Evaluating Stresses in Adhesive Bond Lines

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ABSTRACT

Adhesive bond lines are difficult to model in structural analysis because their small dimensions, typically .003 to .010 inches thickness, are so small with respect to the dimensions of a normal structural model that the analyst becomes trapped between computational accuracy and problem size. This paper presents a technique used recently to evaluate the adhesive bonded joints in an aluminum sheet metal structure.

The solution includes an analysis of the important causes of high bond stresses and detail modeling of typical bond line constructions. The paper includes guidelines the author found useful to avoid computational problems in this kind of analysis.

INTRODUCTION

An electronics box was recently designed of adhesive bonded aluminum sheet metal. The advantages this construction were smaller size and reduced weight compared to conventional construction techniques for boxes which need to be sealed against moisture and EMI (the adhesive employed was conductive). Welding and brazing were avoided because the high temperatures in these processes tend to warp some of the features that need to be held to high precision to enhance the cooling of the electronics.

The disadvantages of this design are that adhesive joint strengths are very dependent on the quality of the process controls employed, significant uncertainty in the allowable strength of the adhesive bonds, and the inability to avoid tensile stresses in the design of the bond lines (adhesives are substantially weaker in tension than in lap shear). In order to quantify and control these difficulties it was necessary to perform a detailed analysis of the assembly to determine the anticipated stresses in the adhesive joints.

THE STRUCTURAL MODEL

The electronics box of concern was assembled mostly of thin sheet aluminum panels with lap joints except for the mounting toggle blocks which were bonded to flat portions of the panels away from the edges. The box was designed so the lap joints would see nearly pure lap shear under all load conditions. However this was not possible with the toggle blocks which needed to be recessed from the edges and not exceed specified envelope dimensions. The toggle blocks would see nearly pure tension in the bond line. Figure 1 shows the layout of a typical toggle block location.

A finite element model of the entire box and its contents was made for analysis in MSC/NASTRAN. The model was constructed principally of shell type elements which would allow recovery of the element forces and moments. The element forces could be directly converted into lap shear stresses, knowing the length of the lap joint. A similar procedure was needed to convert element forces or moments into joint tensile stresses under the toggle blocks .

Figure 2 shows a "free body diagram" of the typical toggle block mounting. Simple analysis of the diagram indicates that the tensile stresses caused by the moment in the sheet metal are three or four orders of magnitude larger than the direct tensile stresses caused by a one pound load. Evaluation of the tensile stresses in the toggle block bond lines required the analyst to determine the tensile stresses in the adhesive bond line caused by local moment loads in the sheet metal panels. Since the assembly structural model was constructed of shell type elements is would be possible for the analyst to recover the element moments in the vicinity of the toggle block. It was then necessary to be able to convert this moment to an adhesive bond line tensile stress.

A simple longhand analysis indicated that a reasonable upper bound for the adhesive tensile stress produced by a sheet bending moment of 1.0 lb.-in. per in. would be about 2400 psi. (assuming that the most effective portion of the bond line is about the same width as the thickness of the sheet).

It was decided to make a finite element model of a small portion of the bond line as shown in Figure 3. A unit moment, M (representing the moment in the sheet metal), would be applied to the model and the resulting maximum tensile stress in the adhesive would be calculated. The model would be run a number of times varying the mesh density and length of the lap joint used to determine the optimal model parameters and the resulting maximum tensile stress in the bond line.

THE MESH DENSITY STUDY

Three MSC/NASTRAN finite element models were developed using HEXA(8) elements as shown in Figure 4. All the models had four elements through the thickness of the aluminum sheet and three elements through the thickness of the bond line. The numbers of element used in the length of the bond line were 5, 10 and 20 for the 1st, 2nd and 3rd models respectively.

A simple regression analysis of the average grid point stresses of the first two models indicated a convergence to about 3700 psi., considerably higher than the value of 2400 psi. which had been estimated as a reasonable upper bound (see Figure 5). The results from the third model were even higher. Inspection discloses a reasonable significant trend in these three data points; as the grid point spacing is halved the tensile stress is nearly doubled.

Further investigation of the average grid point stress data resulted in the plots of Figure 6. At positions near the applied load (length = 0 in Figure 6) the average grid point stresses develop a strong oscillation. The oscillation is worse for more refined meshes, and the stress at length = 0 goes up markedly as the mesh is refined. Element stresses show the same general behavior, with the fluctuations being moderated somewhat. Figure 7 shows the distribution of the elements stresses for the 20 element model.

