NASA Contractor Report 159110

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DESIGN, FABRICATION AND TEST OF GRAPHITE/POLYIMIDE
COMPOSITE JOINTS AND ATTACHMENTS FOR ADVANCED
AEROSPACE VEHICLES

Quarterly Technical Progress Report No. 3

BOEING AEROSPACE COMPANY
Seattle, Washington 98124

NASA Contract NAS1-15644
October 1979

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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CONTRACT NAS1-15644

OCTOBER 15, 1979

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Langley Research Center
Hampton, Virginia 23665

BOEING AEROSPACE COMPANY

Engineering Technology
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N80-20316#

FOREWORD

This report summarizes the work performed by the Boeing Aerospace Company (BAC) under NASA Contract NAS1-15644 during the period July 1, 1979 through September 30, 1979.

This program is sponsored by the National Aeronautics and Space Administration, Langley Research Center (NASA/LaRC), Hampton, Virginia. Dr. Paul A. Cooper is the Technical Representative for NASA/LaRC.

Performance of this contract is by Engineering Technology personnel of BAC. Mr. J. L. Arnquist is the Program Manager and Mr. D. E. Skoumal is the Technical Leader.

The following Boeing personnel were principal contributors to the program during this reporting period: D. L. Barclay, Design; J. B. Cushman, Analysis; G. D. Menke, Materials and Processes; R. E. Jones and S. M. Williams, Finite Element Analysis.

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Program Manager

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SUMMARY

This document reports on activities from July 1, 1979, through September 30, 1979, of an experimental program to develop several types of graphite/polyimide (GR/PI) bonded and bolted joints. The program consists of two concurrent tasks. TASK 1 is concerned with design and test of specific built-up attachments while TASK 2 evaluates standard and advanced bonded joint concepts. The purpose is to develop a database for the design and analysis of advanced composite joints for use at elevated temperatures [561K (550°F)]. The objectives are to identify and evaluate design concepts for specific joining applications and to identify the fundamental parameters controlling the static strength characteristics of such joints. The results from these tasks will provide the data necessary to design and build GR/PI lightly loaded flight components for advanced space transportation systems and high speed aircraft.

During this reporting period the principal program activities dealt with joint concept screening, verification of GR/PI material, fabrication of design allowables panels, defining test matrices and analysis of bonded and bolted joints. A "2nd cut" screening to select the best 2 or 3 concepts for each attachment type has been completed. Design ground rules were updated to reflect comments received during the screening process. Prepreg processing problems have been resolved resulting in successful fabrication of 13 panels for design allowables testing. Test matrices and specimen configurations have been defined in detail for design allowables (Matrix 1), ancillary adhesive tests (Matrix 2), standard joints (Matrix 3) and small specimens (Matrix 4). The design allowable panels are currently being conditioned and specimens prepared per the test matrix requirements.

Preliminary analysis of bonded and bolted titanium plate to honeycomb sandwich tension joints (Type 3 joint) has been completed. A preliminary design of a bolted Type 3 joint is presented. Detailed finite element analyses of double lap bonded joints were performed to assess effects of varying the adherend extensional stiffness at the adhesive interface. Results indicate that a softer layer at the adhesive interface reduces the peak adhesive shear stresses.

SECTION 1.0

INTRODUCTION

This is the 3rd quarterly report covering results of the 3 months activity during the period July 1, 1979, through September 30, 1979.

The purpose of this program is to provide a database for the design of advanced composite joints useful for service at elevated temperatures [561K (550°F)]. The current epoxy-matrix composite technology in joint and attachment design will be extended to include polyimide-matrix composites. This will provide the data necessary to build graphite/polyimide (GR/PI) lightly loaded flight components for advanced space transportation systems and high speed aircraft. The objectives of this contract are twofold: first, to identify and evaluate design concepts for specific joining applications of built-up attachments which could be used at rib-skin and spar-skin interfaces; second, to explore advanced concepts for joining simple composite-composite and composite-metallic structural elements, identify the fundamental parameters controlling the static strength characteristics of such joints, and compile data for design, manufacture, and test of efficient structural joints using the GR/PI material system.

The major technical activities follow two paths concurrently. The TASK 1 effort is concerned with design and test of specific built-up attachments while the TASK 2 work evaluates standard and advanced bonded joint concepts.

The generic joint concepts to be developed under TASK 1 are shown in Figure 1-1. The total program is scheduled over a period of 27 months as shown in Figure 1-2.

In TASK 1.1, several concepts will be designed and analyzed for each bonded and each bolted attachment type. Concurrent with this task a series of design allowable and small specimen tests will be conducted under TASK 1.2. The analytical results of TASK 1.1 and the design data from TASK 1.2 will allow a selection of the most promising bonded and bolted concepts.

In TASK 1.3, the two most promising concepts for each joint type (16 concepts total) will be fabricated, tested, and evaluated. The evaluation will yield the preferred joint concepts and will be based on weight efficiency, ease of fabrication, detail part count, inspectability and predicted fatigue behavior.

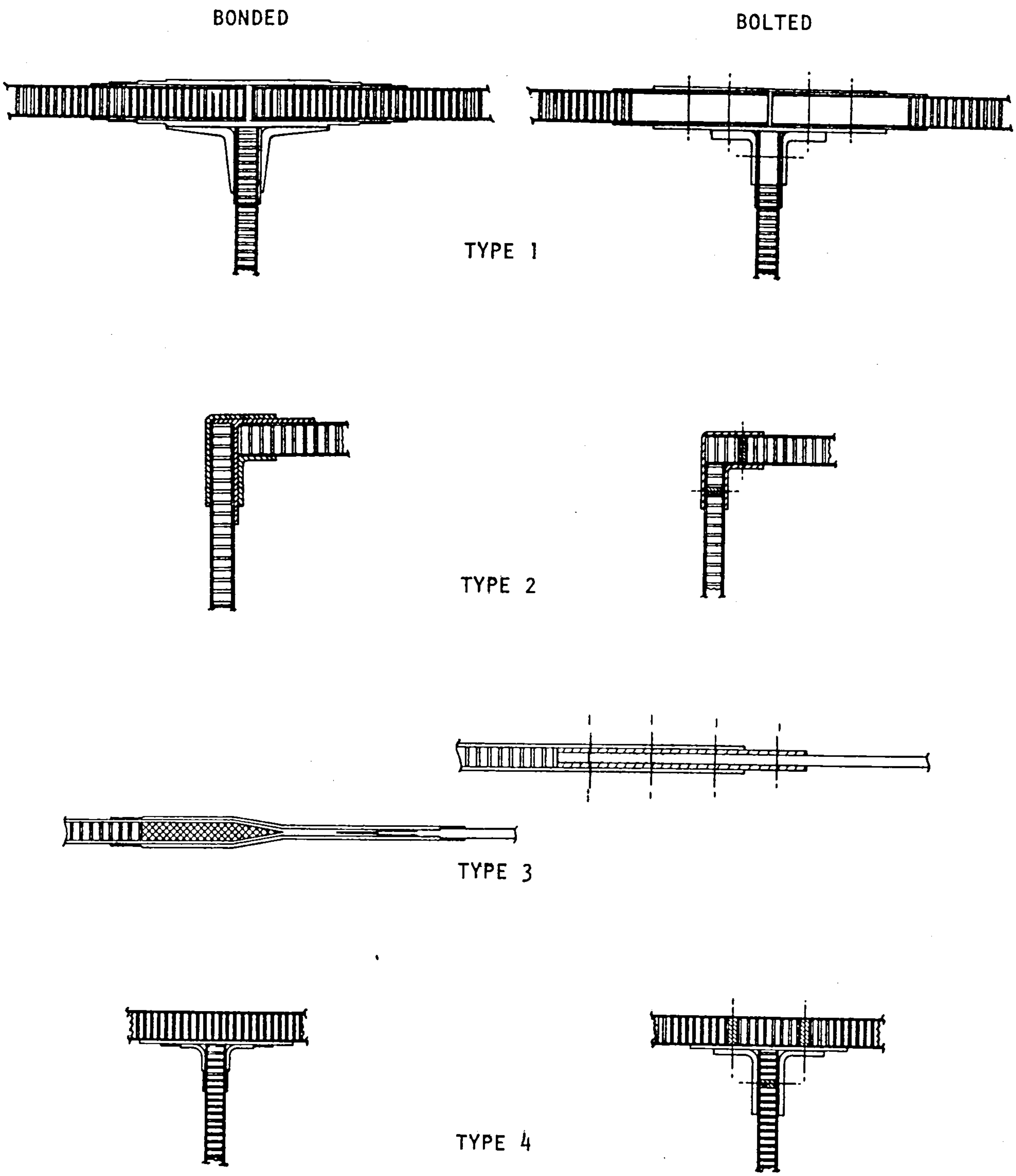

FIGURE 1-1: GENERIC JOINT CONCEPTS FOR 4 ATTACHMENT TYPES

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DESIGN, FABRICATION AND TEST OF GRAPHITE/POLYIMIDE COMPOSITE JOINTS AND ATTACHMENTS FOR ADVANCED AEROSPACE VEHICLES

