NASA Technical Memorandum

NASA TM - 108418

N94-11275

Unclas

G3/39 0176739

(NASA-TM-108418) A STUDY OF STRENGTH EVALUATIONS OF EDNi/EDCu/NARloy-Z BONDED JOINTS (NASA) 27 p

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A STUDY ON STRENGTH EVALUATIONS OF EDNi/EDCu/NARloy-Z BONDED JOINTS

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Science and Engineering Directorate

July 1993

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center

MSFC - Form 3190 (Rev. May 1983)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1993	Technical memorandum

4. TITLE AND SUBTITLE

A Study on Strength Evaluations of EDNi/EDCu/NARloy-Z Bonded Joints

5. FUNDING NUMBERS

6. AUTHOR(S)

J.B. Min and K.L. Spanyer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM - 108418

11. SUPPLEMENTARY NOTES

Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified—Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Dissimilar material interfaces can be found in many materials and structural bonds such as composite materials, welded parts, inclusion in matrix, bond between metallic and ceramic materials, and so forth. One of such structural bonds can be seen in the main combustion chamber (MCC) of the space shuttle main engine (SSME). In this study, from a practical sense, the primary concern is to understand the systems response of EDNi/EDCu/NARloy-Z bonded joints using stress values approximated by the finite element method to determine an influence of the variation of structural bond parameters on the bonded joints, and consequently to support a process control for developing defect-free, strong bonded joints of EDNi/EDCu/NARloy-Z in the main combustion chamber of the space shuttle main engine. The results presented in this study could be an appropriate indicator for a good bond of EDNi/DECu/NARloy-Z layers with the desired thickness of copper deposition in the SSME MCC manufacturing process. Furthermore, the results from this study appear to be applicable to any bonded joints that can be characterized by the parameters and assumptions used in this analysis.

14. SUBJECT TERMS

EDNi/EDCu/NARloy-Z bonded joints, space shuttle main engine, finite element analysis, bonded strengths, bonded parameters, stress concentrations, initial failure

15. NUMBER OF PAGES 28

16. PRICE CODE NTIS

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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A STUDY ON STRENGTH EVALUATIONS OF EDNi/EDCu/NARloy-Z BONDED JOINTS

I. INTRODUCTION

Dissimilar material interfaces can be found in many materials and structural bonds such as composite materials, welded parts, inclusions in matrix, bond between metallic and ceramic materials, and so forth. One of such structural bonds can be seen in the main combustion chamber (MCC) of the space shuttle main engine (SSME). Several manufacturing techniques are used in the MCC fabrication process. One such technique is the electrodeposition of nickel (Ni) onto the NARloy-Z liner to form the structural jacket for the chamber (figs. 1 and 2). At the stage of the liner fabrication, copper (Cu) is electrodeposited onto the NARloy-Z before nickel is applied to prevent hydrogen embrittlement to the nickel. The jacket is a primary load-carrying member, therefore, it is important that the integrity of the bond of these layers with the desired thickness of copper deposition should be maintained. If a greater amount is deposited, failure will occur in the copper layer during hot fire conditions. Too little copper will allow eventual corrosion. Although the well-established fabrication process for the MCC is defined, debonds have often been reported in these EDNi/EDCu/NARloy-Z bonded layers. A failure of these bonds would result in the catastrophic loss of chamber and surrounding hardware. Therefore, this possible consequence has become a concern because of the difficulty in inspecting the quality of the bonds. Any internal debond regions are not detectable by normal nondestructive inspection methods because the materials are in such intimate contact that they appear bonded. The assurance of a good bond, therefore, rests upon process control and proposed pressure proof test/ultrasonic inspection. The pressure proof test is intended to load the bond so that any debond regions that might be present would separate and be apparent to an ultrasonic inspection.

Among approaches to analyze the bonded structures, two really quite different, extreme approaches to mechanical response could be considered. The approach which emphasizes the role of the interface between the different materials of the bonded structures is one extreme approach. The approach in which the role of the interface is, in essence, ignored and an attempt is made to understand composite response in terms of the bulk response of the two phases and a geometry is the other extreme approach. The former approach, by nature, is a molecular or chemical approach. It attempts to link a change in composite response directly and solely to a change in molecular structure at the interface. Molecular structures at the interface, which change the interaction energies between the phases of the composite, act directly and solely to change the mechanical response of that composite. On the other hand, in the latter approach, although the interface is not really totally neglected, it is simply relegated to a status in which it is one of two types—well bonded or poorly bonded. If it is a well bonded interface, meaning that failure does not appear visually to occur there, then its presence is neglected. However, if it is a poorly bonded interface, meaning that it looks as if the failure occurred there, then the response is considered to be determined by the interface and not by bulk mechanical properties. At least from the descriptions of the extreme approaches, it is quite evident that there are aspects of similarity between the two approaches which center on the interface. The main dissimilarities are those which one would expect between the approach of a chemist—molecular structure, interaction energies, bonding[1] and of a mechanical engineer—macroscopic response and fracture. Then, what are the major shortcomings of the two approaches? In the chemical approach, if one is going to point to interface as the source of strength or weakness in a composite, one is going to have to come to grips with the questions of "how strong?" and "how weak?" That is, one is going to have to develop means to describe quantitatively the relationship between interface structure and composite mechanical response, including ultimate strength, in whatever mode of failure. On the other hand, approaches which solely address the bulk behavior of the elements of the composite are limited in the ability to produce true descriptions of response because the focus is on a single aspect of response. As known, one cannot always consider bond joints to be "simple" composite structures only of a few bulk solid phases. To approach the development of an understanding of its response by focusing on a single factor is not productive unless one can justify eliminating other factors from consideration. Unfortunately, it is not often possible.

In this study, from a practical sense, the structural response in a system is the primary concern. That is, it is concerned with describing, explaining, and finally understanding how the response of the individual, not necessarily independent, parts of the system interact to determine response of the system as a whole. The primary purpose of this study was, therefore, to understand the systems response of EDNi/EDCu/NARloy-Z bonded joints using stress values approximated by the finite element method to determine an influence of the variation of structural bond parameters on the bonded joints and consequently to support a process control for developing defect-free, strong bonded joints of EDNi/EDCu/NARloy-Z in the MCC of the SSME. Specifically, the main objectives of this analysis were: (1) to identify weaker interface layers, (2) to determine the effect varying bonding structural parameters, i.e., bond lengths and bond thicknesses, on joint stresses, and (3) to determine the best selection of bonding parameters by measuring bond strengths with various bonding structural parameters in terms of the Von Mises yield failure criteria.

II. METHODS AND MATERIALS

For practical reasons, the designer usually attempts to load bonds in shear. As a consequence, the most commonly used bond test is the lap shear test. It is also generally known from the studies of adhesive bonded joints[2 3] that failure in an adhesive joint can occur in one of two ways: (1) adhesive failures that occur at the interface between the adhesive and adherents, and (2) cohesive failures, which occur either in the adhesive or in the adherents. With this background of bonded joints, the plane strain finite element models of EDNi/EDCu/NARloy-Z joints similar to the adhesive bonded joints were generated for the analysis using FRANC (FRacture ANalysis Code).[4] Based on the observations from the analyses of adhesive bonded joints, the stresses near the bond terminations have particularly been concentrated on. All the specimens for lap joints were modeled with EDNi thickness of 0.174 in and NARloy-Z thickness of 0.044 in. The bond lengths (i.e., overlap length in lap joints) and bond thicknesses modeled for this study are shown in table 1. The physical configurations of the lap joint are shown in figure 3 and the representative element configuration is shown in figure 4. The density of the elements varies as indicated in figure 4, the pattern being adopted to account for the stress gradient at EDNi/EDCu and EDCu/NARloy-Z interfaces. The thickness of EDCu was divided into 5, 10, and 15 layers of elements using the same element aspect ratio corresponding to the variation of the EDCu thickness. The existence of stress gradients through the thickness of the EDCu layer and its interfaces with EDNi and NARloy-Z layers were examined with these thin element layers.

The constant pressure loads were applied as illustrated in figures 3 and 5 for the loading conditions.

Most of the previous studies on the adhesively bonded joints do not address the fact that the deformations and stresses in a joint depend on the type of boundary conditions used. Recently, the influence of boundary conditions in a single lap joint were investigated by Reddy and Roy.[5] The geometrical boundary conditions suggested by them were taken for a single lap joint in this analysis. Axial displacements and transverse displacements of one end of specimens were set equal to zero to simulate a clamped end, and transverse displacements of the other end were set equal to zero. Illustrations for the boundary conditions are shown in figure 5.

Linear elastic conditions for materials were assumed, and the following material properties were used:

For EDNi

Young's Modulus (E) = 26.1×10^3 ksi
Shear Modulus (G) = 7.975×10^3 ksi
Poisson's Ratio (ν) = 0.264.

For EDCu

Young's Modulus (E) = 18.8×10^3 ksi
Shear Modulus (G) = 6.94×10^3 ksi
Poisson's Ratio (ν) = 0.355.

For NARloy-Z

Young's Modulus (E) = 18.4×10^3 ksi
Shear Modulus (G) = 6.8×10^3 ksi
Poisson's Ratio (ν) = 0.33.