Inspection of the deformed structure plots (Figure 4) and the displacement vector data did not exhibit this oscillating behavior. A regression analysis was performed using the three models and the peak displacement in the bond line. The results are shown in Figure 8. For these data a linear regression seems reasonable and yields a stress value of 1950 psi. for a very fine mesh density. This value is also reasonable with respect to the upper bound estimated to be 2400 psi.

At this point it was decided to try the analysis in a different code, MSC/pal being available. The 10 element model was converted to a MSC/pal input file using the same boundary conditions. Unfortunately, MSC/pal does not have rigid elements so the load was applied as the corresponding nodal forces normal to the surface and parallel to the bond line. The results of this model are shown in Figure 9 (10 elements) and seem reasonably well behaved. The maximum stress is about 1280 psi., significantly lower than either the MSC/NASTRAN displacement regression analysis or the average grid point stresses, except for the 5 element model which showed a peak stress of about 1313 psi.

THE BOND LINE LENGTH STUDY

The MSC/pal model was extended to an overall length of .20 inches with 21 elements. In analysis this model was also well behaved and is shown in Figure 9 with the 10 element model. The peak stress is calculated to be 1129 psi. A plot of the MSC/pal model is shown in Figure 10. The 21 element model was assumed to be sufficiently accurate for out purposes.

APPROXIMATING THE ACTUAL LOAD CONDITIONS

As can be seen in Figure 10 the surface where the load is applied is considerably distorted. In the MSC/NASTRAN analysis this surface included a rigid element which kept the surface planar and of constant thickness under the load. A better simulation of the actual loading conditions may be obtained by extending the aluminum sheet beyond the end of the adhesive bond line and applying the loading at the extension. This change was made in the MSC/pal model by eliminating three columns of bond line elements nearest the loading end. This means that although the whole model will be 21 elements long, the bond line will be only 18 elements long. Based upon the previous results, this will still be acceptably accurate if the results are well behaved.

Figure 11 shows the MSC/pal model with the three columns removed to form a bond line relief. A plot of the bond line tensile stress distribution for this model is shown in Figure 12 and compared with the 21 element solution without the relief. Interestingly, the data appear to exhibit slight oscillations in the tensile stress distribution (similar to the MSC/NASTRAN results) near the loaded end of the model. Knowing this makes it possible to infer modest but observable oscillations in the original MSC/pal runs in Figure 9.

DESIGN SUMMARY

The final analysis of the assembly used the MSC/pal computations. MSC/pal appeared to offer more stable solutions to this kind of problem. The analysis showed large negative margins of safety and predicted failure of the bond lines associated with the toggle blocks. So far, no hardware failures have been reported. The lack of failures is most probably due to large uncertainties over the tensile strength of the adhesive bond line system (an order of magnitude) and the resulting allowable tensile stresses were probably far too conservative. It is felt that the analysis performed was sufficiently accurate and valid.

CONCLUSIONS

In light of the fact that as much time was spent on the evaluation of the bond line tensile stress evaluation as the analysis of the whole rest of the assembly, several suggestions are offered to the analysts interested in this procedure:

1) The time spent doing an initial long hand estimate to bound the problem's probable answers was an indispensable aid in keeping the whole project in budget;

2) Always start with a modest scale model;

3) Always check the results for reasonableness, even small to modest size models may have computational problems that will lead the analyst the wrong direction;

4) Be aware that computational instabilities can occur in data recovery also .

It is realized that this material has described a computational problem without offering any explanations or solution. Under the immediate pressures of completing the engineering project it has not been possible yet to extend the work to the investigative phases. Several interesting avenues of study suggest them selves and in time these will be followed to try to find a way to avoid these problems in the future. For other investigators who may be interested in duplicating and extending the work described here, samples of both the MSC/NASTRAN and MSC/pal data files used in this analysis are included at the end of this paper. As the reader can see the files are modest and the problems are inexpensive to run. The investigative work will be mostly the intellectual processes of interpreting the results and understanding them so the computational procedures may be improved.

