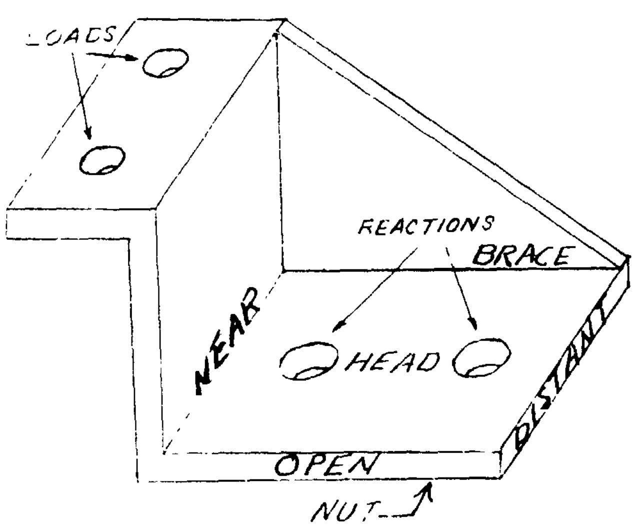
The advantage for an analysis, such as this, is that it gives much more information than an experimental set-up using strain gages, because the finite element mesh has a smaller gage length and has several orders of magnitude more measurements. The load path becomes well traced and the peaking and releasing of stresses which leads to cracks and fatigue is well defined.

APPLICATION

To illustrate how this method worked in practice, this paper will trace the steps taken in homing in on an admissible set of constraints for a single loading condition.

SUBCASE 3412; XYZ loads at the cradle are -283/-559/-422

It might be easier to describe the evolution of reactions if positions are oriented with respect to the bracket parts. For instance, the place where loads go in is the cradle and the triangular shaped ligament connecting the cradle to the base is the brace. Opposite the brace the side is named "open". Positions in the other direction are distinguished by the terms "distant" from the loaded cradle and "near" the load. The bores are not of equal size. The bore nearest the cradle is the larger so the terms large bore (LB) and small bore (SB) help to keep the reaction straight. Finally, the vertical direction can be designated by the bolt head side on top and the bolt nut side on the bottom. See the sketch with labels per this scheme.



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The initial SPC set was assigned in an attempt to balance the loads with pushing forces only. To oppose the -X load, a set of SPC's was put in place at the LB(large bore) on the cardinal point towards the open side. The couple created by the X load and the LB X reaction can be balanced by putting a constraint on the cardinal point at the SB(small bore) towards the brace side.

To oppose the -Y load an SPC set was put on the nut side of LB causing a moment which could be opposed by an SPC on the head side of SB.

To oppose the -Z load the cardinal points toward the near side of both bores, constraints were put on the near side of both LB and SB. To oppose the moment in Z forces about the X-axis, a constraint was applied at the distant edge.

In particular, the initial combination of SPC sets consisted of:
(a) a full array of 3 pairs of points (nut surface, mean surface, and head surface) on the SB brace location for X reaction.
(b) a full column of 3 points (nut, mean, and head) on the LB open location for X reaction.
(c) a 270 degree arc of points from "near" around "brace" to "distant" on the head surface around SB for Y reaction.
(d) a 270 degree arc of points from "near" around "open" side to "distant" on the nut surface around LB for Y reaction.
(e) a line of points on the "distant" edge beyond SB for Mx reaction.
(f) a full array of 3 pairs of points on the SB near side for Z reaction.
(g) a full column of 3 points on the LB near side for Z reaction.

The results showed a number of places that were pulling, but the one giving the greatest offense was the line of points on the distant edge.

The first modification tried to temper the effect of the distant edge by introducing an additional constraint on the brace egde opposite SB, while keeping all else unchanged. The results showed no relief in the pulling of the distant edge and only slight correction around the bores.

The second modification abandoned the distant edge line. The arc on the nut surface of LB was shifted from 270 degrees on the open side to 180 degrees on the brace side.

The arc on the head surface of SB was reduced to 180 degrees on the brace side.
The triplet of points on the brace edge of SB was reduced to a pair.
The results were considerably improved, but some pulling in Z persisted.