In general, the nodal stresses by the finite element methods are determined by first computing the stresses at the integration points closest to the nodes and then to extrapolating those results out to the nodes. This extrapolation is usually done using a bilinear or trilinear least squares curve fitting procedure. In addition, nodal stresses are computed through a process of averaging the component stresses as well as the combined stresses at nodes used by more than one element. Therefore, the average stresses may or may not be accurate due to these approximations, particularly in the joints bonded with dissimilar materials. Thus, in this study the stresses at the integration points of the elements close to the region of bondlines were calculated to avoid such questions in nodal stress calculations of the bondlines. Five different levels were taken to reduce the error of approximations in predicting stresses of the bondlines: (1) above (level 5) and below (level 4) of an interface of EDNi/EDCu, (2) centerline (level 3) of EDCu, and (3) above (level 2) and below (level 1) of an interface of EDCu/NARloy-Z. Illustration of these levels is shown in figure 6.

In determining a bond strength, it was assumed that failure is reached when the peak stress reaches a critical level and that there is purely elastic behavior up to the point of failure.[6–8] This is equivalent to saying that failure will occur when the stress or strain reaches a particular value (yield stress or strain). Failure initiation in materials is usually a localized phenomenon that is more dependent on maximum stresses (or energy) at a point reaching some critical value than on the average induced values. In this analysis, the Von Mises equivalent stresses were used for considering the bond strengths. The equivalent stress, s_e , indicates the magnitude of the multiaxial stress state along the interfaces. Based on Mises criterion, the joint strengths under combined loading conditions were predicted by the strength criterion corresponding to EDNi, EDCu, and NARloy-Z materials:

$$F_i = (\sigma_x^2+\sigma_y^2-\sigma_x\sigma_y+3\tau_{xy}^2)^{1/2}/\sigma_y i = 1.0 \quad (i = 1,2,3) \ ,$$

where $\sigma_y 1$, $\sigma_y 2$, and $\sigma_y 3$ denote the yield stresses of EDNi, EDCu, and NARloy-Z, respectively.[9] With these assumptions, the loads to reach a yield stress of the materials were calculated and used to determine the bond strength with respect to the variation of the bond lengths and bond thicknesses. In this study, the typical yield stresses at the room temperature (70 °F) were used for each material:

$$\sigma_{yd}(\text{EDNi}) = 66.0 \text{ ksi}, \ \sigma_{yd}(\text{EDCu}) = 24.9 \text{ ksi, and } \sigma_{yd}(\text{NARloy-Z}) = 22.6 \text{ ksi.}$$

The following are the results of stress analysis and strength prediction obtained through the system described above.

III. RESULTS AND DISCUSSIONS

The axial (σ_x), normal (σ_y), and shear (τ_{xy}) stresses at the levels (fig. 6) were plotted in figures 9 to 23 along a bond length from the left-side bond termination (EDNi/EDCu) to the right-side bond termination (EDCu/NARloy-Z). In these figures the stresses were normalized (non-dimensionalized) by dividing by the applied stress.

First, the results from the models of different bond lengths with the same bond thickness are discussed. As expected, the stresses change radically as the bond termination is approached. The stress concentrations of axial stresses at the bond terminations of EDNi/EDCu and EDCu/NARloy-Z layers can be observed in figures 9, 12, and 15. The stress concentration along with its associated moment is seen to be diminished by increasing the overlap. A shorter bond (0.25 in) produces higher stress concentration at the bond terminations. As illustrated in figure 7, the maximum stresses are influenced greatly by a bending moment induced, just outside the overlap, by the eccentricity in the load path.

The normal stresses along the bondlines indicate in figures 10, 13, and 16 that stress concentrations occur only at an EDNi/EDCu termination. It is also observed in these figures that longer bonds (0.50 and 0.75 in) produce less stress concentrations at the bond termination. This tendency was also observed in the shear stresses as shown in figures 11, 14, and 17.

Second, the results from the models of different bond thicknesses with the same bond length are discussed. In figures 18, 12, and 21, the axial stresses along the interfaces (levels 1 to 5) for different thicknesses of EDCu layer were plotted. From these figures, it was observed that the stress concentrations occur at the bond terminations and an interface of EDNi/EDCu is the most stressed layer. Also, it was indicated that a thinner thickness of EDCu (0.003 in) produces higher stresses compared to the cases of 0.006- and 0.009-in thicknesses. It is noted that the difference of axial stresses from 0.006- and 0.009-in cases may almost be negligible.

The distributions of normal stresses for these cases are shown in figures 19, 13, and 22. As observed earlier from the variation of bond lengths, the normal stresses are less than the axial stresses, and only a bond termination of EDNi/EDCu yields the stress concentration. The shear stresses obtained from these cases (bond thicknesses variation) also show the same tendency in figures 20, 14, and 23 like the cases of bond lengths variation.

It was observed in all the cases that the axial stresses are greater than the normal stresses and shear stresses. It was also indicated that the tearing (normal) stresses are more severe than the shear stresses. As expected, the stress behaviors become the singular form as the bond terminations are approached. In much of the literature on linear elastic analyses of lap joints, the stress concentration factor at the bond terminus has been discussed. When linear elastic analyses are used and the bond terminus not rounded off, the stress concentration factor is infinity because of the stress singularity at this point.

From the observations discussed above, the upper left corner of EDNi/EDCu interface is prone to initial failure due to predominantly bending under eccentric load path or severe peel stresses (fig. 8). Therefore, the bond strengths with respect to the variation of bond lengths and bond thicknesses are discussed and compared at this location. However, whether stress concentrations for the initial bond geometry actually control debond initiation is open to question since inherent flaws such as bondline voids could exist in the high stress areas that are larger than the entire singularity region. If inherent flaws are ignored, the problem of bond termination singularities could be avoided entirely by using properly contoured bond termination fillets and rounded edges.

From the procedures mentioned in section II about the bond strength measurement, the bond strengths were calculated for the variation of bond (EDCu) thicknesses (i.e., 0.003, 0.006, and 0.009 in). The results were summarized in table 2. From the table, it was observed that a thicker bond (0.009-in EDCu) is stronger than thinner bonds (0.003- and 0.006-in EDCu). Also, the results for the variation of bond lengths were summarized in table 3. It was observed that a longer bond (0.75-in long EDCu) is stronger than shorter bonds (0.25- and 0.50-in long EDCu).

Although the observations mentioned above on bond characterization has been confined to static analyses, the equally important problem is the fatigue performance of bonded joints. A related factor is the decrease in residual bond strength with age and environmental exposure. Also, any influence of EDCu ductility was confined to assume that the failure occurs near the yield line. Consequently, it appears likely that the static strength capacities of the bond joints cannot be fully utilized without experimental evidence. Therefore, the design process accounts for this variation in structural behavior during service life.

IV. CONCLUSIONS

The numerical analysis described in this analysis placed particular emphasis on the regions very close to the bond terminations and interfaces since it is in these regions that failure is generally thought to originate. The overall bond failure involves many nonlinear effects and material properties to be determined experimentally. However, in a practical sense, the results presented in this analysis to determine response of the system as a whole could be an appropriate indicator for a good bond of EDNi/EDCu/NARloy-Z layers with the desired thickness of copper deposition in the SSME MCC manufacturing process by reducing the peak stresses and adjusting the influential variables. Furthermore, the results produced from this study appear to be applicable to any bonded joints that can be characterized by the parameters and assumptions used in this analysis.

Based on the results presented, the most important conclusions to be drawn from this study for the EDNi/EDCu/NARloy-Z bonded joints are summarized as follows:

(1) It was observed from the joints considered in this study that the weakest location is the upper left corner of EDNi/EDCu interface. This evidence indicates that significant EDNi yielding occurs prior to EDCu failure. In other words, the initial failure is likely induced by the EDNi and not EDCu.

(2) Another aspect of the bond characterization is an influence of the EDCu thicknesses. Generally, very thin layers represent obvious weaknesses, while excessively thick layers are usually found to be inferior because of excessive voids. In MCC design, thicknesses of EDCu layer have been observed at about 0.003- to 0.009-in thick. The phenomenon associated with the EDCu thicknesses indicates that thinner EDCu aggravates the joint stresses at the end of the overlap, and the bond strengths are less severely affected by thicker EDCu.

(3) The third phenomenon is associated with the bond lengths (overlap lengths in single overlap joints). The moment induced at the ends of the overlap are reduced as the overlap is increased, so increasing the overlap can significantly increase the joint strength. It is apparent that higher EDNi and NARloy-Z bendings impose greater stress concentrations at the end of overlap than do low bendings. Therefore, it is evident that extremely great overlap is to approach the maximum bond strength for the joints. In other words, lap length (bond length) is a significant influence on the bond strength.

Although the bond strengths for different bond parameters are consequently analyzed in terms of an effective linear elastic stress, it is recognized that more experimental work remains to be done in this field. Therefore, it is most important to mention that with these conclusions the above findings must be correlated by experiments.

REFERENCES

1. Liang, F., and Dreyfus, P.: "Durability of Adhesive Bonds between Glass or Metal Substrates and a Polybutadience-Polyuretanes." J. of Applied Polymer Science, vol. 29, 1984, pp. 3147–3159.

2. Goland, M., and Reissner, E.: "The Stresses in Cemented Joints." Appl. Mech., vol. 1, 1944, pp. A17–A27.

3. Adams, R.D., and Peppiatt, N.A.: "Stress Analysis of Adhesively Bonded Lap Joints." Strain Anal., vol. 9, 1974, pp. 185–196.

4. FRANC code: Fracture Analysis Consultants, Inc., Ithaca, New York, 1992

5. Reddy, J.N., and Roy, S.: "Nonlinear Analysis of Adhesively Bonded Joints." Int. J. Nonlinear Mechanics, vol. 23, No. 2, 1988, pp. 97–112.

6. De Bruyne, N.A.: "The Measurement of the Strength of Adhesive and Cohesive Joints." Adhesive 12, Elsevier Publishing Company, 1962.