MSC/NASTRAN INPUT FILE

```
NASTRAN MESH
ID BOND LINE
SOL 24
TIME 10
RF 24D74
$
CEND
```

```
$
TITLE=BOND LINE, 1.0#-IN/IN, 5 EL.
$
SPC=10
LOAD=10
$
SET 1=111 THRU 115
STRESS=1
$
OUTPUT(PLOT)
SET 1=ALL
FIND SCALE, ORIGIN 1 SET 1
PLOT STATIC DEFORMATION, SET 1, ORIGIN 1
$
BEGIN BULK
$
EGRID,1,
=,2,,2.5,==
=,3,,=,.005,=
=,4,,0.,==
=,5,,=,0.,.055
=,6,,2.5,==
=,7,,=,.005,=
=,8,,0.,==
$
$ BOND LINE.
$
LIST,1,.001667,2,.0125,3
$
GRIDG,1,,,5,-1,-2,-3,
,1,-4,-1,-5,-6,-7,-8
$
CGEN,HEXA8,101,10,1
$
PSOLID,1,1
=,2,2
$
PGEN,10,1,115,2
$
MAT1,1,1.3+6,,.12
=,2,10.+6,,.33
$
$ LOADS AND CONSTRAINTS
$
SPCG,10,1,123456,A,C
=,=,=,2,0100,0714
$
SETG,1,.0305,0615,,RBE2,1,10705,123456,
,1,0715
$
MOMENT 10,10705,,.005,,1.0
$
PARAM,AUTOSPC,YES
$
ENDDATA
```

MSC pal INPUT FILES

(This initial file is for building the model.)

```
TITLE BOND LINE ANALYSIS, ALL SOLID ELEMENTS, WITH RELIEF
C UNITS P,I,S
NOD
1,0,0,-.005
22,.2,0,-.005
44,.2,.005,-.005
23,0,.005,-.005
133,0,0,0
154,.2,0,0
176,.2,.005,0
155,0,.005,0
309,0,0,.05
330,.2,0,.05
352,.2,.005,.05
331,0,.005,.05

NOD 31
1,22,44,176,1,22,44
133,154,176,352,1,22,44

MAT 1.3E+6,0,0,.12
HEXA
ELE 31
1,19,41,173,1,22,44

MAT 10E+6,0,0,.33
ELE 31
133,154,176,352,1,22,44

ZERO 31
RA,1,22,44,352,1,22,44

END
```

(This file is for solving the loading case.)

```
DISP APP 21
TA,0,1,22,44,1,22

DISP APP 31
TY,0,45,66,88,352,1,22,44

FORCE 1
FX,-.03282,330,352
FX,-.03750,286,308
FX,.03750,198,220
FX,.03282,154,176

SOLVE
QUIT
```

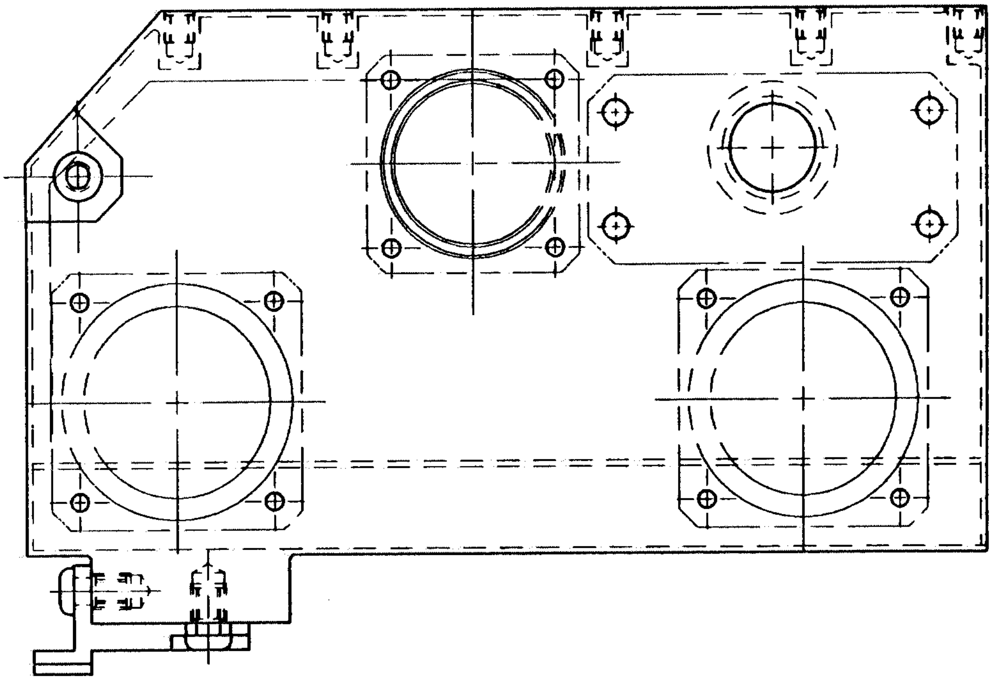


Figure 1. End View of Electronics Box Showing Toggel Block.