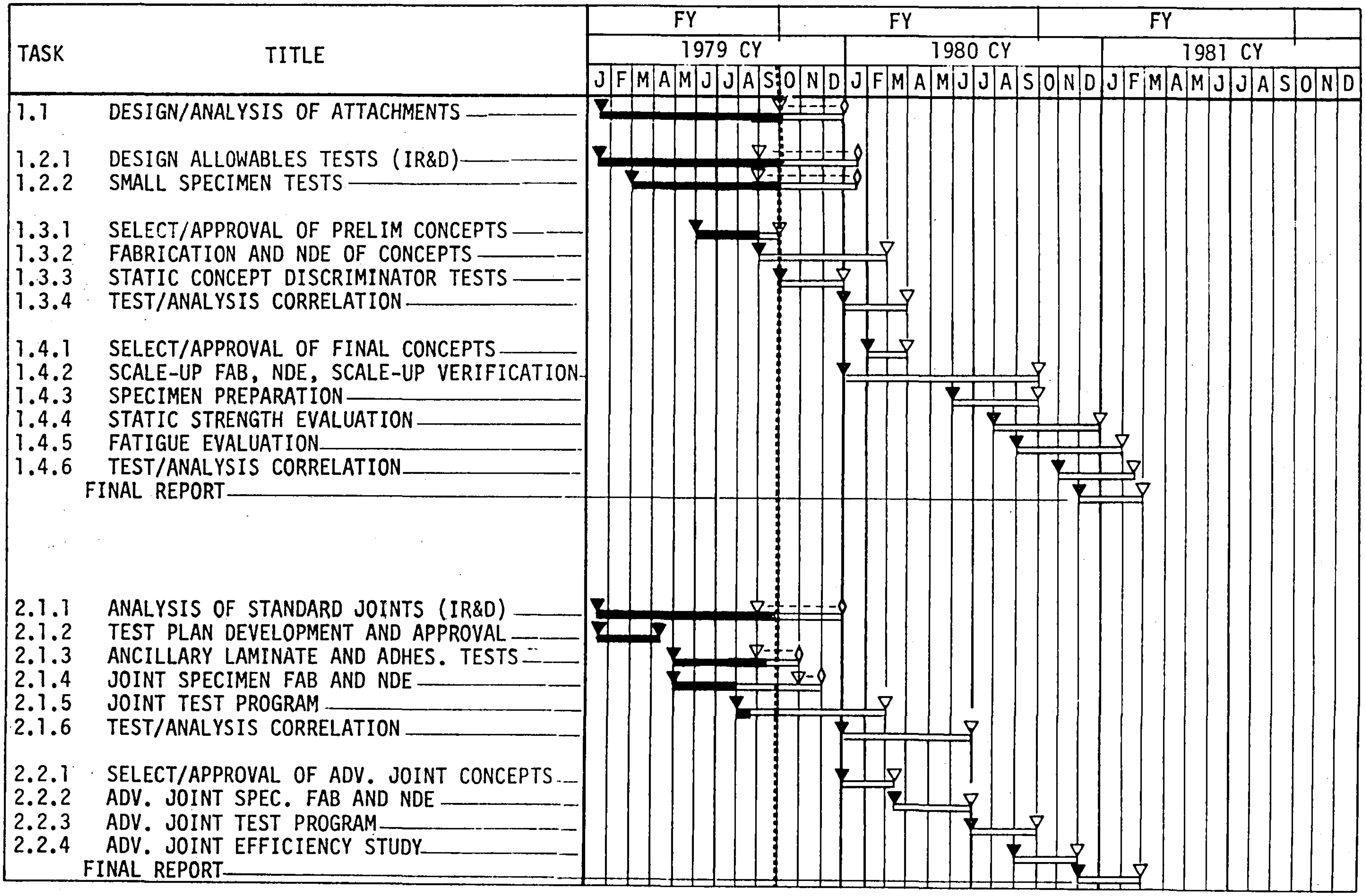


FIGURE 1-2: MASTER PROGRAM SCHEDULE

LEGEND
▼ STARTING DATE
▽ ENDING DATE

Finally, eight joint concepts (2 of each joint type) will be fabricated in TASK 1.4 on a scaled-up manufacturing basis to assure that reliable attachments can be fabricated for full-scale components. A series of static tests will be performed on specimens cut from the scaled-up attachments to verify the validity of the manufacturing process. Additional specimens will be thermally conditioned and tested in a series of static and fatigue tests. Test results will be compared with the analytical predictions to select final attachment concepts and design/ analysis procedures.

The TASK 2 activity will establish a limited database that will describe the influence of variations in basic design parameters on the static strength and failure modes of GR/PI bonded composite joints over a 116K to 561K (-250°F to 550°F) temperature range. The primary objectives of this research are to provide data useful for evaluation of standard bonded joint concepts and design procedures, to provide the designer with increased confidence in the use of bonded high-performance composite structures at elevated temperature, and to evaluate possible modifications to the standard joint concepts for improved efficiency.

To accomplish these objectives, activity under TASK 2.1 will consist of design, fabrication, and static test of several classes of composite-to-composite and composite-to-metallic bonded joints including single-and-double-lap joints and step-lap joints. Test parameters will include lap length, adherend stiffness and stacking sequence at room and elevated temperatures. Toward the latter part of this program, under TASK 2.2, a selection will be made of advanced lap joint concepts which show promise of improving joint efficiency. Possible concepts are pre-formed adherends, mixed adhesive systems, and lap edge clamping. These concepts will be added to the static strength test program and the results compared with the results from the standard joint tests.

SECTION 2.0

TASK 1 ATTACHMENTS

2.1 TASK 1.1 - Design and Analysis of Attachments

This section discusses the results achieved during this reporting period on the literature survey and on design and analysis of attachments.

2.1.1 Literature Survey

A comprehensive literature search was initiated at the beginning of this program (Ref. 1) to compile applicable experimental data and analyses concerned with the processing control, properties, and fabrication of GR/PI composite materials. In addition, the search was focused on design/analysis and evaluation of test data of bonded and bolted composite attachments.

The search has revealed an extensive amount of basic research, both completed and on-going, concerning attachments of composite structural members. As expected, the current emphasis is on the utilization of graphite/epoxy composite materials (Ref. 2).

Additional literature which has been reviewed and evaluated during this reporting period is listed in References 3 through 8 and are summarized below:

A summary of "standard" test methods that are in common usage to measure adhesive properties can be found in Reference 3. The use of adhesive fracture mechanics is discussed including some of the necessary assumptions that must precede such an analysis. The authors emphasize that care must be exercised in testing because the adhesive fracture energy values are influenced by loading rate, loading mode and test temperature, as well as physical parameters such as surface preparation and moisture.

An in-depth assessment of fatigue mechanisms and failure modes related primarily to adhesively bonded metal/metal joints is reported by Romanko in Reference 4. The joints, which are thick adherend types, are analyzed by finite element techniques to determine the stress-strain distributions within the adhesive. Through these analyses the effects of cure cycle, residual stresses, and expansion and contraction due to moisture are characterized. The effects of bending stresses and time and temperature dependence of the constitutive relations of the adhesive are included in a nonlinear analysis. Iterative analysis and instrumented joint and adhesive material testing are used to correlate the analytical and experimental results. The author suggests development of a phenomenological model of cumulative damage based on the approach proposed by Halpin and Polley (Ref. 5). This model involves a representation of accelerated aging effects occurring in combined environments of mechanical, thermal, and chemical (corrosion) stresses.

Nondestructive testing of adhesive bonded joints is treated in a summary fashion in Reference 6. The capabilities and limitations of currently available methods are discussed. The emphasis is on metal-to-metal joints, however, the various methods of defect identification are generally applicable to bonded composite joints. The calibration or interpretation of data requires the determination of material properties or characteristics that can be measured or observed without damage to the material, yet bear a close relationship to its strength properties.

A review of the NASA "Composites for Advanced Space Transportation Systems" (CASTS) research is contained in Reference 7. Papers presented at this conference included fabrication, design and analysis, test methods, and advanced technology developments as applied to graphite/polyimide material systems.

Properties of polyimide adhesives are reported in Reference 8. Adhesives include LARC-13, modifications of LARC-13, LARC-160, PMR-15 and FM-34. While all systems evaluated had acceptable lap shear strength the condensation-type adhesive (FM 34) lacked the ability to form void-free, large area bonds.

2.1.2 Design and Analysis

The steps being followed to develop the joint designs are shown in Figure 2-1 which illustrates the interaction between design, analysis and test. Shaded areas identify approximate percent completion.

The joints and attachments are being designed to withstand thermal cycling between 116K and 589K (-250°F and 600°F) with at least 125 hours exposure at 589K. However, the testing program is being conducted at a maximum temperature of 561K (550°F). The rationale for testing at 561K (550°F) instead of 589K (600°F) is presented below.