7. Crocombe, A.D.: "A General Bonded Joint Peel Analysis." Proc IMechE Conf. on Structural Adhesives in Engineering, MEP Ltd, 1986.

8. Bigwood, D.A., and Crocombe, A.D.: "Bonded Joint Design Analysis." Adhesion 13, Elsevier Applied Science Publishers, 1989.

9. Ikegami, K., and Sugibayashi, T.: "A Method of Estimating the Strength of Adhesive Bonded Joints of Metals." J. Adhesion, vol. 21, 1987, pp. 211–227.

Table 1. Cases modeled for variation of bonding parameters.

Cases	Parameters				
	L (in)	$t1$ (in)	$t2$ (in)	$t3$ (in)	d (in)
Bond Length (d) Variation	3.0	0.174	0.006	0.044	0.25
	3.0	0.174	0.006	0.044	0.50
	3.0	0.174	0.006	0.044	0.75
Bond Thickness ($t2$) Variation	3.0	0.174	0.003	0.044	0.50
	3.0	0.174	0.006	0.044	0.50
	3.0	0.174	0.009	0.044	0.50

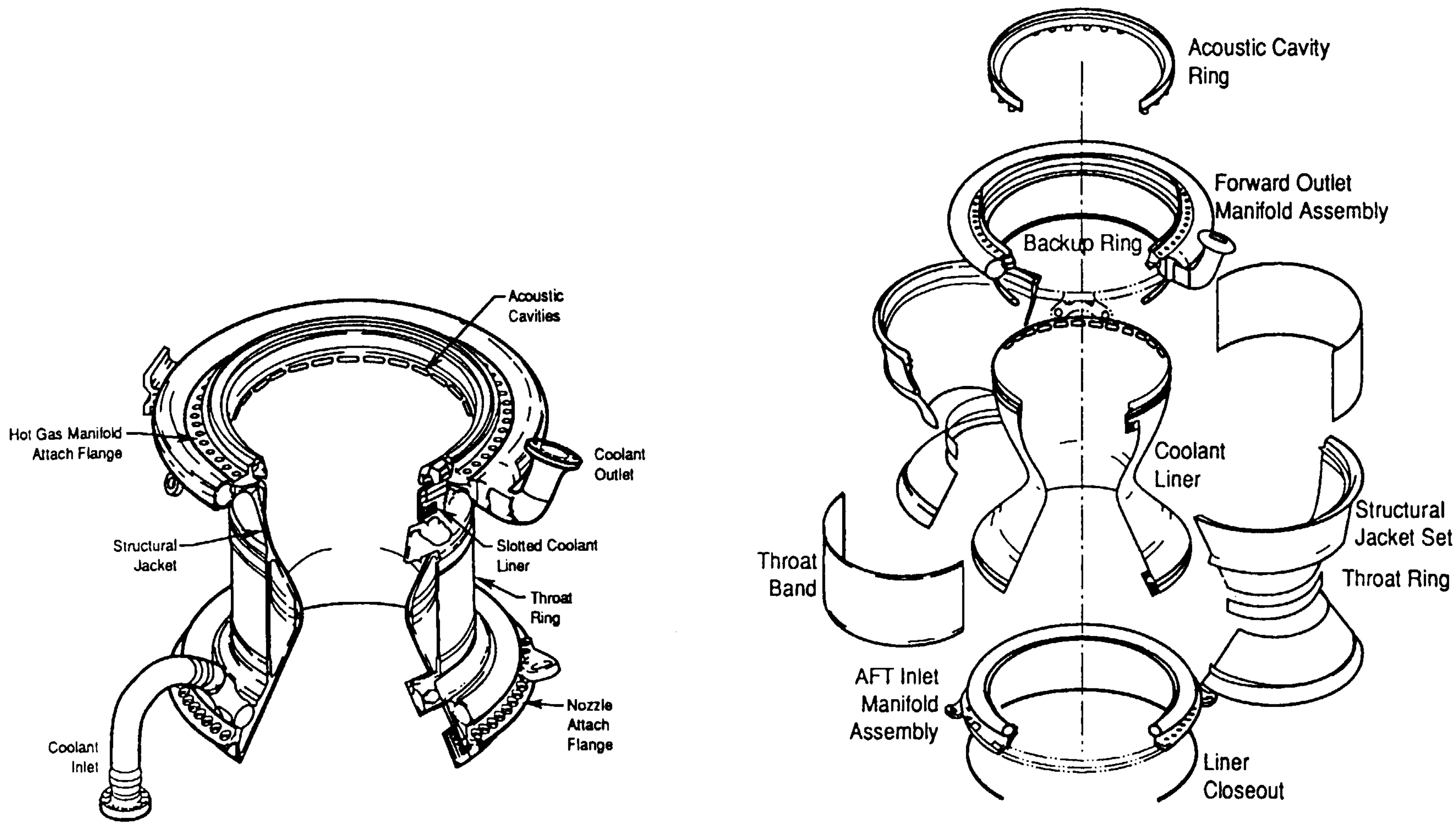
Table 2. Bond strengths to variation of bond thicknesses.*

Bond Strength (lb)	$t2$ (in)					
	0.003		0.006		0.009	
	Location (in)					
	$x = 0.0$	$x = 0.025$	$x = 0.0$	$x = 0.025$	$x = 0.0$	$x = 0.025$
Level 4	1,016.58	0.0	653.456	0.0	1,437.603	25.785
Level 5	0.0	0.0	0.0	0.0	0.0	73.897

Table 3. Bond strengths to variation of bond lengths.*

Bond Strength (lb)	d (in)					
	0.25		0.50		0.75	
	Location (in)					
	$x = 0.0$	$x = 0.025$	$x = 0.0$	$x = 0.025$	$x = 0.0$	$x = 0.025$
Level 4	266.956	0.0	653.456	0.0	787.407	28.097
Level 5	0.0	0.0	0.0	0.0	0.0	0.0

* Bond strength is the remaining strength to reach up to the yield stress of materials.



Main Combustion Chamber

Exploded View of MCC

Figure 1. Fabrication of the SSME MCC.

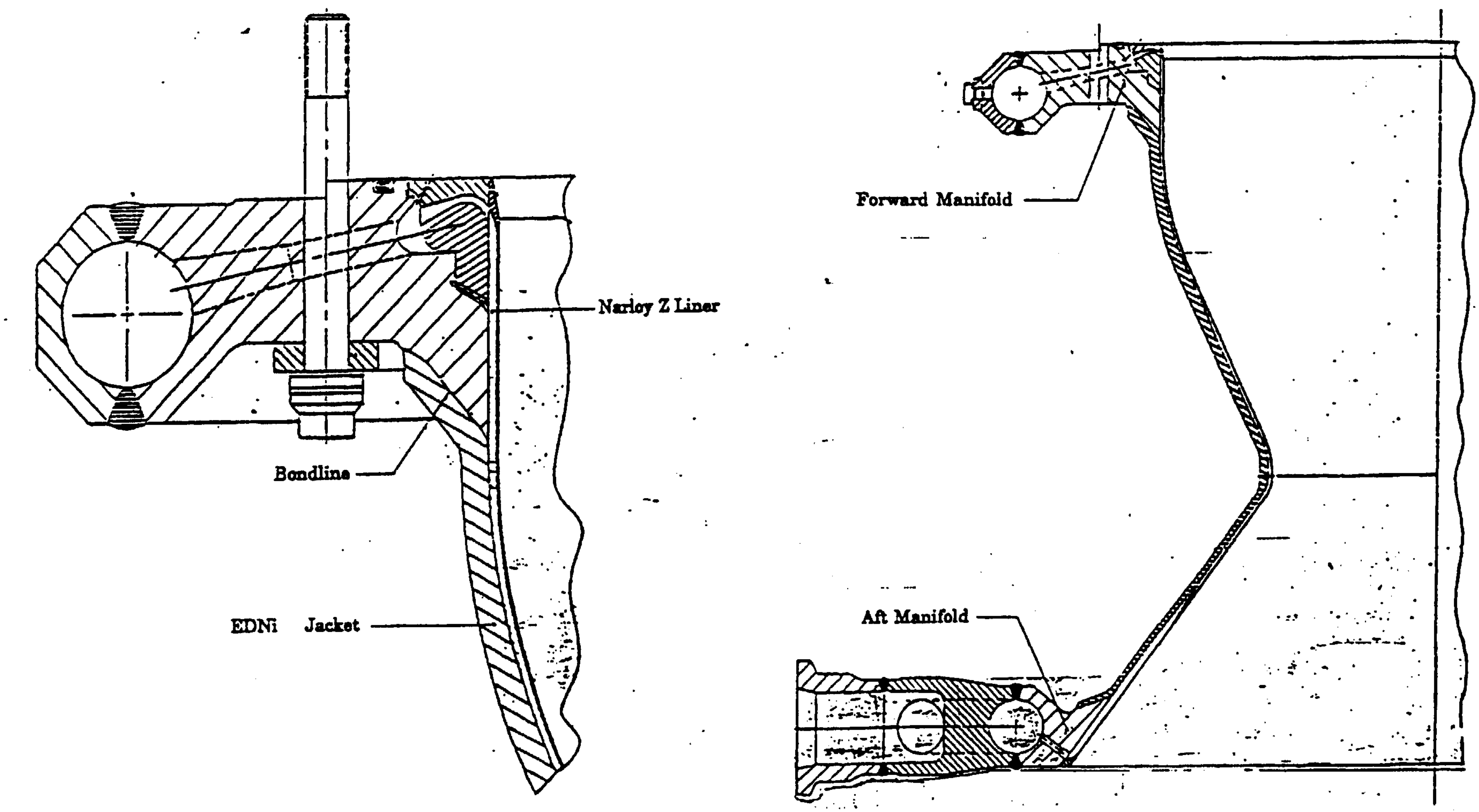


Figure 2. Close view of bonded area.