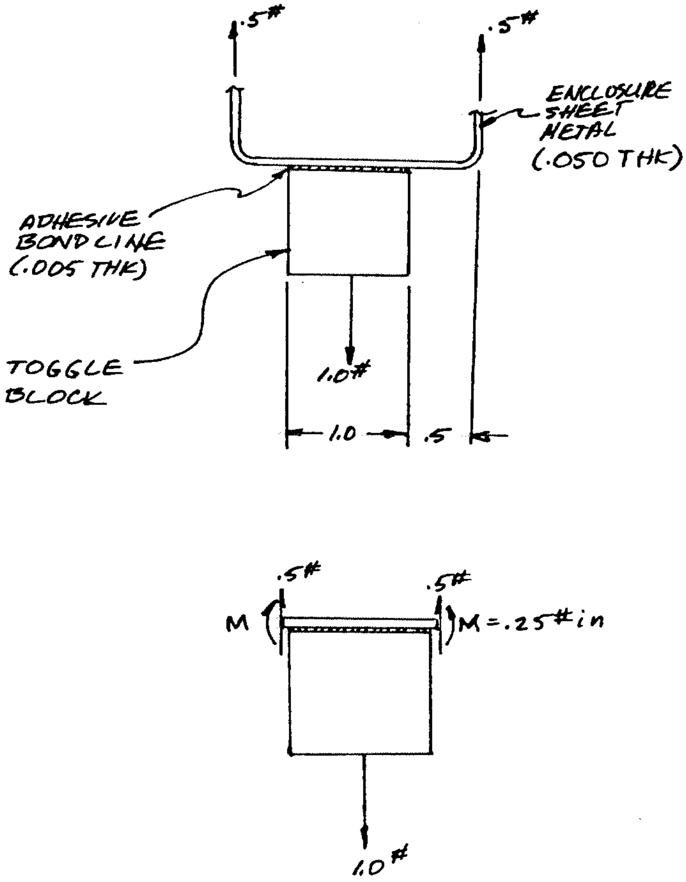


Figure 2. Toggel Block Free Body Diagram.

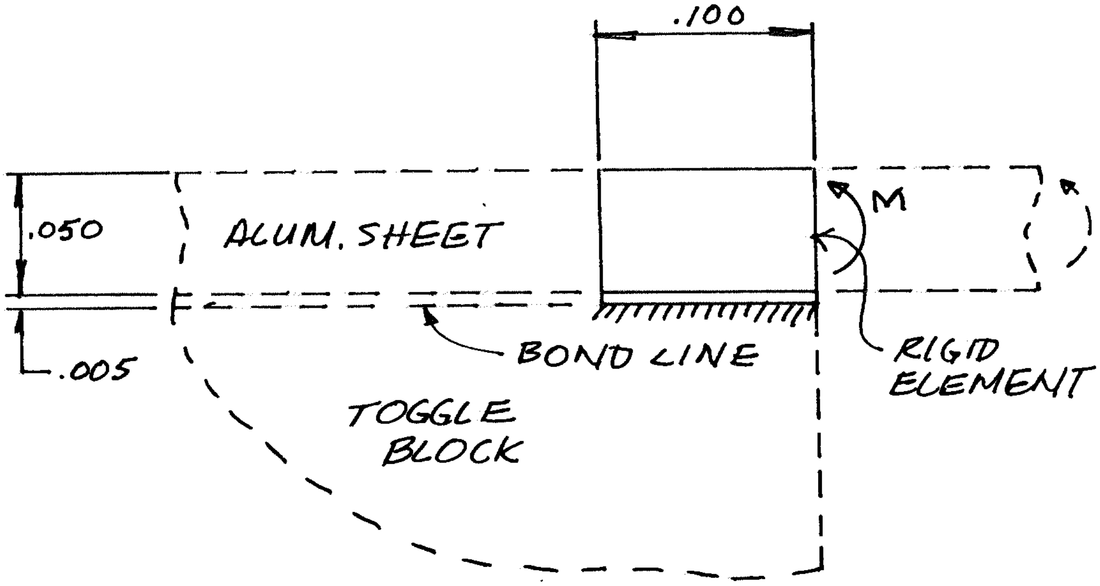


Figure 3. Assumed Boundary Conditions.