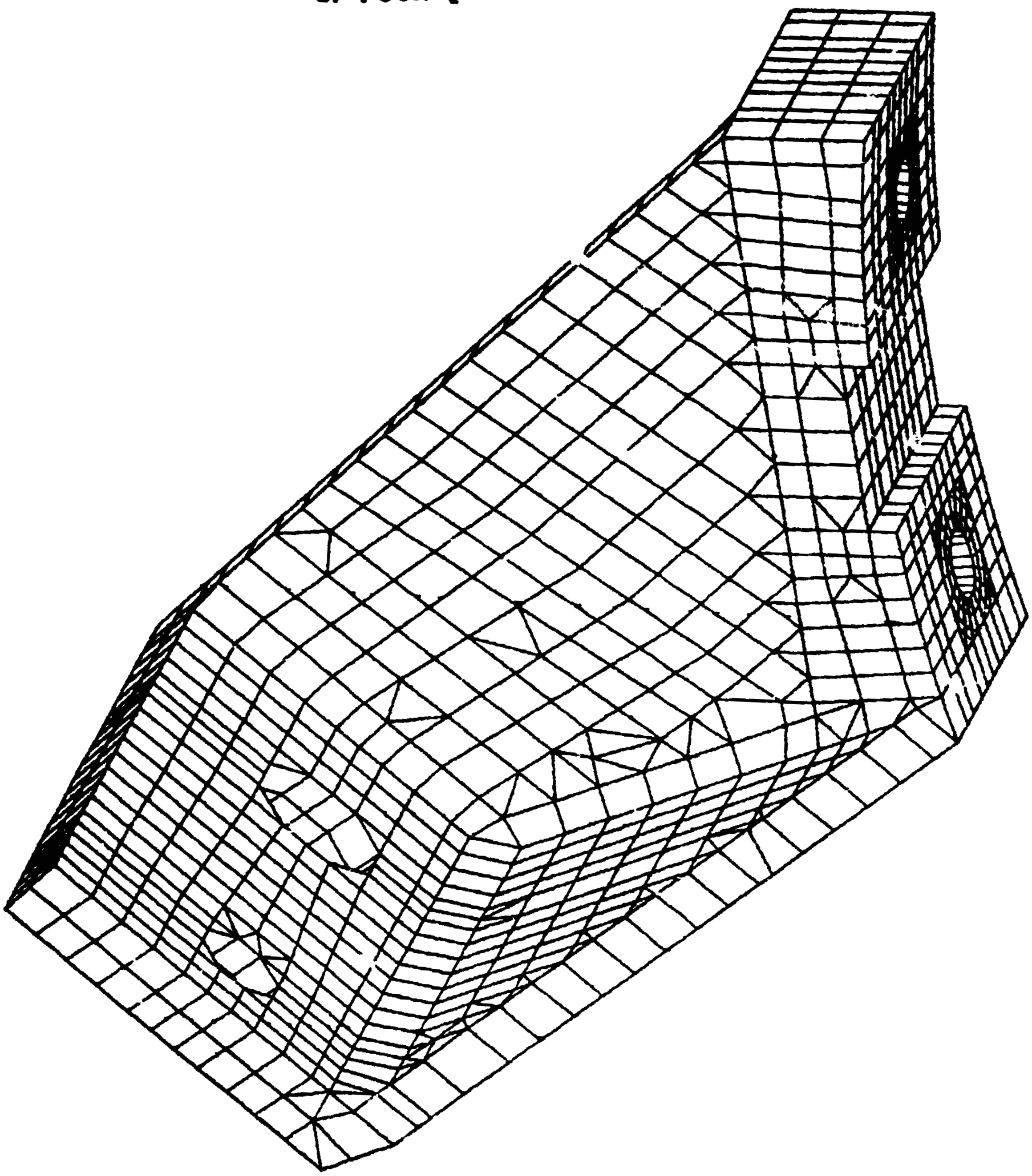
The third modification reduced 3 pairs in the SB near side to the upper 2 pairs.
The column of constraints in LB near side were removed.
The triplet on the open side of LB was reduced to the upper pair.
The results showed there was still pulling in Y, and the Z pushing magnitudes on SB were high.