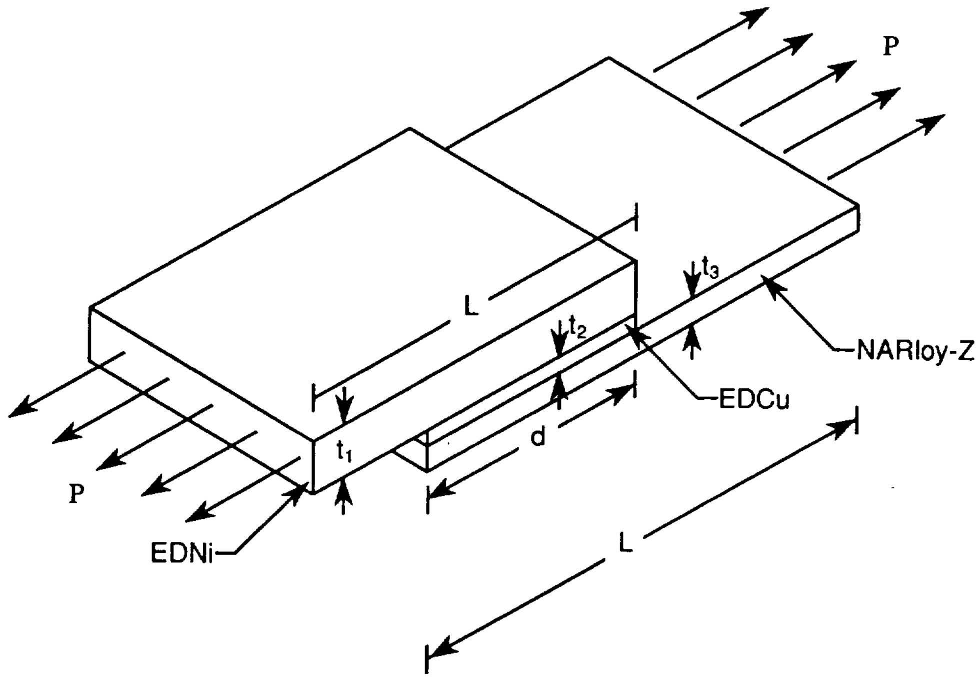


Figure 3. Diagrammatic lap joints to show bond layers.

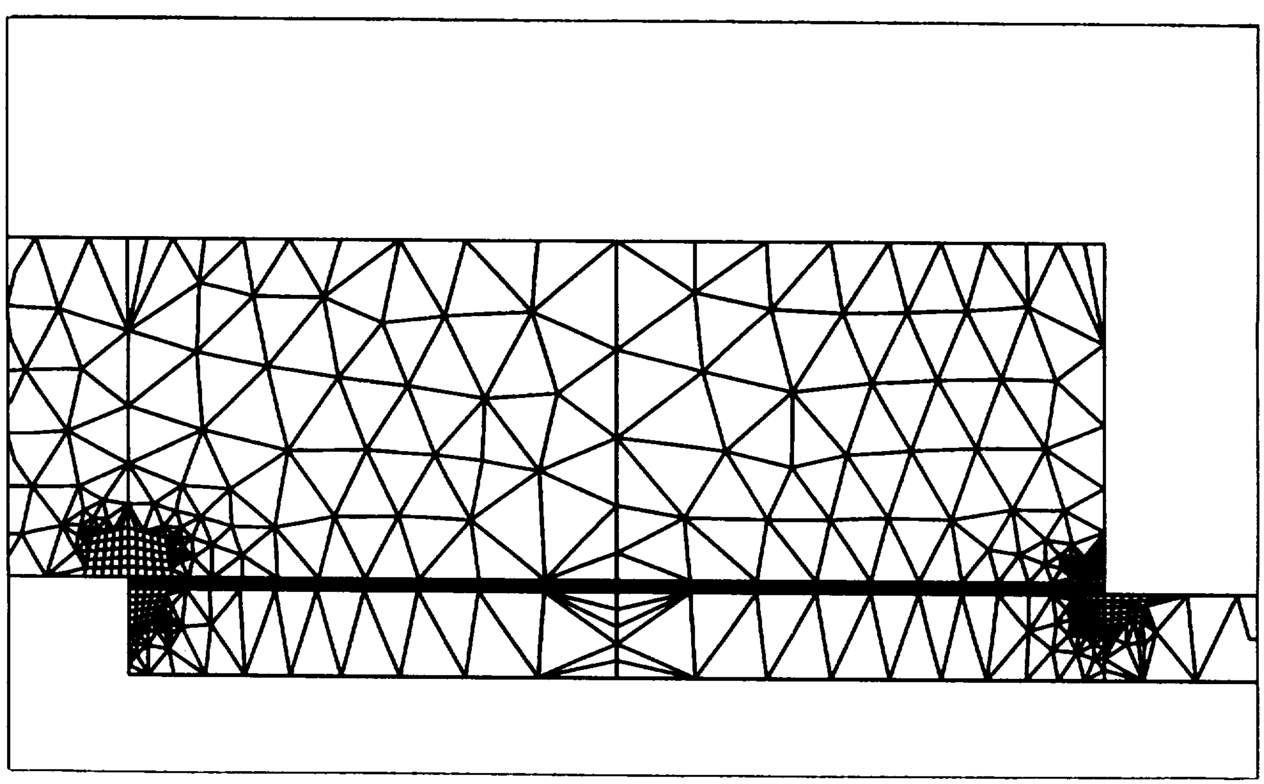


Figure 4. Finite element configuration.

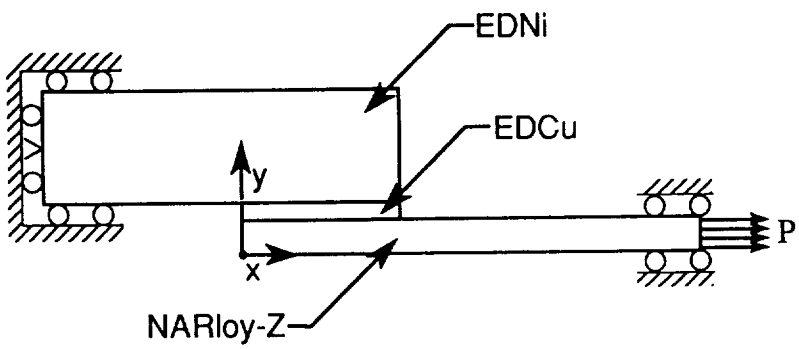


Figure 5. Boundary condition for models.

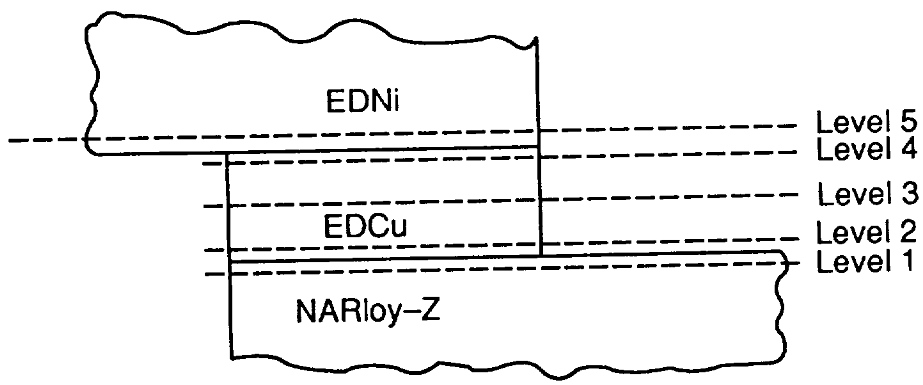
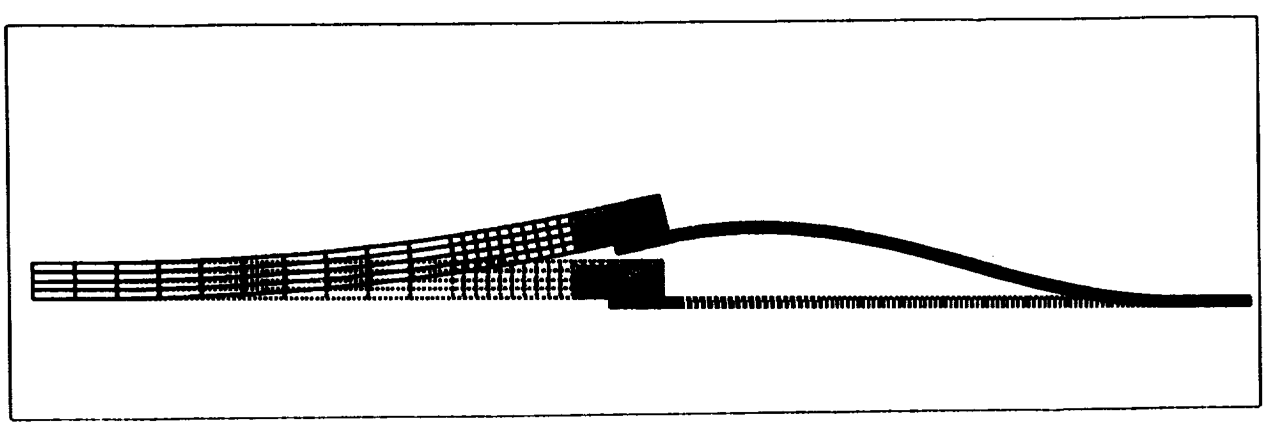


Figure 6. Different levels in predicting stresses of bondlines.