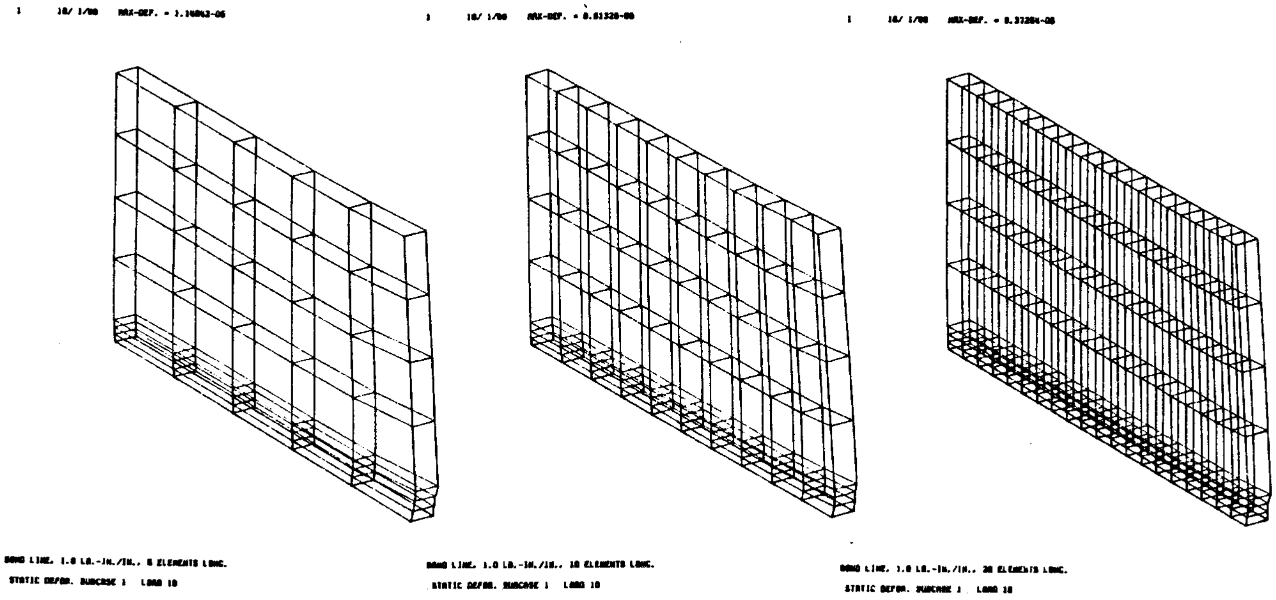


Figure 4. Three MSC/NASTRAN Models.

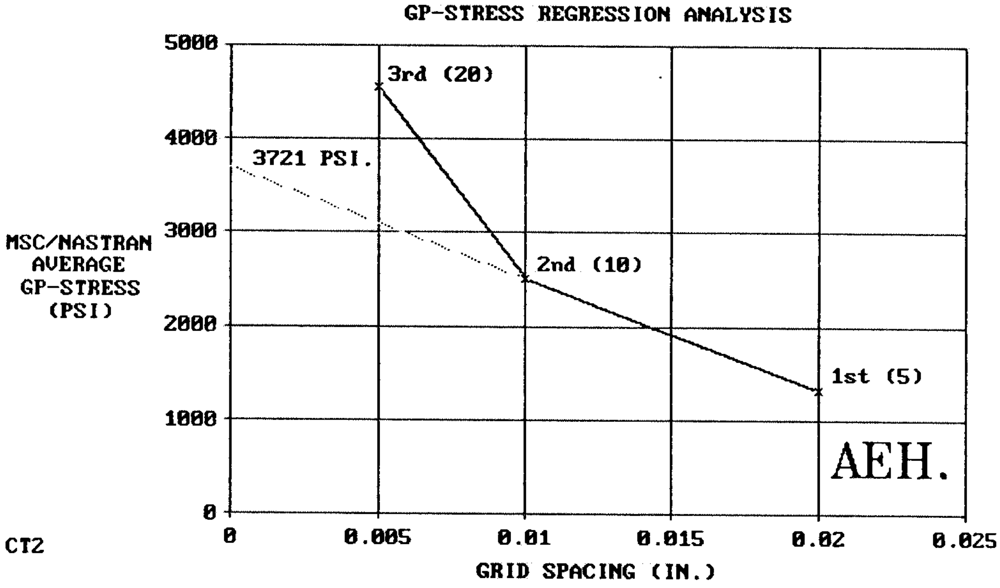


Figure 5. GP-Stress Regression Analysis Curve.