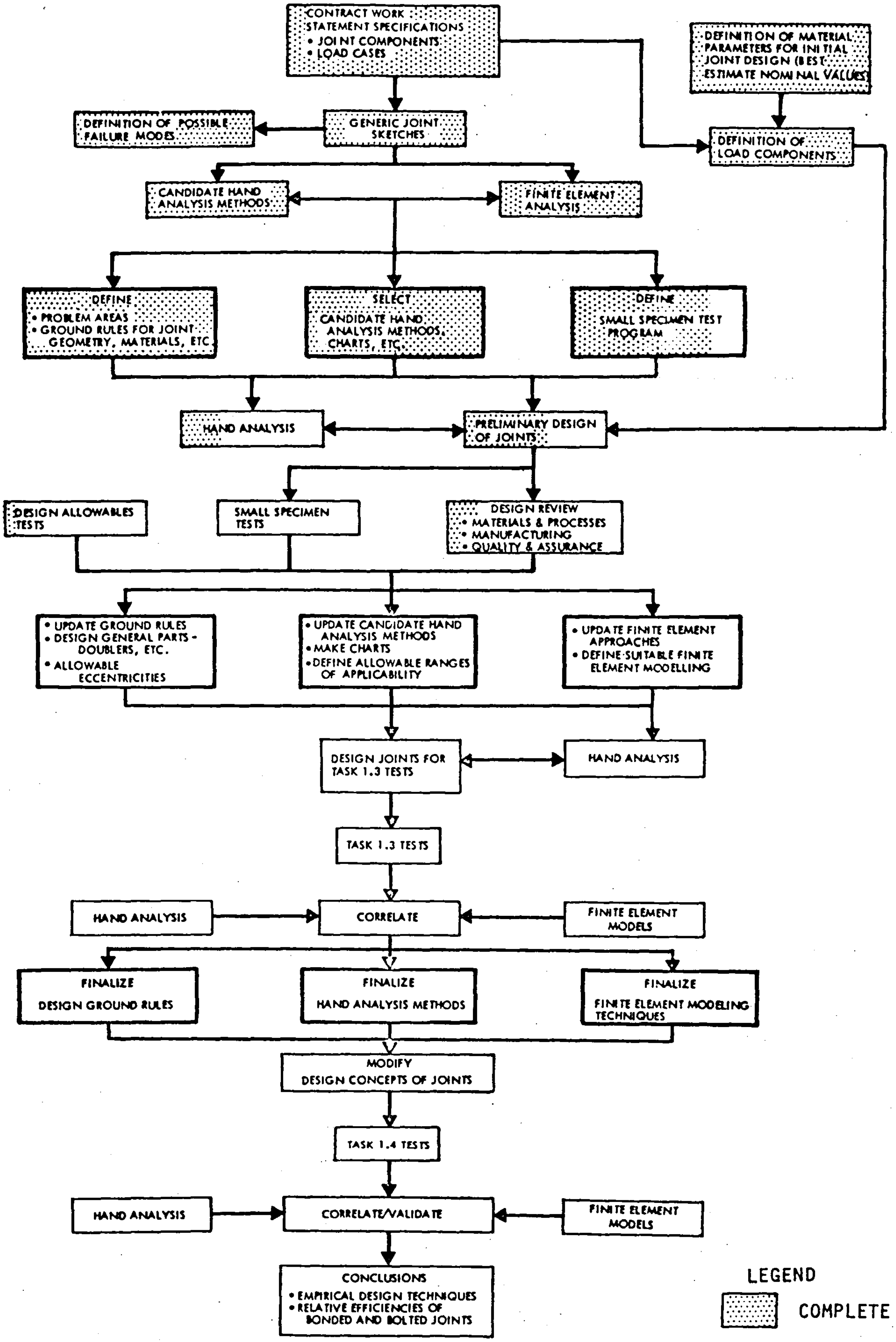


FIGURE 2-1 Task 1 Design/Analysis/Test Flow Diagram

For composite specimens where the matrix properties significantly affect strength, the measured strength decreases relatively rapidly as test temperature approaches 589K (600°F). The net result of testing at 589K (600°F) could be poor correlation between the pre-test analytical predictions and the test results. By reducing the test temperature to 561K (550°F), the correlation between analytical prediction and test should be improved. Note that all specimen aging and thermal cycling is being conducted with a peak temperature of 589K (600°F).

Design Ground Rules - The design ground rules are based on the joint types, environments, loads and materials specified in the Contractual Statement-of-Work. These ground rules, which were previously itemized in Reference 2, have been updated to the following:

- A bonded joint is defined as one that is assembled primarily by means of a bonding process. Mechanical fasteners may be used in a bonded joint to reduce critical bond stresses. A bonded joint, however, cannot be separated into its major component parts by the removal of the mechanical fasteners.

- A bolted joint is defined as one that can be separated into its major component parts by removal of the mechanical fasteners.

- Joint Types 1, 2 and 4, and 3 (bolted) are two-piece assemblies.

- Joint Type 3 (bonded) is integral structure.

- Composite materials specified:

  Laminate - Celion 6000 or 3000/PMR-15
  Adhesive - A7F (LARC-13/Amide-Imide modified adhesive)
  Core - HRH 327, Fiberglass/Polyimide

- Component assembly requirements:

  Face skins, angles, and brackets precured - 620K (625°F) at 1.379 MPa (200 psi), plus postcure.*
  Adhesive cure - 589K (600°F) at 0.689 MPa (100 psi), plus postcure.*

* Postcure is the unbagged part exposed to 620K (625°F) for 6 hours at 1 atmosphere.

- o Joint conditioning requirements:

  (1) As cured/postcured

  (2) Aged 450 ks (125 hr) at 589K (600°F)

  (3) 125 thermal cycles, 116K (-250°F) to 589K (600°F)

- o Joint operating environments:

  Loads as defined in Reference 1.

  Temperatures:

  116K (-250°F)

  Room Temperature

  561K (550°F)

- o Special design techniques associated with aerodynamic smoothness, e.g., flush head bolts, will not be considered in this study. The reasons for this are:

  (1) An aerodynamic smoothness requirement is not specified in the work statement.

  (2) Many potential applications for GR/PI components; e.g., shuttle aft body flap, will require a surface covering of insulation for temperature protection which makes bolt flushness for aerodynamic smoothness redundant.

- o The corner joints (Type 2) will be an "L" configuration as depicted in Figure 2 of the Statement of Work. "T" configurations will <u>not</u> be considered.

- o The joints will be designed on the assumption that they will be accessible on all sides so that the required bonding temperature and pressure can be applied for the bonded joints and the required installation tools can be used for the bolted joints.

- o The joints for Types 1, 2 and 4 will be designed on the assumption that the shape of the surfaces range from flat to slightly contoured. Test specimens, however, will be designed with flat surfaces.

- The joints for Type 3 will be designed on the assumption that the surfaces will be flat.

- In actual practice, the designs of ribs and spars must account for the component assembly sequence and accessibility to the joint during assembly. Ribs and spars therefore may be able to use a bonded joint at the intersection of one skin panel surface, but may require a bolted joint at the other surface. However, in this study, because our intent is to determine the relative efficiencies of each pair of bonded and bolted attachment types, the above considerations associated with component assembly will be ignored. Within the selection process, however, we will weigh the comparative ease of assembly of the candidate joints for each type.

Concept Screening - A flow chart showing the approach to screen and evaluate the joint concepts is given in Figure 2-2.

All joint concepts originally identified during the "1st cut" screening, the screening parameters and weighting factors, are presented in Reference 2.

The "2nd cut" screening has been completed. Remaining concepts and their rankings are discussed below.

Web to Cover Attachment - Bonded Joint Concepts Types 1 & 4

The three concepts selected from the 2nd screening are shown in Figure 2-3.

Concept 1b was ranked the highest. It is the simplest and most economical from the standpoint of detail parts, assembly and tooling. The load transfer is straightforward; directly into each face skin. Also, the two flanges provide a redundant load path.

Concept 1n is ranked second. There is some concern that this joint with the single attach angle can be made adequate for the loads involved. An additional angle facing in the opposite direction could be added, if necessary, to make this a more viable concept. But, if this needs to be done it seems more appropriate to return to 1b. The majority of the load, if not all, will be carried by the flanged face skin (which appears to be adequate) rather than shared equally by both skins.

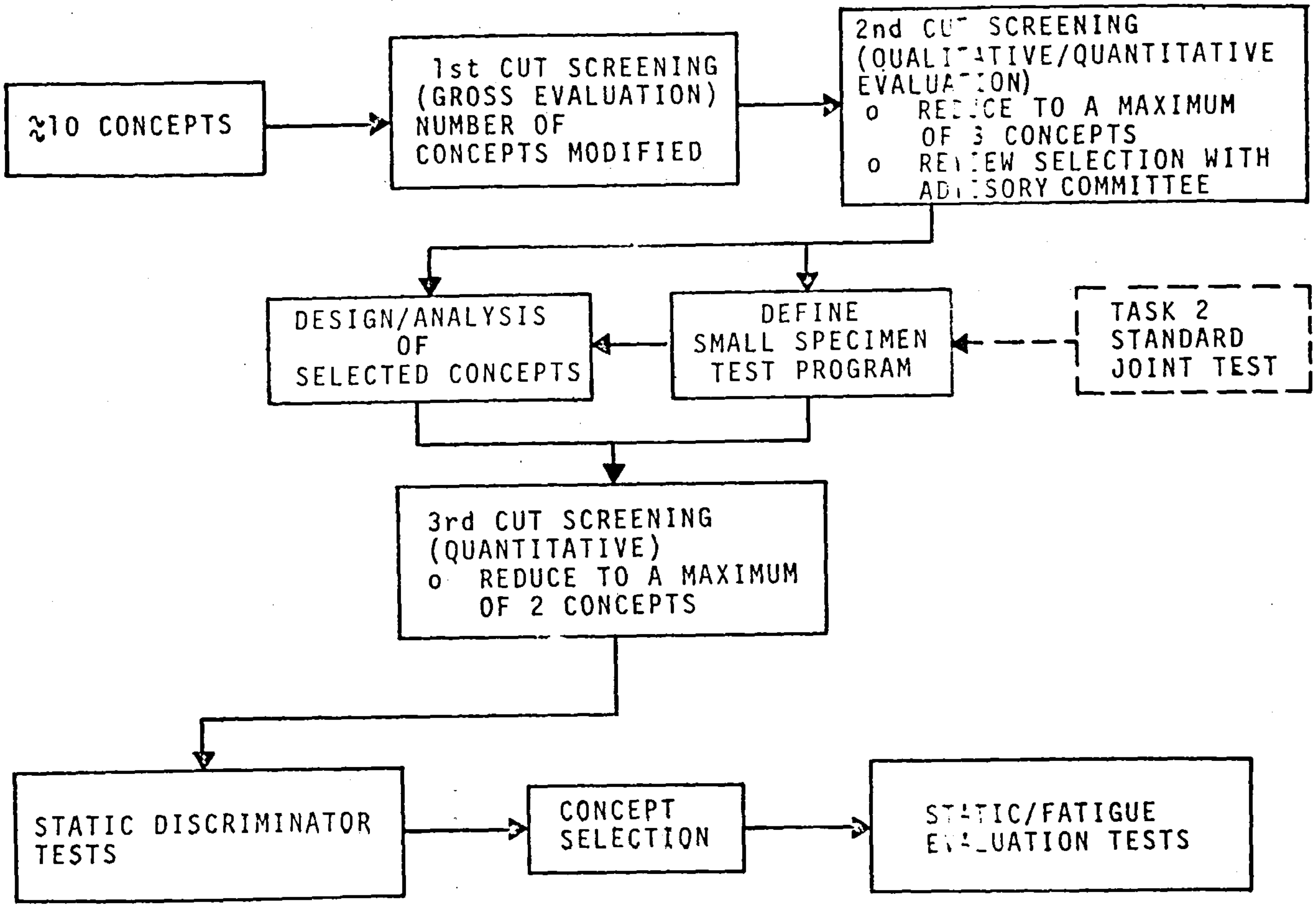


Figure 2-2 Attachment Joint Concepts Screening Flow Chart

Concept 1i is ranked third. This concept has two advantages that serve to offset some of its complexity. First, the tee attachment arrangement should provide a stronger web to cover attachment than either 1b or 1n. Second, the ramped skin/angle arrangement distributes the load more evenly, provides a more positive seal-off of the core, and provides more bending stiffness than 1n.