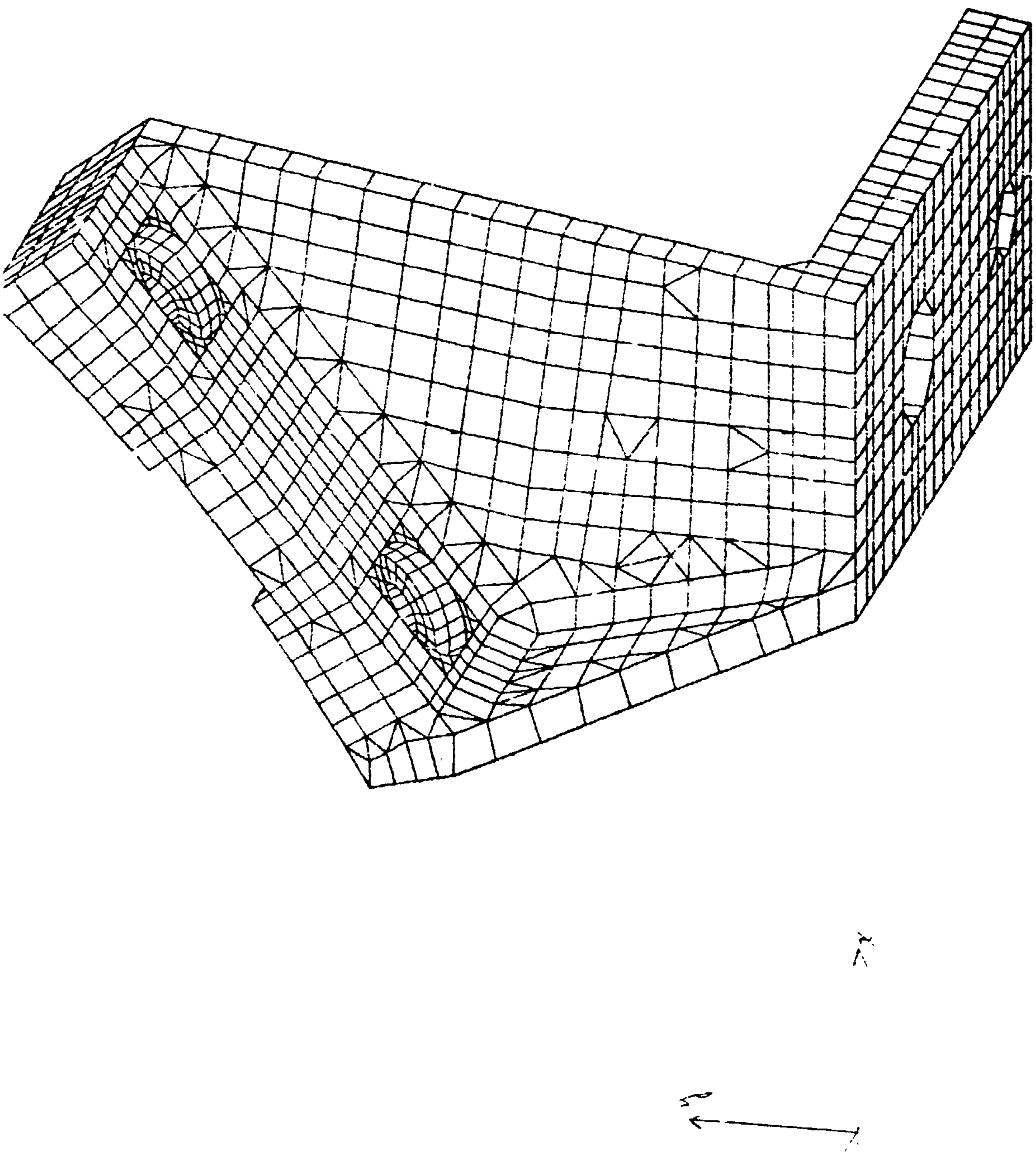
The fourth modification reduced the 180 degree arc on the nut surface of LB to a 45 degree arc on the brace side.
The triplet on the near side of LB was resoted to moderate those in SB.
The results were close but there was some pulling on the brace side of SB and on the near side of LB.