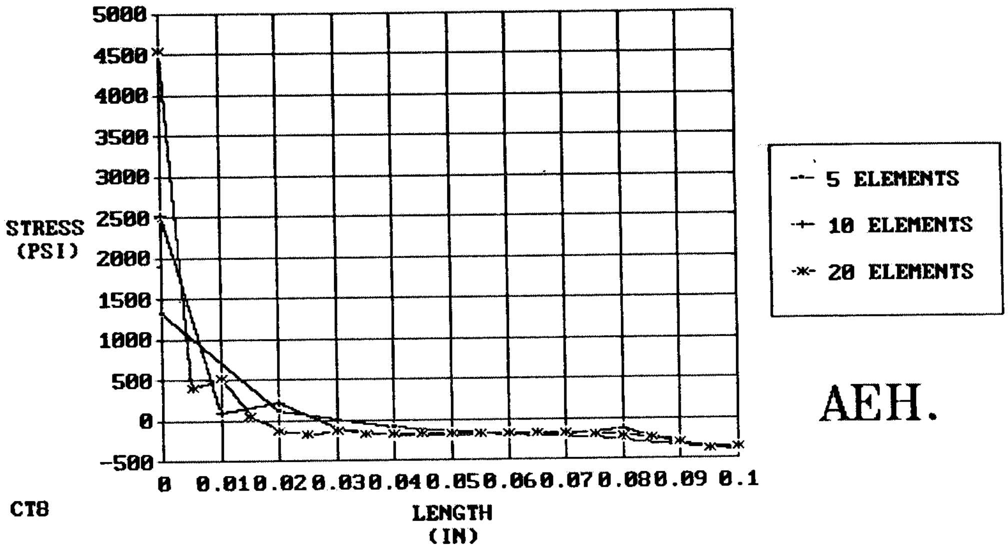


Figure 6. GP-Stress Distribution in Bond Line.

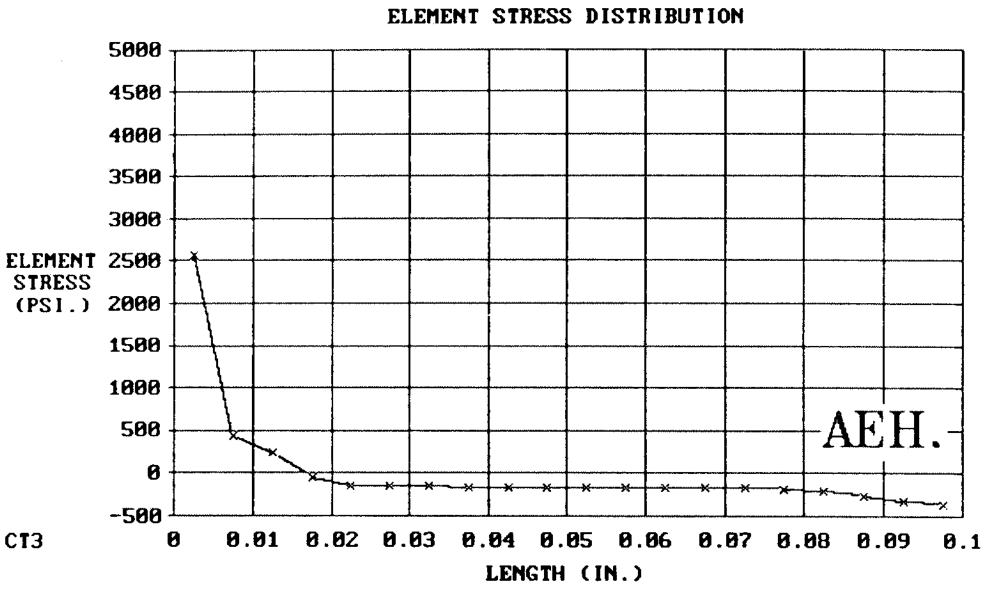


Figure 7. Element Stress Distribution in Bond Line.