Web to Cover Attachment - Bolted Joint Concepts Types 1 & 4

The three concepts selected from the 2nd screening are shown in Figure 2-4.

These concepts are similar to those selected for the Types 1 and 4 bonded joint web to cover attachments. The rationale for the bolted concept selection is essentially the same as that discussed above for the bonded.

Cover - Bonded Joint Concepts Type 1

The concept selected from the 2nd screening is shown in Figure 2-5.

Concept 1a is the most practical in terms of good load carrying capability and detail part and assembly simplicity.

Cover - Bolted Joint Concepts Type 1

The concept selected from the 2nd screening is shown in Figure 2-6.

Concept 1a is the most practical in terms of good load carrying practicality and detail part and assembly simplicity.

Bonded Joint Concepts Type 2

The two concepts selected from the 2nd screening are shown in Figure 2-7.

Concepts 2f and 2a are closely ranked. For both concepts the load paths between the cover and rib skins are direct. Furthermore, the skins and angles can be beefed up, without difficulty, as required, to carry the design load.

Bolted Joint Concepts Type 2

The concepts selected from the 2nd screening are shown in Figure 2-8.

Concepts 2a and 2c are closely ranked. For both concepts the load paths between the cover and rib skins are direct. Furthermore, the skins and angles can be beefed up, without difficulty, as required, to carry the design load.

Bonded Joint Concepts Type 3

The concept selected from the 2nd screening is shown in Figure 2-9.

Concept 3a is the most practical in terms of required load carrying capability, [2.1 MN/m (12,000 lb/in)] and fabrication simplicity.

Bolted Joint Concepts Type 3

The concepts selected from the 2nd screening are shown in Figure 2-10.

Concept 3b is the most practical in terms of required load carrying capability [2.1 MN/m (12,000 lb/in)] and fabrication simplicity.

Cover - Bonded Joint Concepts - Type 4

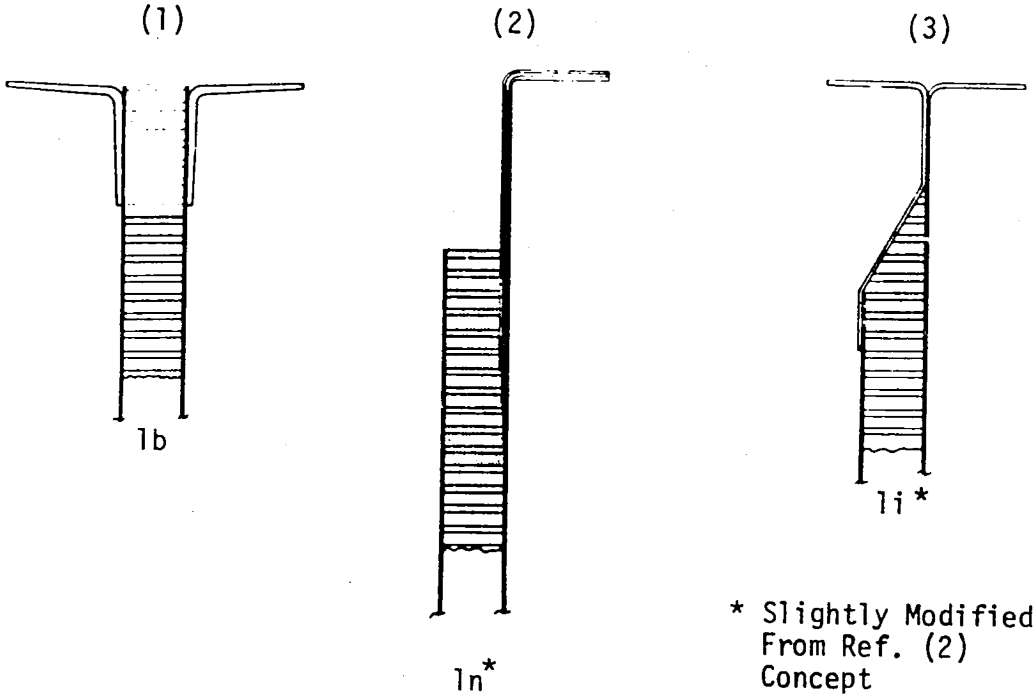
The concepts selected from the 2nd screening are shown in Figure 2-11.

Concepts shown are the most practical in terms of good load carrying capability and detail part and assembly simplicity. No aerodynamic smoothness requirements eliminated the need to consider the more complex internal doublers.

Cover - Bolted Joint Concepts Type 4

The concepts selected from the 2nd screening are shown in Figure 2-12.

Concepts shown are the most practical in terms of good load carrying capability and detail part and assembly simplicity.



* Slightly Modified
From Ref. (2)
Concept

Figure 2-3 SELECTED TYPES 1 & 4 BONDED JOINT CONCEPTS--
WEB TO COVER ATTACHMENTS

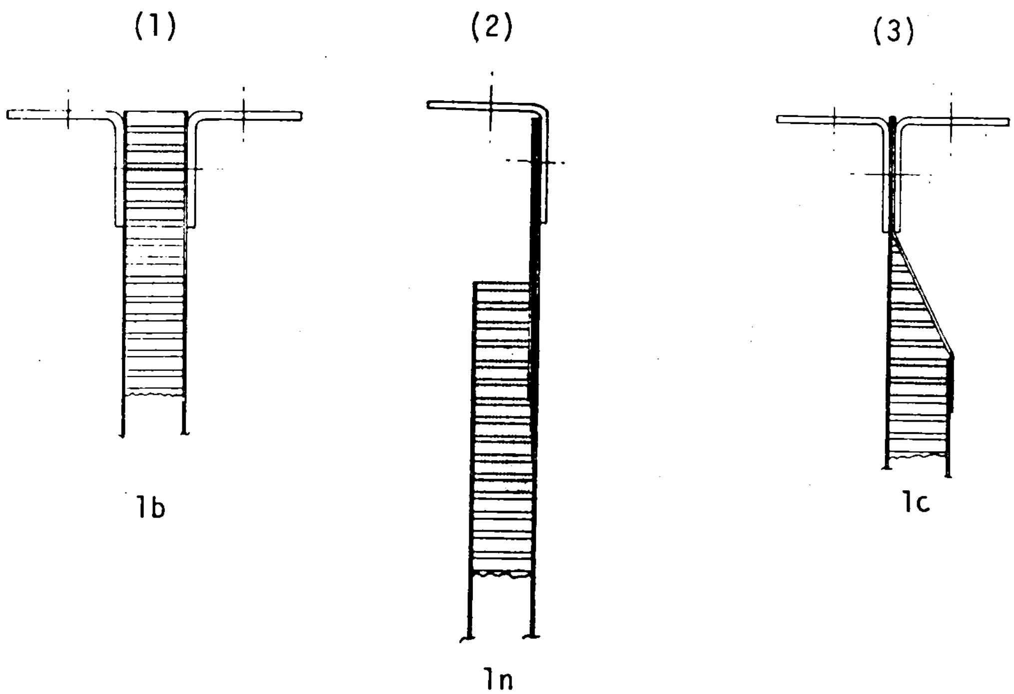
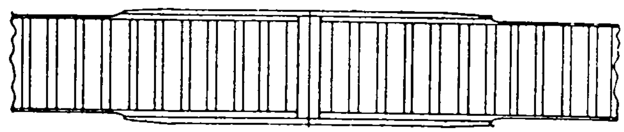


Figure 2-4 SELECTED TYPES 1 & 4 BOLTED JOINT CONCEPTS--
WEB TO COVER ATTACHMENTS

(1)

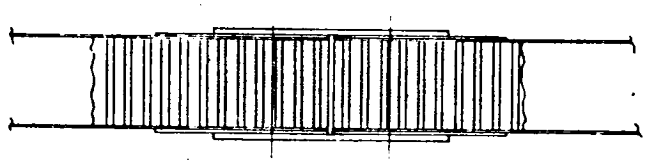


1a*

* Slightly Modified From Ref. 2 Concept

Figure 2-5 SELECTED TYPE 1 BONDED JOINT CONCEPT-- COVER

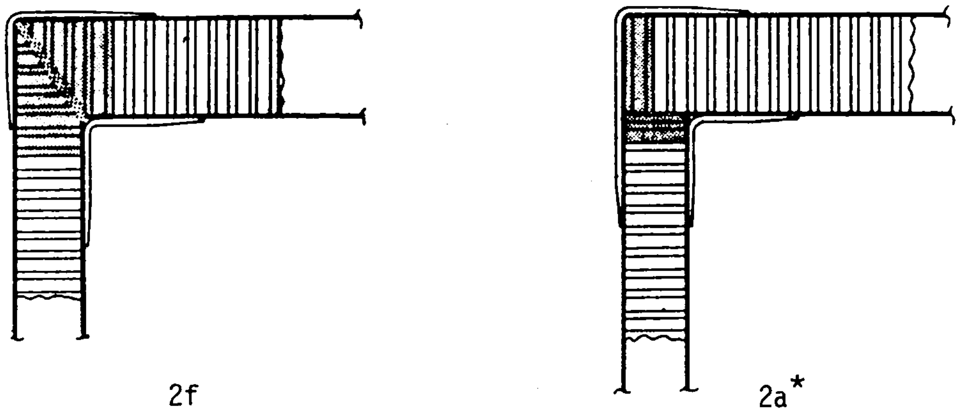
(1)



1a

Figure 2-6 SELECTED TYPE 1 BOLTED JOINT CONCEPT-- COVER

(1) (2)