Magnification factor: 295.8

Figure 7. Deformed shape versus original shape.

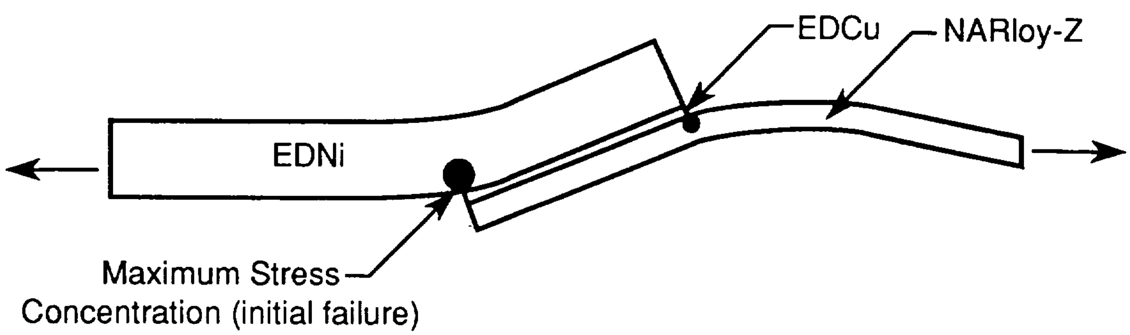


Figure 8. Initial failure predicted by single lap joint of EDNi/EDCu/NARloy-Z.

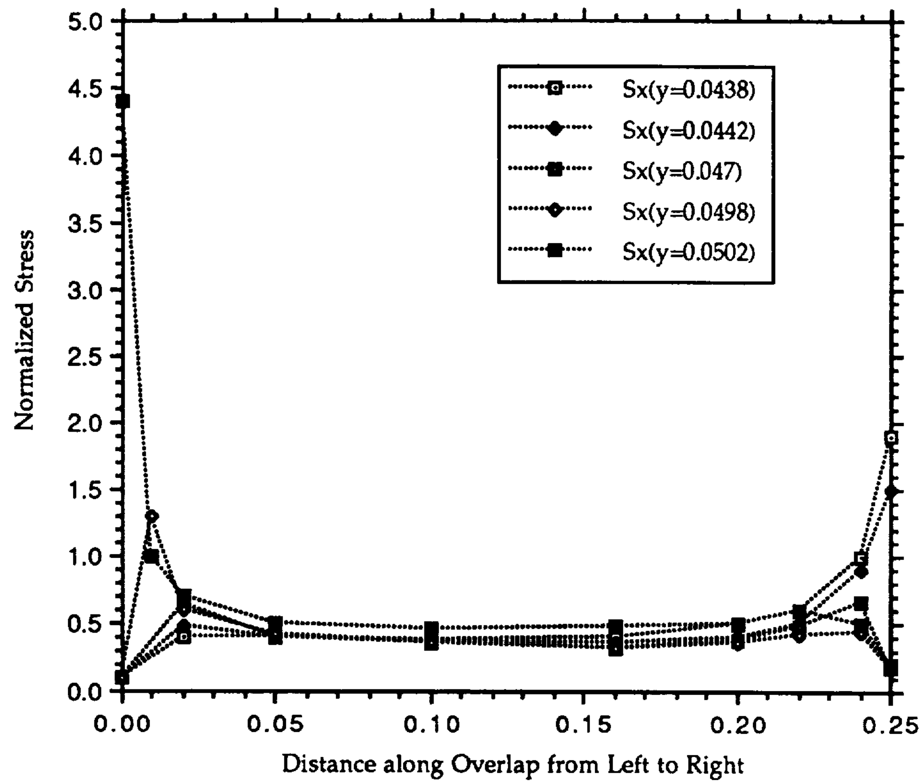


Figure 9. σ_x along different levels of bondline (d = 0.25 in, t_2 = 0.006 in).

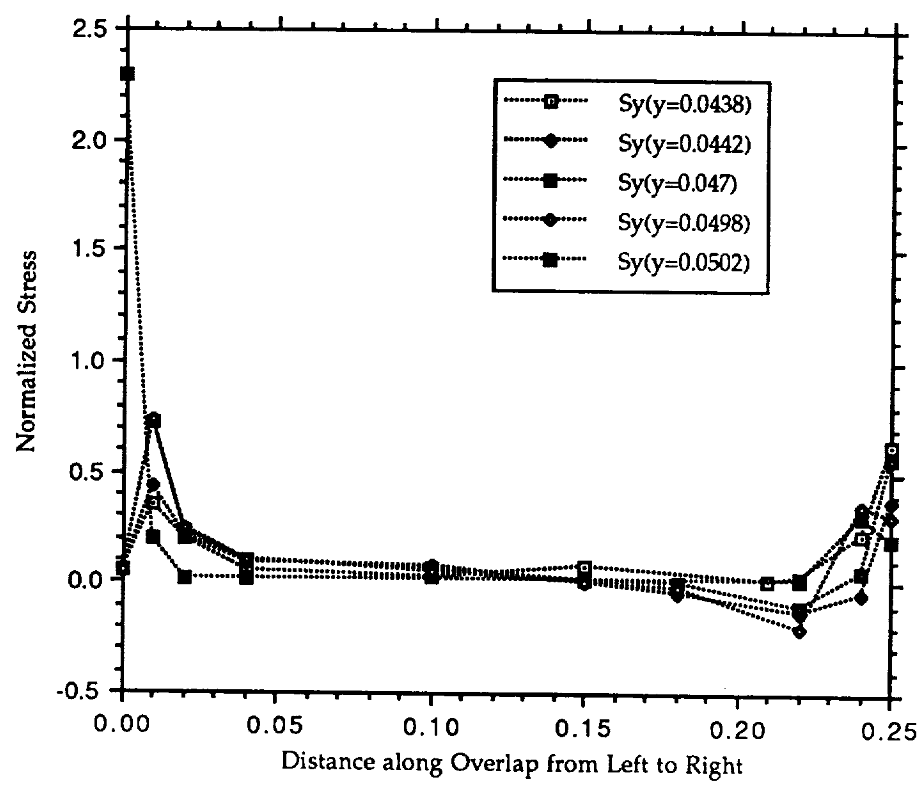


Figure 10. σ_y along different levels of bondline (d = 0.25 in, t_2 = 0.006 in).

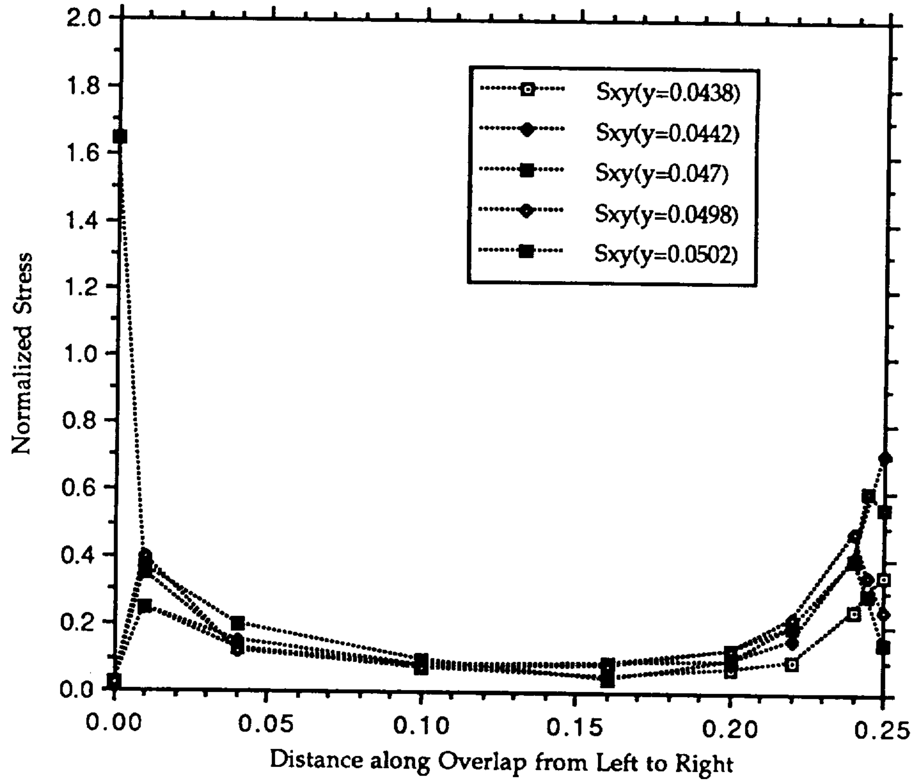


Figure 11. τ_{xy} along different levels of bondline (d = 0.25 in, t_2 = 0.006 in).