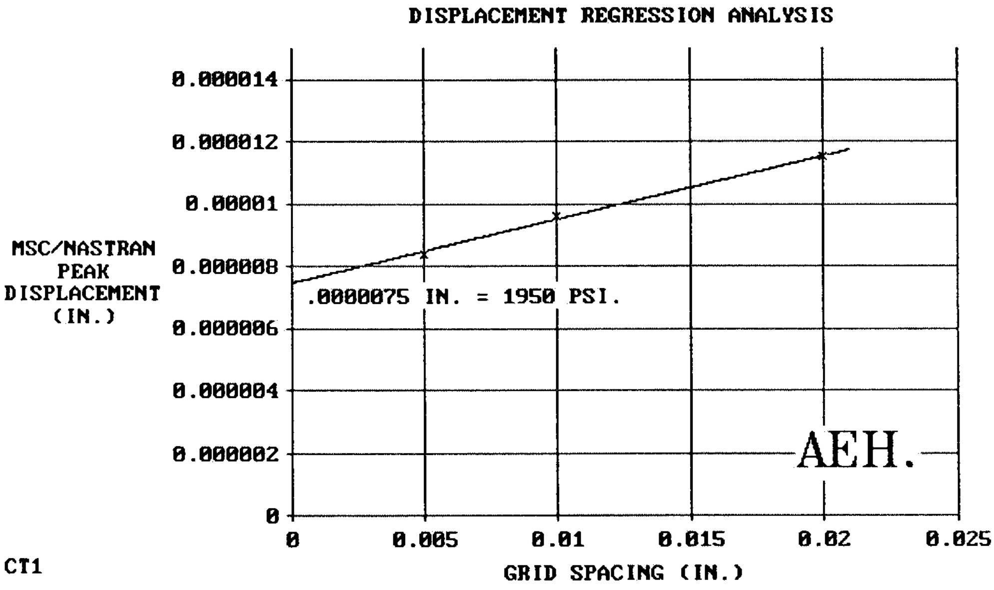


Figure 8. Bond Line Displacement Regression Curve.

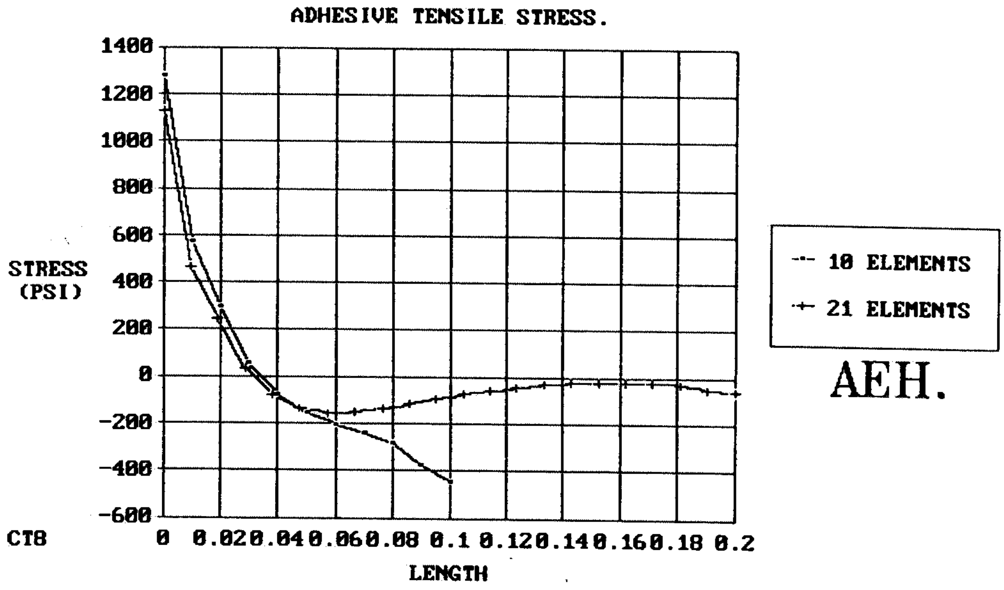


Figure 9. MSC/pal GP-Stress Distribution in Bond Line.