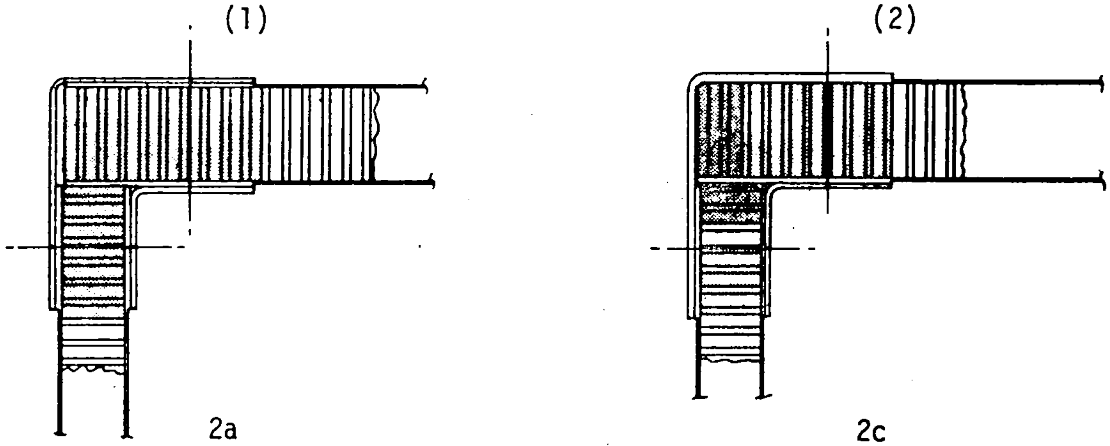


2f 2a*

* Slightly Modified
From Ref. (2)
Concept

Figure 2-7 SELECTED TYPE 2 BONDED JOINT CONCEPTS

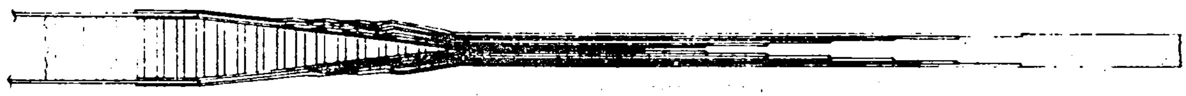
(1) (2)



2a 2c

Figure 2-8 SELECTED TYPE 2 BOLTED JOINT CONCEPTS

(1)



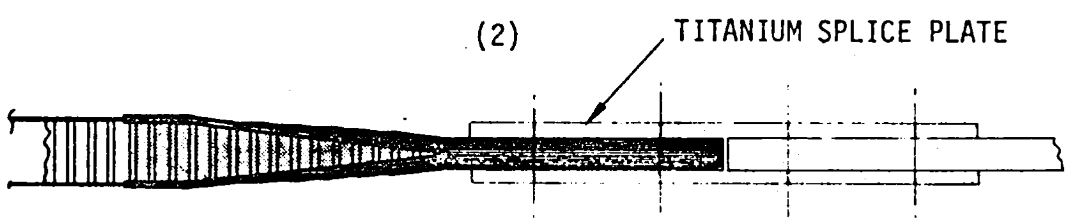
3a

Figure 2-9 SELECTED TYPE 3 BONDED JOINT CONCEPT

(1)

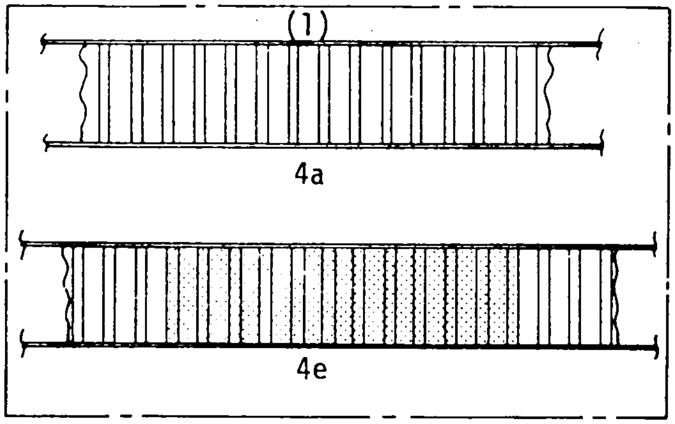
3b

(2)



3b modified

Figure 2-10 SELECTED TYPE 3 BOLTED JOINT CONCEPT



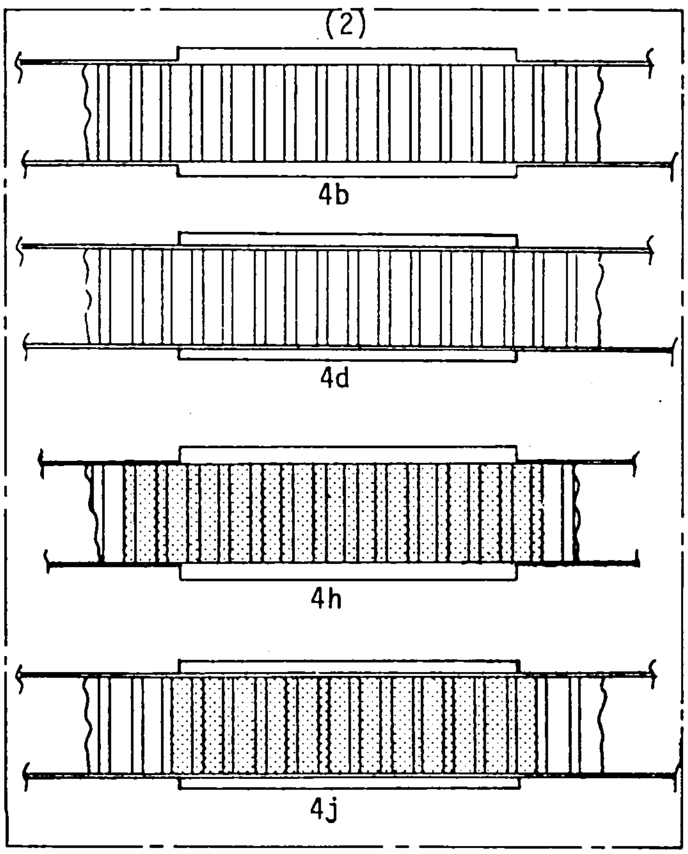
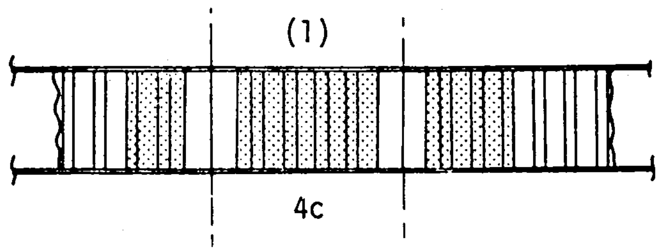


Figure 2-11 SELECTED TYPE 4 BONDED JOINT CONCEPTS--COVER



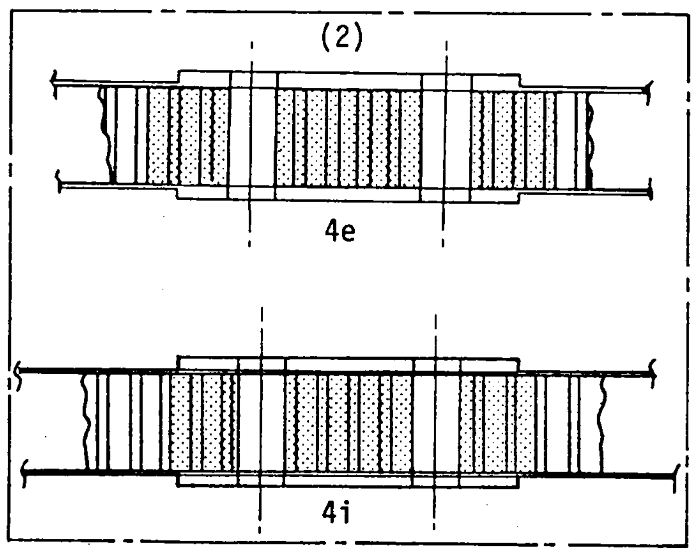


Figure 2-12 SELECTED TYPE 4 BOLTED JOINT CONCEPTS--COVER

Joint Analysis - A preliminary Type 3 bolted joint was sized using analysis procedures discussed in Reference 9, Section 1.3.2. Material properties for GR/PI in a bolted joint were based on data given in Reference 7. Values used, degraded for 561K (550°F) operation, are given in Figure 2-13. The joint design is shown in Figure 2-14.

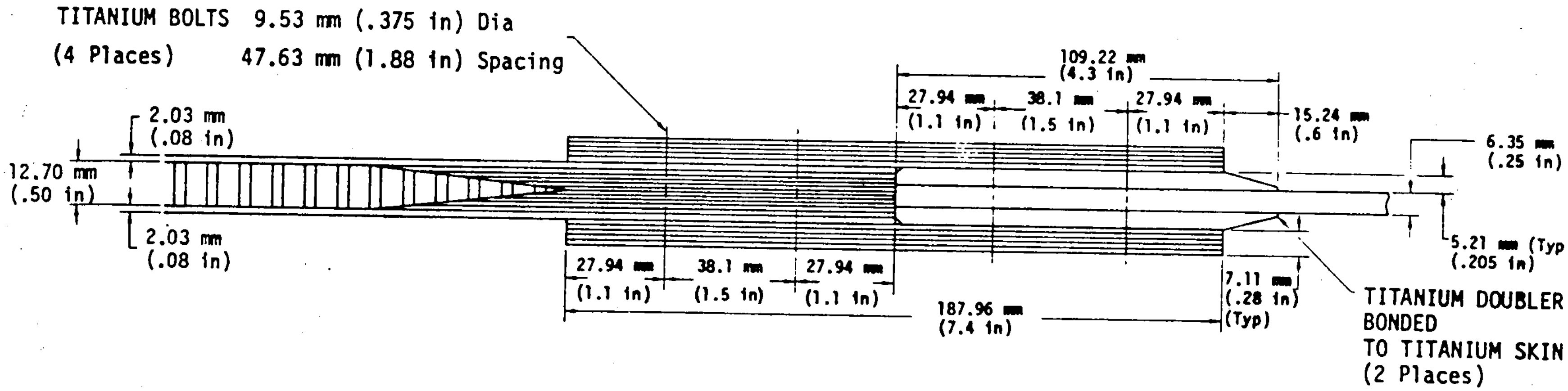
Figure 2-13: Assumed Material Properties @ 561K (550°F)

Property	GR/PI	Titanium
$F_{TU_{net}}$	186 MPa (27 ksi)	648 MPa (94 ksi)
F_{BRU}	621 MPa (90 ksi)	1213 MPa (176 ksi)

Material properties for GR/PI will be updated as results from the allowables and small specimens test program become available.