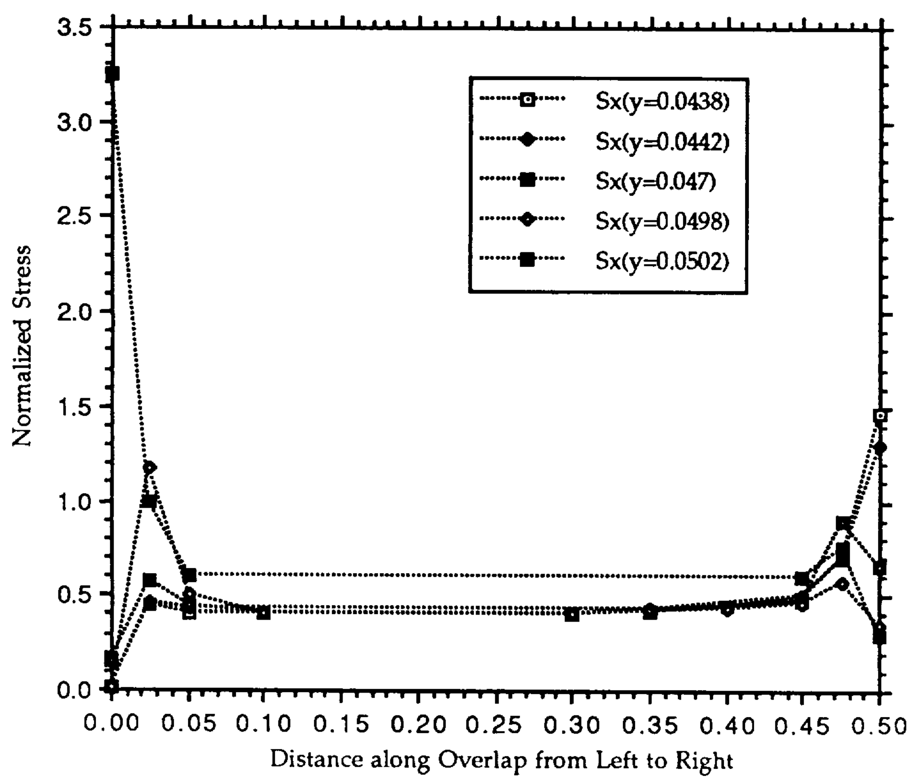


Figure 12. σ_x along different levels of bondline (d = 0.50 in, t_2 = 0.006 in).

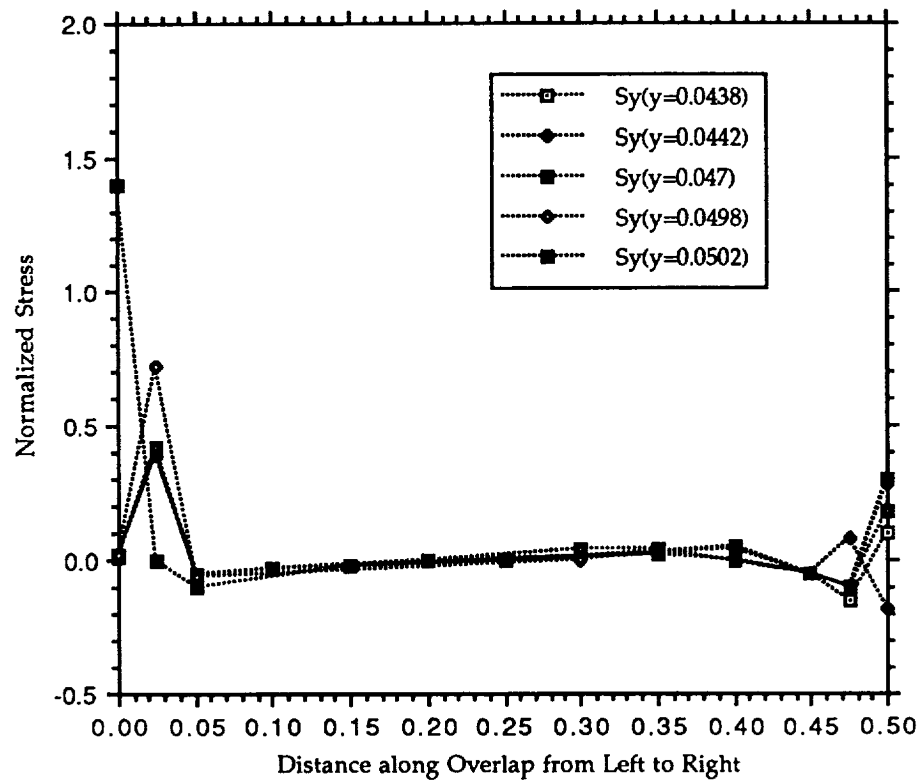


Figure 13. σ_y along different levels of bondline (d = 0.50 in, t_2 = 0.006 in).

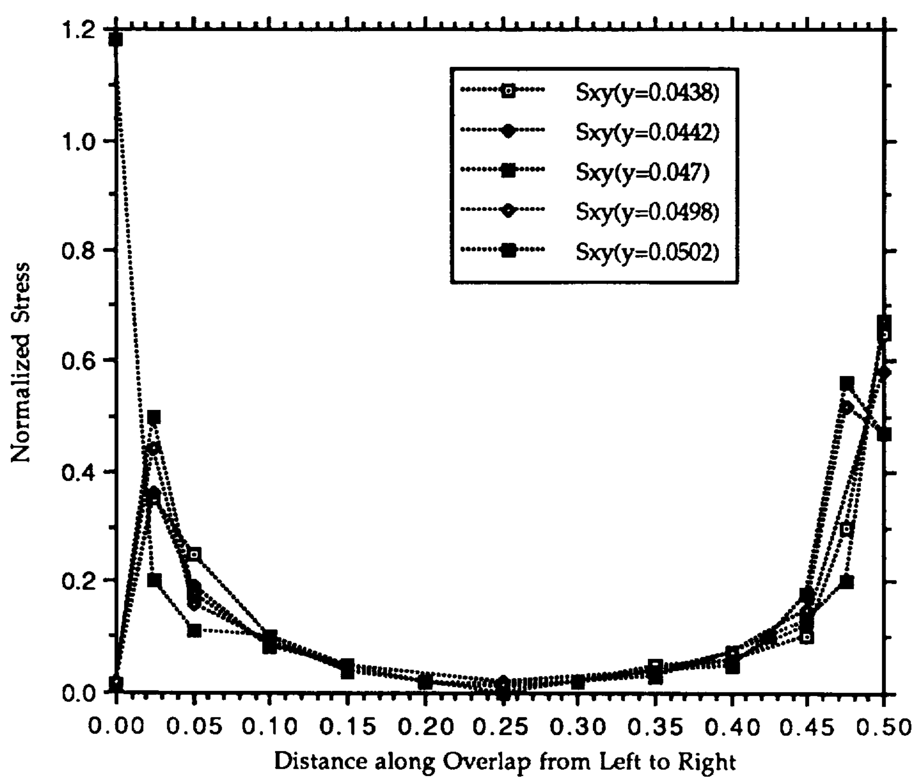


Figure 14. τ_{xy} along different levels of bondline (d = 0.50 in, t_2 = 0.006 in).

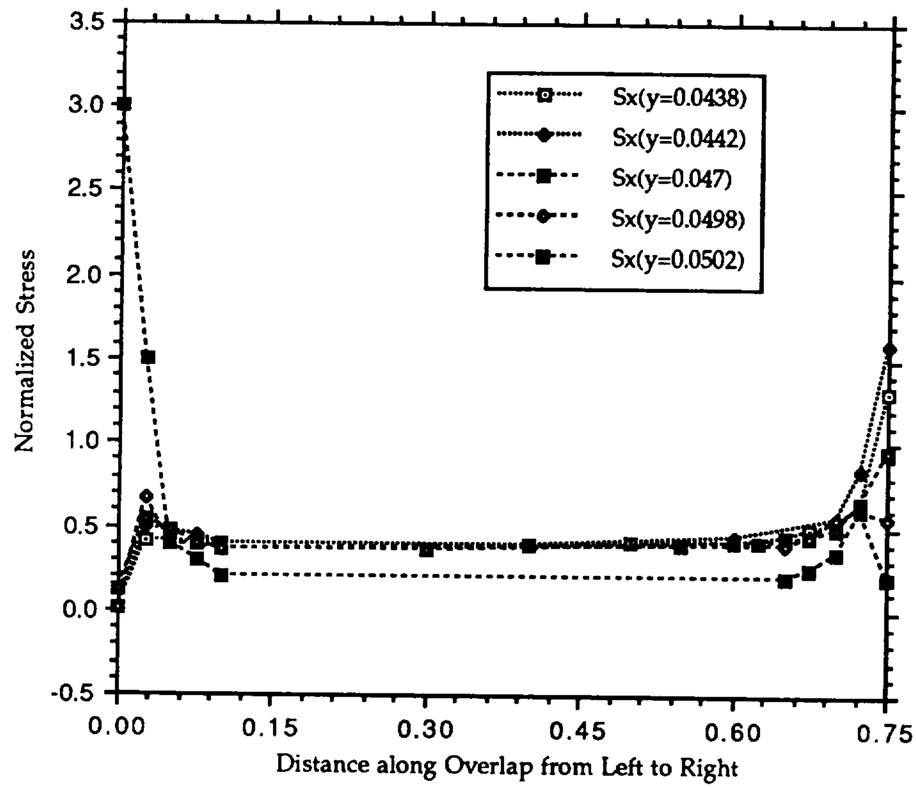


Figure 15. σ_x along different levels of bondline (d = 0.75 in, t_2 = 0.006 in).