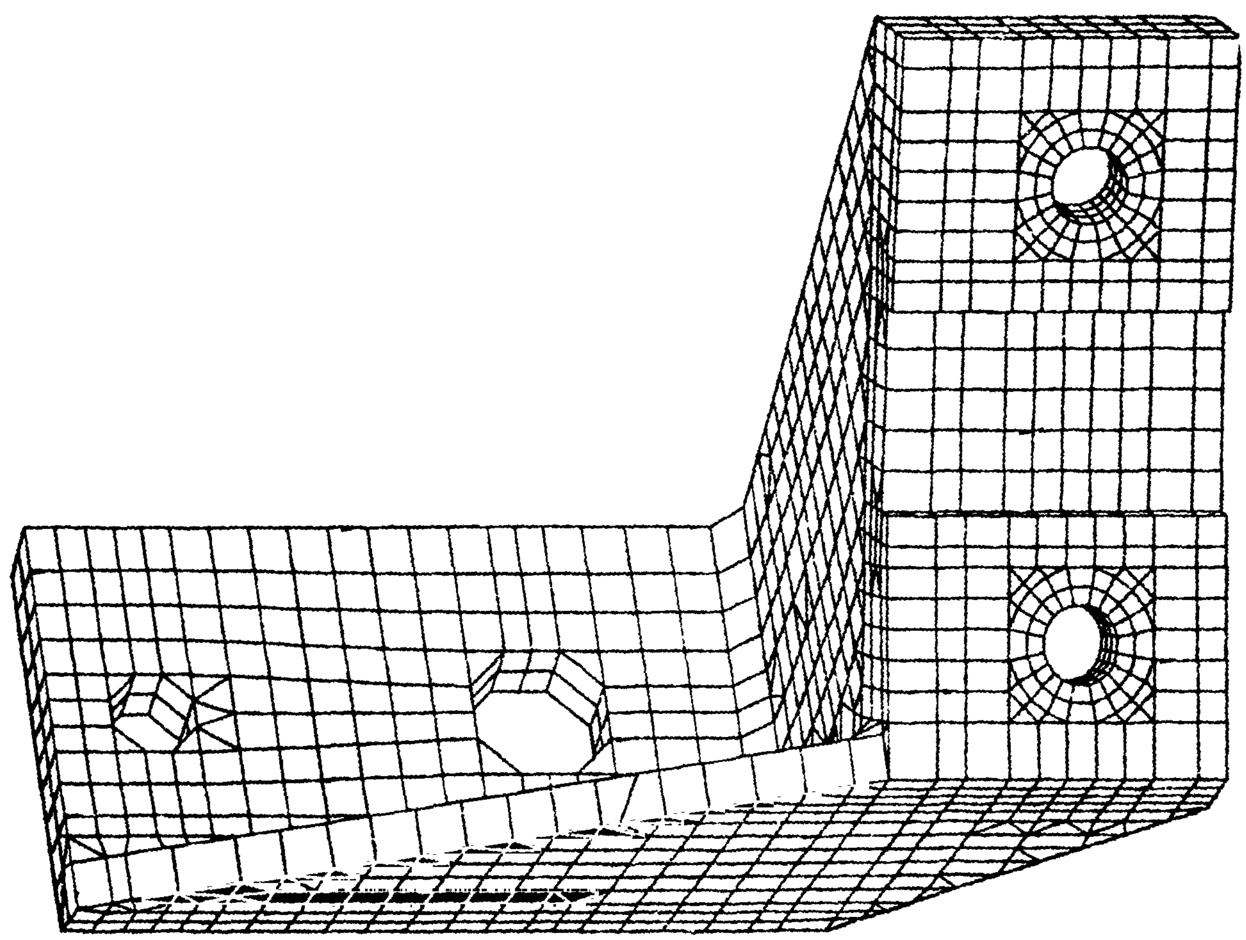
The fifth modification reduced the 3 pairs to the lower 2 pairs on the brace side of SB.
The triplet on the near side of LB was reduced to the lower pair.
The results were admissible!

In summary, the net overall change entailed:
reducing a full 3 pairs of SB brace side to the lower 2 pairs;
reducing a full triplet of LB open side to the upper pair;
eliminating the distant edge line and enabling a pair of points on the brace edge of SB;
moving the LB 270 degree arc on the open side of the nut surface to a 45 degree arc on the brace side of the nut surface;
reducing a full 3 pairs of SB near side to the upper 2 pairs;
reducing a full triplet of LB near side to the lower pair.