Preliminary analyses have also been performed on bonded type 3 joints using the A4EG computer code. This code, written by L. J. Hart-Smith of Douglas Aircraft Company for analysis of symmetric step-lap bonded joints, used both elastic and elastic-plastic analyses to predict ultimate joint strength. The analyses account for effects of adherend stiffness and thermal mismatch. Input data are joint geometry, adherend stiffness and strength, coefficient of thermal expansion (CTE), and adhesive properties. The joint is assumed to fail when the adhesive elastic or elastic-plastic strain are exceeded or the adherend strengths are exceeded.

Since the actual properties of the LARC-13 (Modified) adhesive are not available, analyses to date have been made using assumed properties. These analyses have been aimed at identifying performance trends rather than quantitative joint strengths. Analyses have resulted in eliminating some of the step-lap joint test variables from the original small specimen test matrix by showing that they would not yield the expected test results. Additional analyses will be performed as actual adhesive properties become available from our allowables and ancillary test programs.



- N_x is 2.10 MN/m (12,000 lb/in)
- UNCERTAINTIES
  - Load Distribution
  - Honeycomb Closeout
  - Material Properties

Figure 2-14 PRELIMINARY DESIGN FOR BOLTED ATTACHMENT TYPE 3.

2.2 TASK 1.2 - Material and Small Component Characterization

This section discusses prepreg quality control, design allowables testing and small specimen tests.

2.2.1 Prepreg Quality Control

The limited storage life problem encountered with the Celion 6000/PMR-15 prepreg delivered last April (Lots 2W4523 and 2W4524) has been attributed to resin changes resulting from resin formulation scale-up. During the "variability" program (Contract NAS1-15009, Task J), resin batch size was a maximum of 7 kg (15 lb); 18 kg (40 lb) batches were made for the prepreg delivered in April. The larger batch size resulted in an uncontrolled exotherm during the MDA addition step; as a result, the resin was not a mix of monomeric reactants only, but included a significant amount of reaction products. Not only do the reaction products tend to be less stable than the monomeric reactants, but the exotherm produced an amount of reaction which would take months to occur under 255K (0°F) storage conditions. Prepreg made using this resin was processable, but only for a limited amount of time.

An 18 kg (40 lb) order for Celion 3000/PMR-15 prepreg was placed in July. As noted in previous reports, Celion 3000 fiber was chosen due to the change to thinner tape (0.063 mm, nominal) required to meet design considerations. Two attempts to make 18 kg (40 lb) resin batches with a controlled exotherm were unsuccessful; reducing the temperature of the two esters prior to adding the MDA/MeOH and increasing reaction vessel cooling to maximum were insufficient to minimize the exotherm. Success (defined as a negligible exotherm on mixing) was achieved when the batch size was reduced back to 7 kg (15 lb) mixed in a smaller vessel; to further increase the probability of success, the two esters were cooled (to a lower temperature than used on the "variability" program) prior to adding the MDA/MeOH. Subsequently, an 11 kg (25 lb) batch of resin was made in the smaller reaction vessel, but under somewhat different conditions than for the 7Kg (15 lb) batch. Both sets of conditions met the requirements established by the "variability" program. These last two batches of resin were used to make 15.5 kg (34 lbs) or prepreg, which were received at Boeing on August 30, 1979. Although two batches of resin were used in prepreging, only one lot number (2W4582) was assigned, with roll 1 having been prepregged with the smaller batch of resin, roll 3 with the larger batch, and roll 2 with some of each. Quality control tests were therefore run on prepreg from both rolls -1 and -3.

Prepreg Quality Control Tests - The tests run on lot 2W4582, rolls -1 and -3, are summarized in Figures 2-15 through 2-20. The flexural properties are low because the cure cycle used does not permit removal of the excessively high amount of resin present in this lot of prepreg (see Figure 2-15). When normalized to 60 FV, properties are good to excellent. HPLC tests were discussed in the next section.

Figure 2-15: Prepreg Physicals Lot 2W4582

Roll No.	(Wet) Resin Solids, %	(Dry) Resin Solids, %	Volatile Content, %	Gel Time, Seconds
1	51.5	44.1	13.3	45-50
2	50.1	42.6	12.0	50
3	50.8	43.3	13.2	50

High Pressure Liquid Chromatography (HPLC) - Although liquid chromatography has the sensitivity required to detect small amounts of undesirable resin constituents, the reproducibility of the equipment and interpretation of the data are still problem areas. The standard HPLC method was used to evaluate and compare PMR-15 resin batches that were prepared by four slightly different techniques. Three other HPLC techniques (varying columns and/or mobile phase) were also used. The four HPLC techniques all differentiated among the four resins, which ranged from resin that had a violent exothermic reaction on MDA/MeOH addition, to the resins used in prepreg lot 2W4582, where the reaction was carefully controlled. However, the HPLC methods require further development before they can be used to guarantee detection of marginal prepreg. Development would include identification of the HPLC peaks and establishing limits on the amount of each undesirable component (e.g., reaction product present).

Figure 2-16: PREPREG LAMINATE PROPERTIES

PROPERTY		PANEL 2W4582-1R (From Roll #1)	PANEL 2W4582-2R (From Roll #3)
FIBER VOLUME, %		49.5	53.3
RESIN CONTENT, % (Weight)		43.1	39.5
SPECIFIC GRAVITY		1.530	1.550
VOID CONTENT, %*		-0.2	-0.4
Tg (TMA Method)		Between 609K & 618K	Between 603K & 605K
PER PLY THICKNESS, Nominal		.081 mm (3.2 mil)	.076 mm (3.0 mil)
FLEXURAL STRENGTH, MPa (Ksi)	At Ambient	1386 (201)	1586 (230)
	At 589K	931 (135)	958 (139)
	Aged, at 589K	938 (136)	1110 (161)
FLEXURAL MODULUS, GPa (Msi)	At Ambient	123 (17.9)	116 (16.9)
	At 589K	101 (14.7)	103 (14.9)
	Aged, at 589K	102 (14.8)	104 (15.1)
SHORT BEAM SHEAR STRENGTH, MPa (Ksi)	At Ambient	101 (14.7)	101 (14.6)
	At 589K	68 (9.9)	63 (9.2)
	Aged, at 589K	63 (9.1)	59 (8.5)

NOTE: Aging consisted of 125 hours exposure to air at 589K (600°F).

* Calculated, based on densities of 1.76 and 1.30 for fiber and resin.