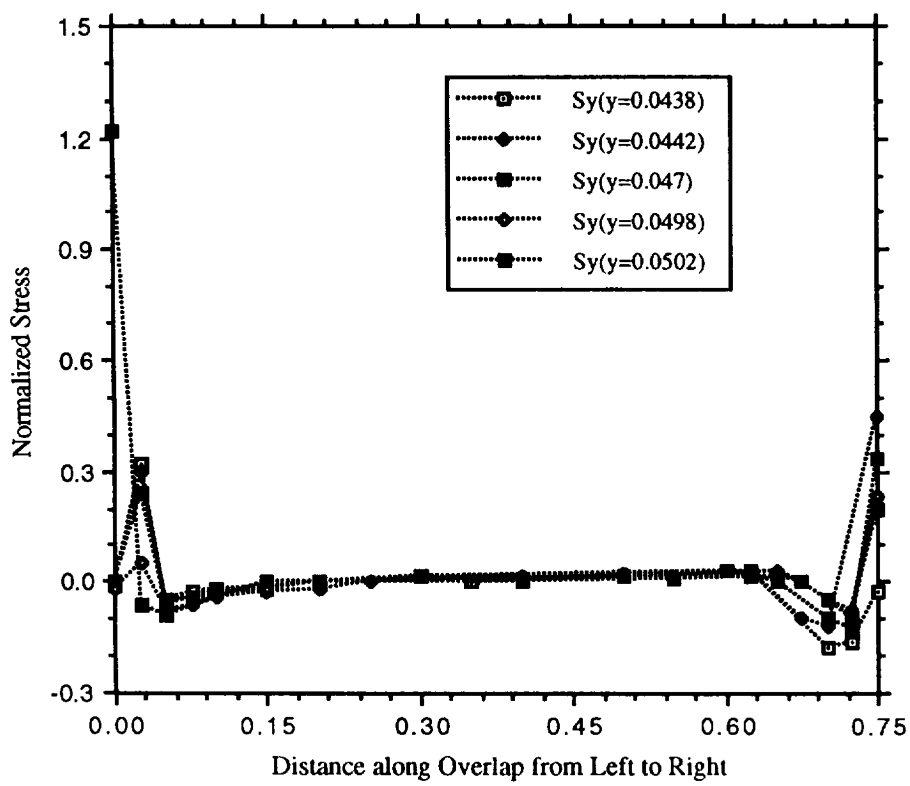


Figure 16. σ_y along different levels of bondline (d = 0.75 in, t_2 = 0.006 in).

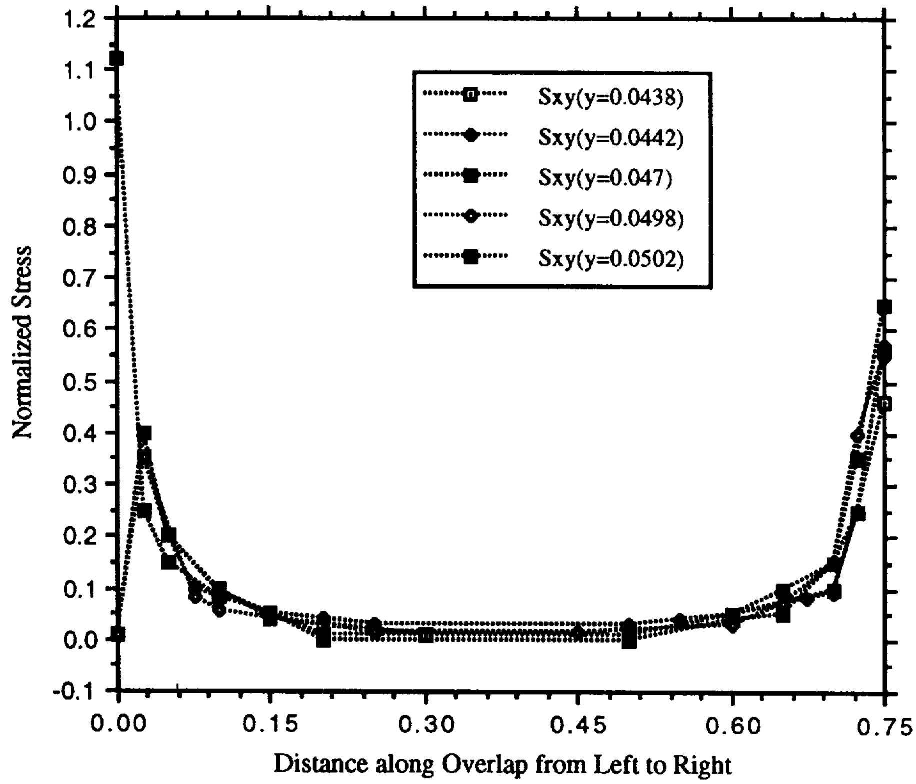


Figure 17. τ_{xy} along different levels of bondline ($d = 0.75$ in, $t_2 = 0.006$ in).

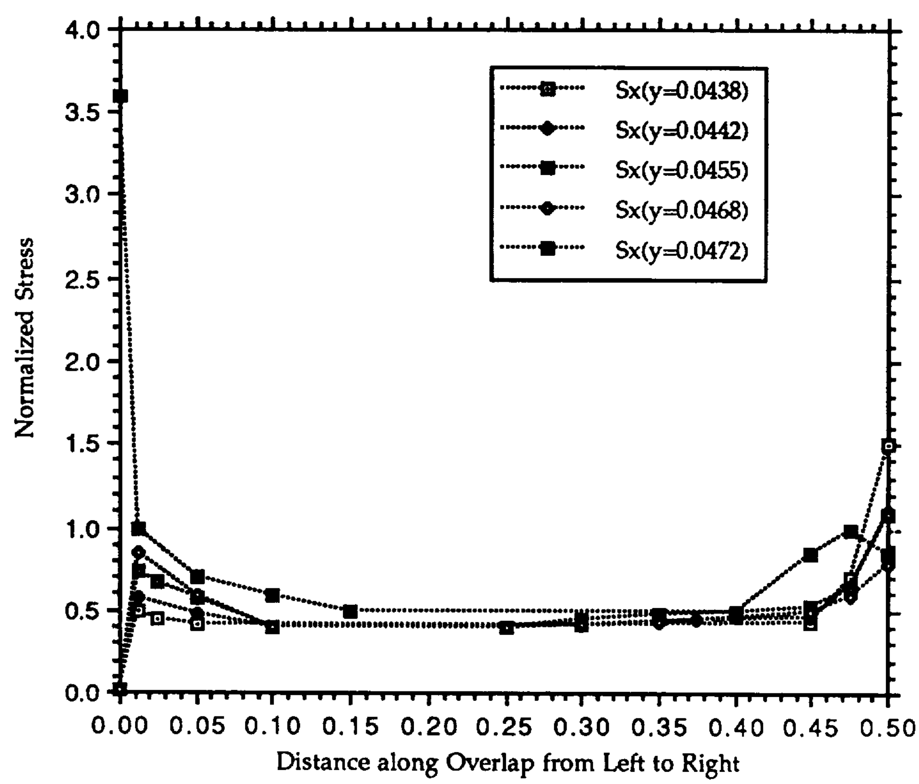


Figure 18. σ_x along different levels of bondline ($d = 0.50$ in, $t_2 = 0.003$ in).

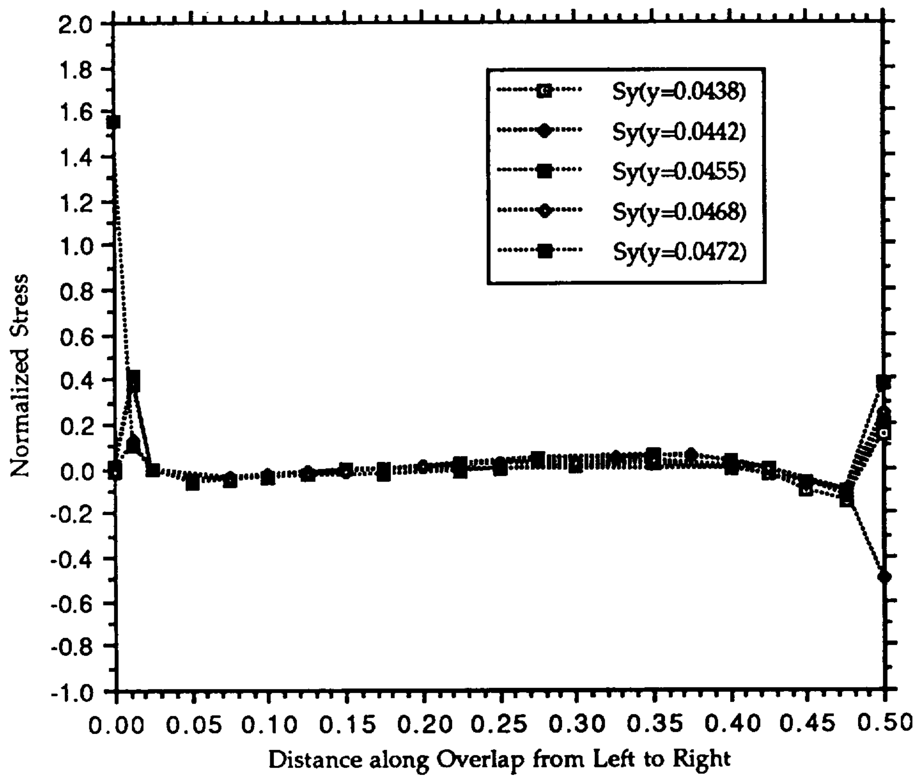


Figure 19. σ_y along different levels of bondline (d = 0.50 in, t_2 = 0.003 in).