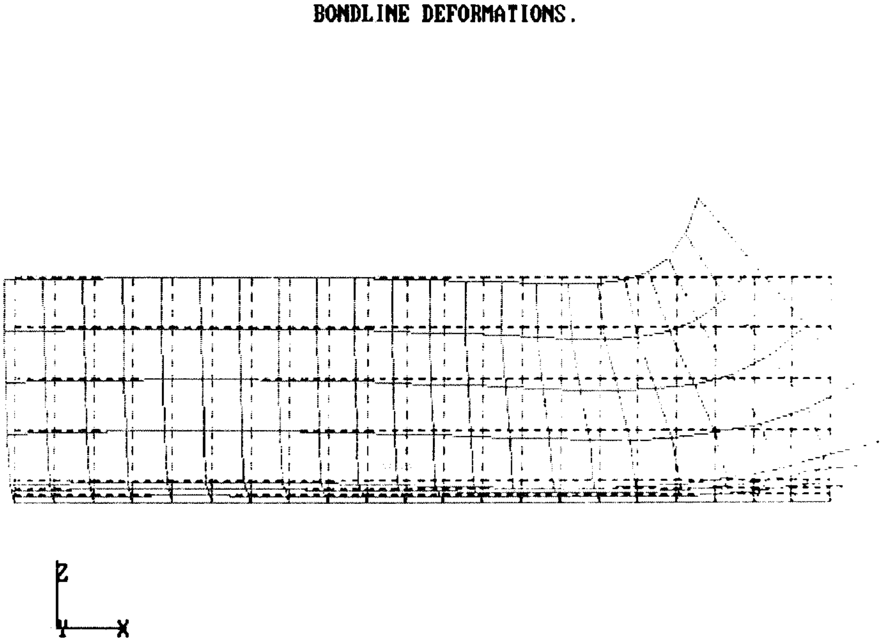


Figure 10. MSC/pal 21 Element Mesh Model

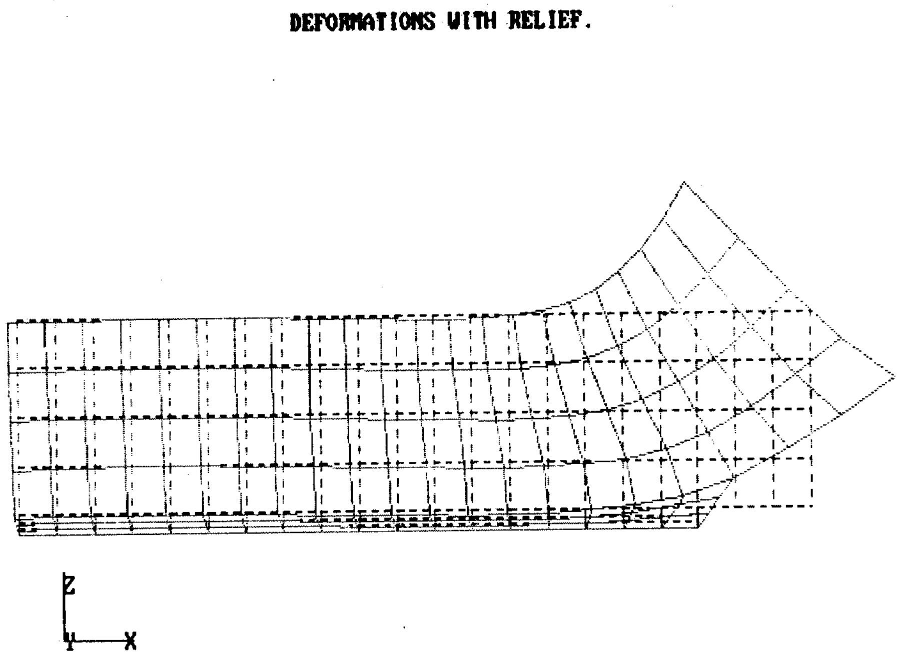
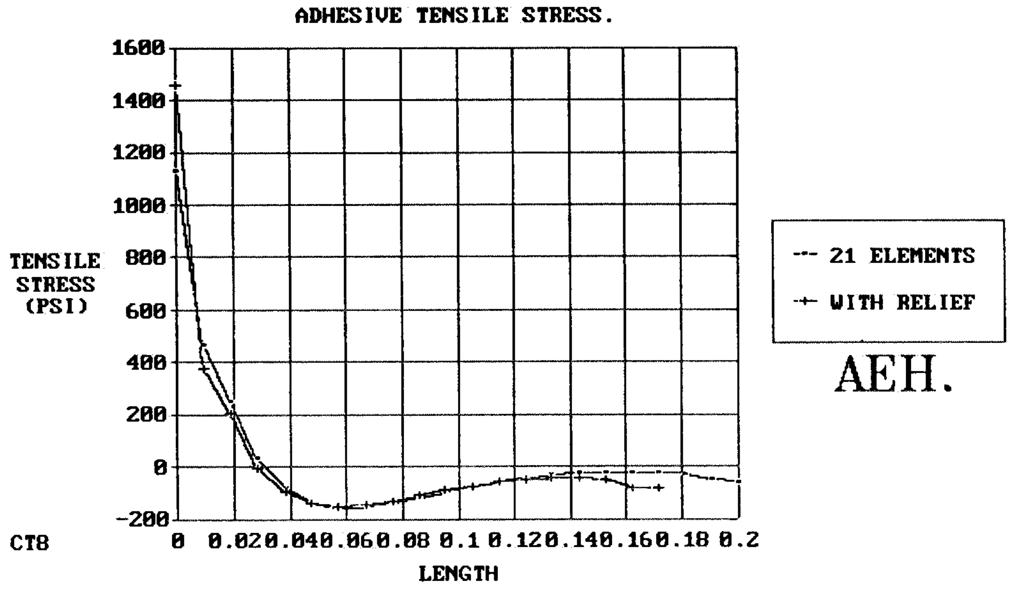


Figure 11. MSC/pal 21 Element Model with Bond Line Relief.



AEH.

Figure 12. MSC/pal GP-Stress Distribution with Bond Line Relief.