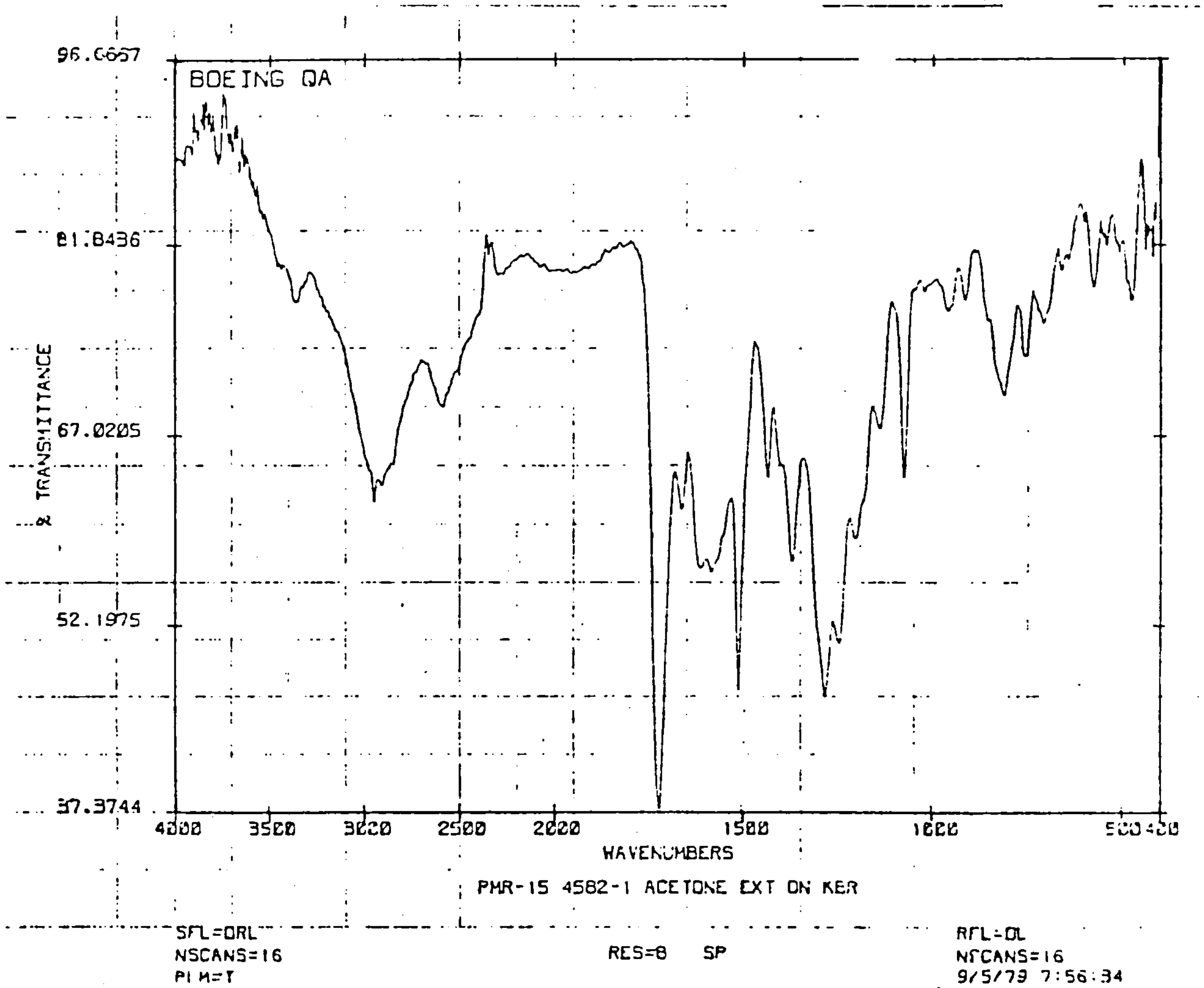


FIGURE 2-17: FTS-IR, WR4582, ROLL 1

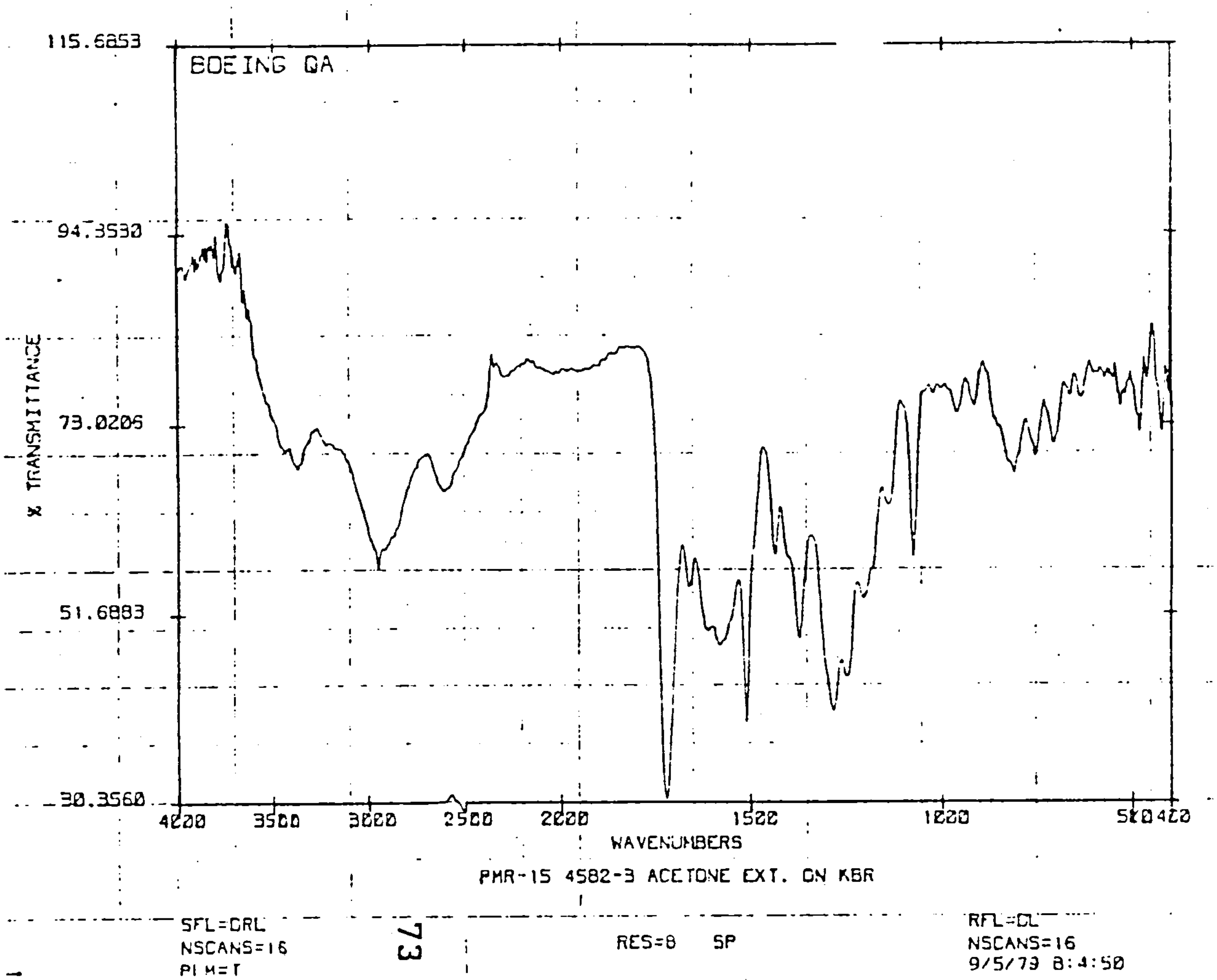


FIGURE 2-18: FTS-IR, WR4582, ROLL 3

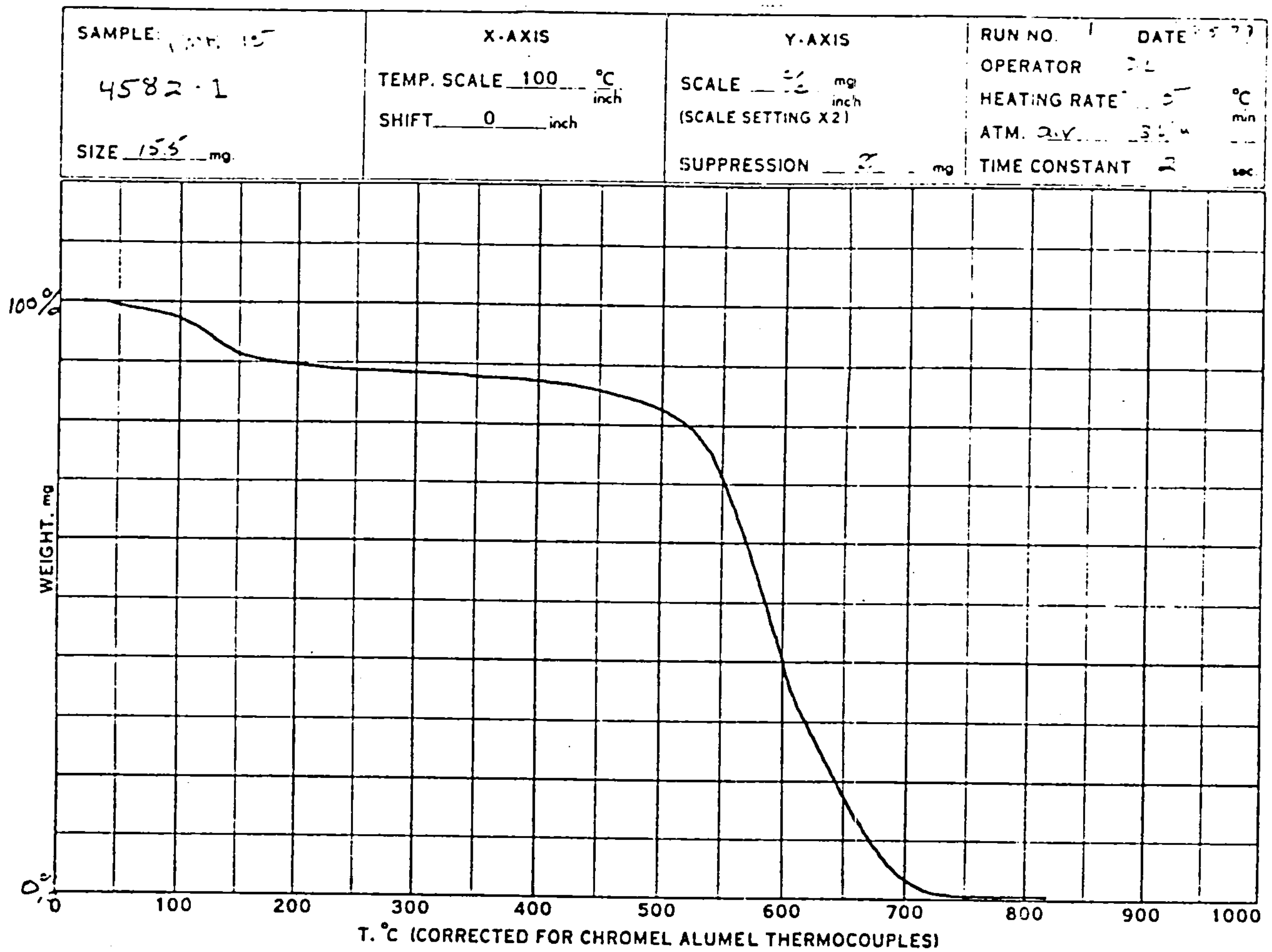


FIGURE 2-19: TGA, WR4582, ROLL 1

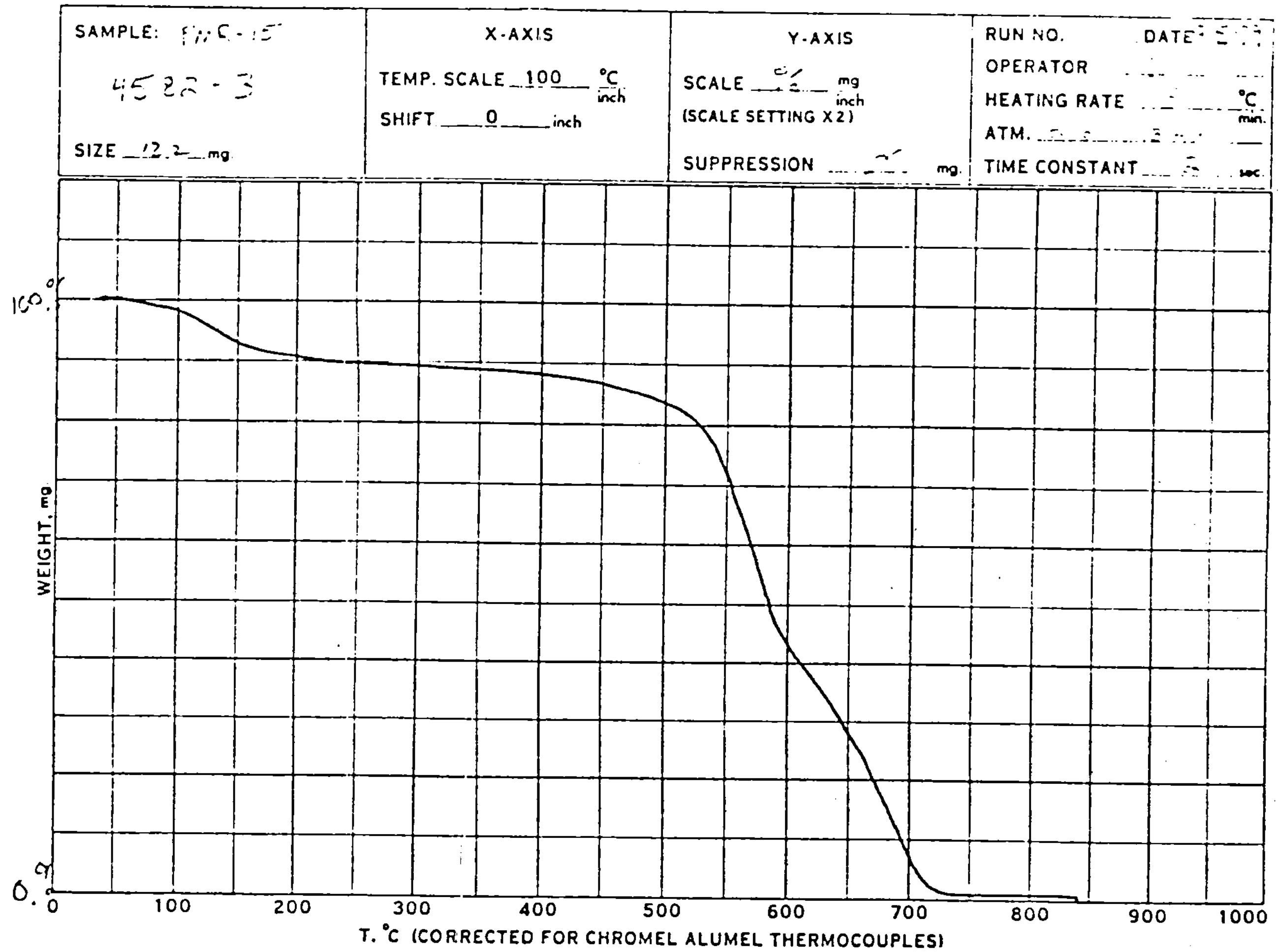


FIGURE 2-20: TGA, WR4582, ROLL 3

2.2.2 TASK 1.2.1 - Design Allowables

A limited design allowables program is being conducted by Boeing under Independent Research and Development funding. The result of this task will develop a database of laminate material properties which will support failure prediction and analysis correlation of the joint tests conducted in subsequent tasks of this program. Results will be published when available.

The test matrix shown in Figure 2-21 has 0°, 90°, ±45° and quasi-isotropic laminates made from Celion 3000/PMR-15 prepreg. Data will be generated at room temperature and at 561K (550°F) for as-cured/post-cured specimens as well as conditioned specimens. Conditioning includes isothermal aging at 589K (600°F) for 450 ks (125 hours), thermal cycling and moisture exposure. The test matrix included 0° sandwich beam compression and bonded rail shear tests which have been added to the matrix shown in Reference 1.

As shown in Figure 2-22, all of the panels required for the design allowables test matrix have been fabricated, postcured, and C-scanned. Aside from a few minor defects all of the panels C-scanned "clean" except for the large area, 16 or 30 ply unidirectional panels, where the C-scans indicate several large areas of porosity. A representative area is shown in Figure 2-23. The cause of the problem is under investigation.

The tensile properties of a $[0/\pm45/90]_{2s}$ laminate made from the previous lot of prepreg (2W4523; panel -2) were reported in the 2nd Quarterly (Ref. 2) as being only 345 MPa (50 ksi) at R.T. and 303 MPa (44 ksi) at 589K (600°F), with a modulous of 50 GPa (7.3 msi). The low strength values were attributed to non-uniform loading through the tabs of the rectangular cross-section specimens, aggravated by poor alignment in testing. More recent data support those conclusions. Pin-located, "tapered bow tie" tensile specimens were machined from the 508 mm by 1143 mm $[0/\pm45/90]_{2s}$ panel 2W4523-4 and three specimens were tested at room temperature. Tensile strengths of 563, 490, and 579 MPa (81.7, 71.1 and 84.0 ksi) were achieved, at an average modulus of 45.5 GPa (6.6 msi). Some of the scatter is attributed to specimen geometry, however, it appears that a specimen design with less taper would be desirable. In any case, tensile strength above 500 MPa indicates good resin and fiber properties, since the strength is as high or higher than that of an equivalent GR/EP laminate.

TEST No.	TEST TYPE	LAMINATE ORIENTATION	CONDITIONING ▷1	NUMBER OF TESTS AT RT	NUMBER OF TESTS AT 561K (550°F)	NUMBER OF TESTS AT 116K (-250°F)	TOTAL NUMBER OF SPECIMENS	TEST PROCEDURES	SPECIMEN CONFIGURATION	INSTRUMENTATION	DATA REQUIRED