This cut and try method was applied to every loading case in order to achieve admissibility. What kept one going was the optimistic certainty that just one more try would bring the constraints into line. And just like Charlie Brown's baseball team something unexpected turned up each time to frustrate the success of the next try. The next three illustrations show the surfaces only of the solid element modelling used for the bracket as viewed from 3 different positions.







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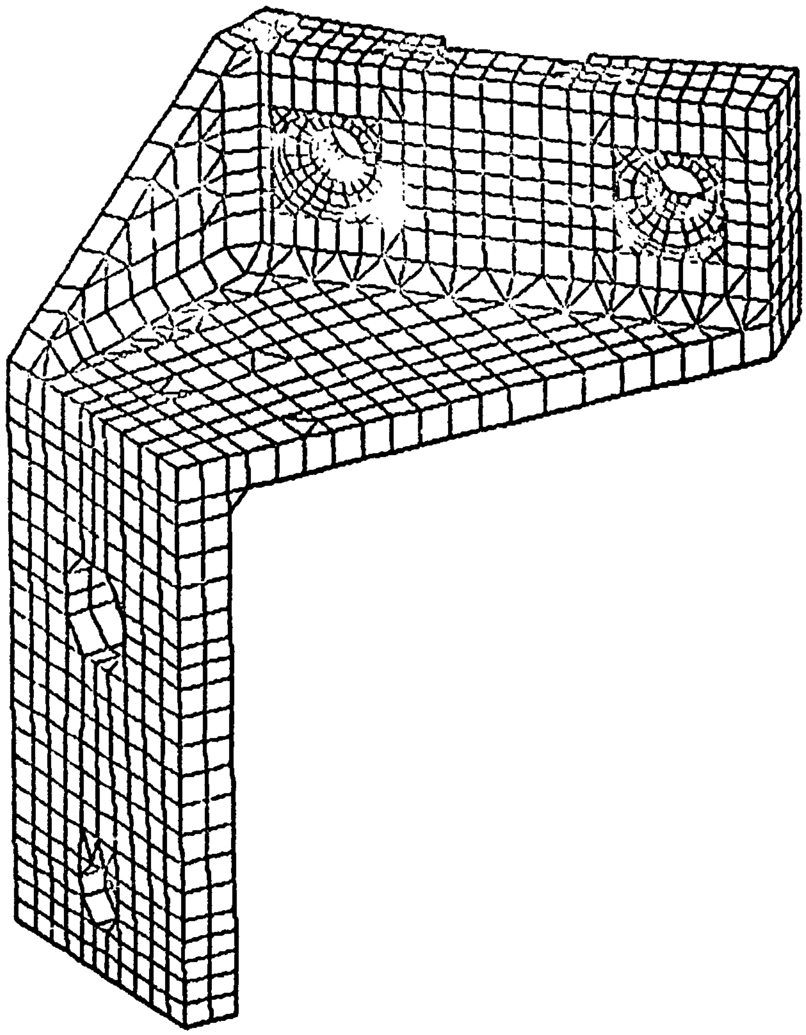
RESULTS

The following illustration shows color contours of stresses from a single loading case.



CONCLUSIONS

In conclusion it is fair to say that the method works and gives reliable results slightly on the conservative side. It still leaves an element of uncertainty as to whether the honed set of constraints is unique, since a reduced set of working locations was used. Some shifting say to intercardinal points might cause some change in the stresses. In spite of this nagging doubt, it claims to be a reasonably good method. It can be tested further by running a set of unidirectional nonlinear springs to obtain a measure of its approximations.

Some comment might be made as to the efficiency of the computing techniques, e.g. Brute Force as was done here which devoted a complete run for every trial. 2. Condensation of all points except boundary candidates with restart of only the modified A-set. 3. Substructuring with a unit substructure assigned to each cluster of boundary points and the bulk to the parent structure. 4. A true nonlinear investigation to recover the magnitudes of the boundary forces for each load case with a companion run of the linear case which would then apply these boundary forces for a lengthy stress recovery phase.

The reason that the Brute Force method was used is that the storage required to implement the other routes taxed the limited resources of the VAX.

The maxim that fits this story is: that whenever the mesh of a model is so fine that a bore can't be represented as a point, one must be prepared for a considerable amount of extra care if the stresses in the region of the boundary are important. In the words of the Great CPU:

HE WHO MESHES FINE,

FINDS A MESH.

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