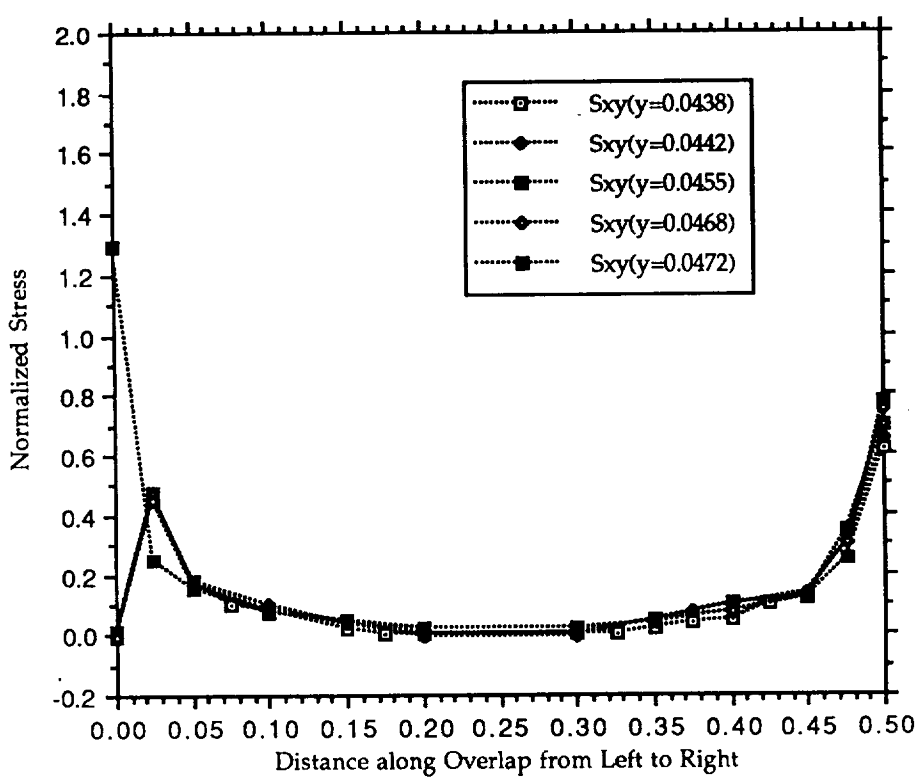


Figure 20. τ_{xy} along different levels of bondline (d = 0.50 in, t_2 = 0.003 in).

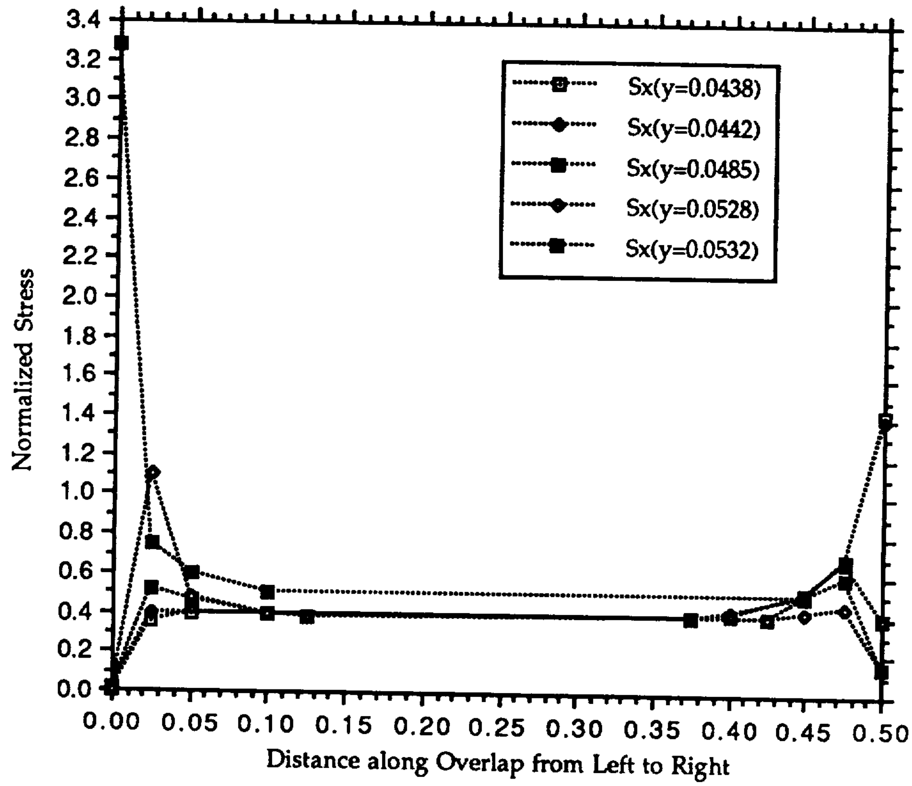


Figure 21. σ_x along different levels of bondline (d = 0.50 in, t_2 = 0.009 in).

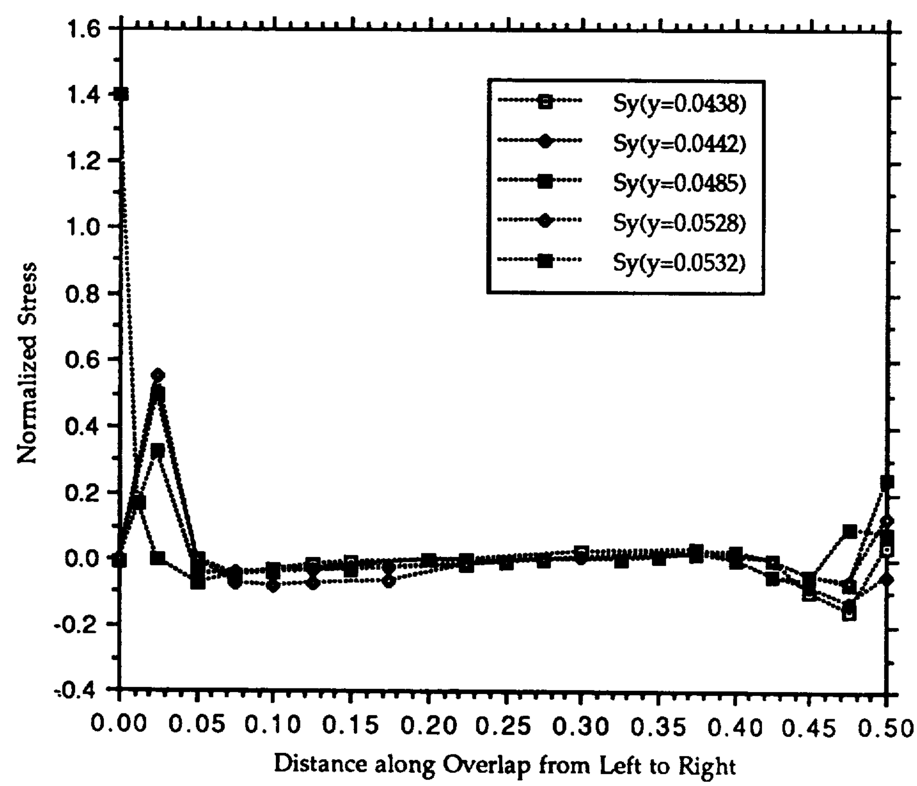


Figure 22. σ_y along different levels of bondline (d = 0.50 in, t_2 = 0.009 in).

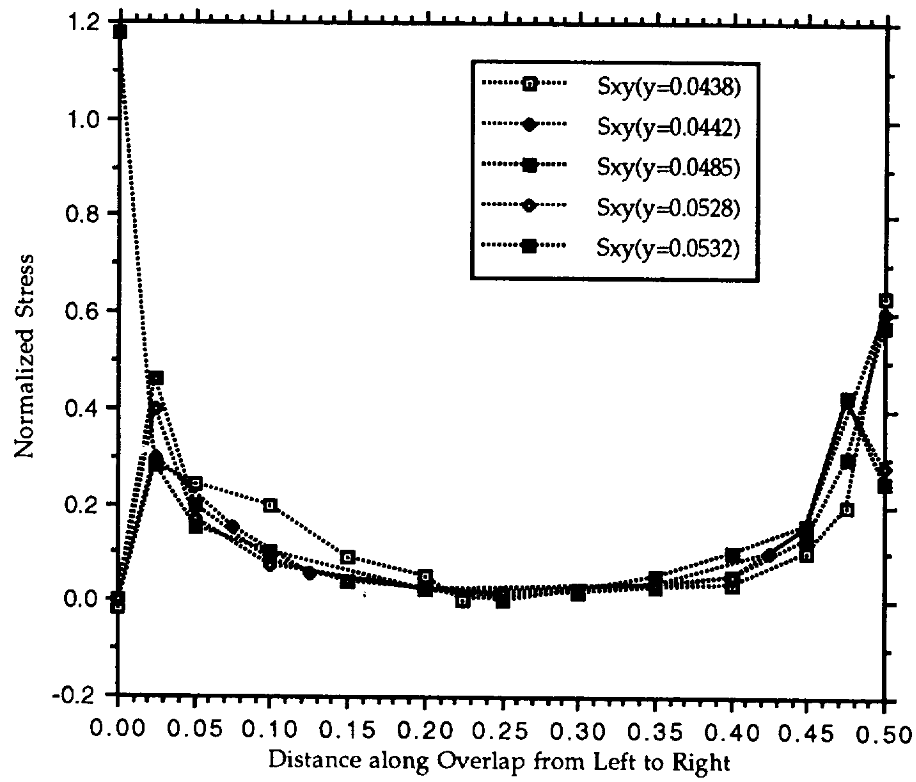


Figure 23. τ_{xy} along different levels of bondline (d = 0.50 in, t_2 = 0.009 in).

APPROVAL

A STUDY ON STRENGTH EVALUATIONS OF EDNi/EDCu/NARloy-Z BONDED JOINTS

By J.B. Min and K.L. Spanyer

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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