1	TENSION	0°_{16}	1 2 3	3 3 5	3 3 5		6 6 10	ASTM D 3039	Figure 2-21A	▷2	• ▷4 • POISSON'S RATIO - 2 SPECIMENS EACH SET OF 5
2	TENSION	90°_{30}	1 2 3 4	3 3 5 3	3 3 5 3		6 6 10 6	ASTM D 3039	Figure 2-21B	▷2	• ▷3 • ▷4
3	TENSION	$(0/\pm45/90)_{4S}$	1 2 3 4	3 3 5 0	3 3 5 5		6 6 10 5	ASTM D 3039	Figure 2-21C	▷2	▷3
4	COMPRESSION	$(\pm45/90/0)_{4S}$	1 2 3 4	3 3 5 3	3 3 5 3		6 6 10 6	ASTM D 695	Figure 2-21D	• EXTENSOMETER • STRAIN GAGE 4 SPECIMENS	▷3
5	COMPRESSION (SANDWICH BEAM)	$(0/\pm45/90)_S$	2	3	3		6	ASTM C 393	Figure 2-21E	• EXTENSOMETER • STRAIN GAGE	• MODULUS • ULTIMATE LOAD
6	SHEAR	$(\pm45)_{8S}$	1 2 3 4	3 3 5 3	3 3 5 3		6 6 10 6	ASTM D 3039	Figure 2-21B	STRAIN GAGE	• SHEAR MODULUS • TENSION ULTIMATE LOAD • TENSION MODULUS
7	FLATWISE TENSION (LAMINATE)	$(0/\pm45/90)_{2S}$	1 2	3 3	3 3	3 3	9 9	ASTM D2095	Figure 2-21F		ULTIMATE LOAD
8	FLATWISE TENSION (H/C CORE)	$(0/\pm45/90)_{2S}$	1 2 3	3 3 3	3 3 3	3 3 3	9 9 9	ASTM C 297	Figure 2-21G		ULTIMATE LOAD
9	CTE	ADHESIVE ▷5	1 2 4	2 2 2	TESTS CONDUCTED FROM 116K (-250°F) TO 589K (600°F)		2 2 2	TMA MACRO EXPANSION	PER PROCEDURES	PER PROCEDURES	CTE VS TEMP ▷6
10	CTE	90°	1 2 4	2 2 2			2 2 2	TMA MACRO EXPANSION	PER PROCEDURES	PER PROCEDURES	CTE VS TEMP ▷6
11	CTE	$(0/\pm45/90)_{4S}$	1 2 4	2 2 2			2 2 2	QUARTZ DILATOMETER	PER PROCEDURES	PER PROCEDURES	CTE VS TEMP ▷6
12	COMPRESSION	0°_{8}	2	3	3		6	ASTM C393	Figure 2-21H	• EXTENSOMETER • STRAIN GAGE	• MODULUS • ULTIMATE LOAD
13	SHEAR	$(\pm45)_{3S}$	1 2 4	3 3 3	3 3 3		6 6 6		Figure 2-21J	• STRAIN GAGE ROSETTE	• MODULUS • ULTIMATE LOAD

▷1 CONDITION CODE

1 - As cured/postcured

2 - Soaked for 125 hrs at 589K (600°F) in a one (1) atmosphere environment (air)

3 - Thermally cycled 125 times in a temperature range from 116K to 589K (-250°F to 600°F) and in a one (1) atmosphere environment (air)

The cryogenic temperature of 116K (-250°F) shall be held for one-half (1/2) hrs and the maximum temperature of 589K (600°F) shall be held for one (1) hr per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min)

4 - Moisture conditioned

Condition in chamber at 75% RH at 353K (175°F) for two weeks. Followed by conditioning in chamber at 50% RH at RT for two months.

▷2 • Extensometer
• T strain gages to measure Poisson's ratio - 4 specimens

▷3 • Ultimate - all specimens
• Modulus - 3 specimens of each set of 3 or 5

▷4 Creep - 2 589K (600°F) specimens from set of 5
- conduct tension test to failure on 1st 3 specimens. Load final 2 specimens to 80% of average ultimate values (1st 3 specimens). Hold this load for 0.5 hr, measure creep, then load specimens to failure.

▷5 A7F (LARC-13, Amide-Imide modified) Adhesive film cured into bulk neat resin specimens.

▷6 Run cycle until data reproduce. Report both initial CTE curve and final curve.

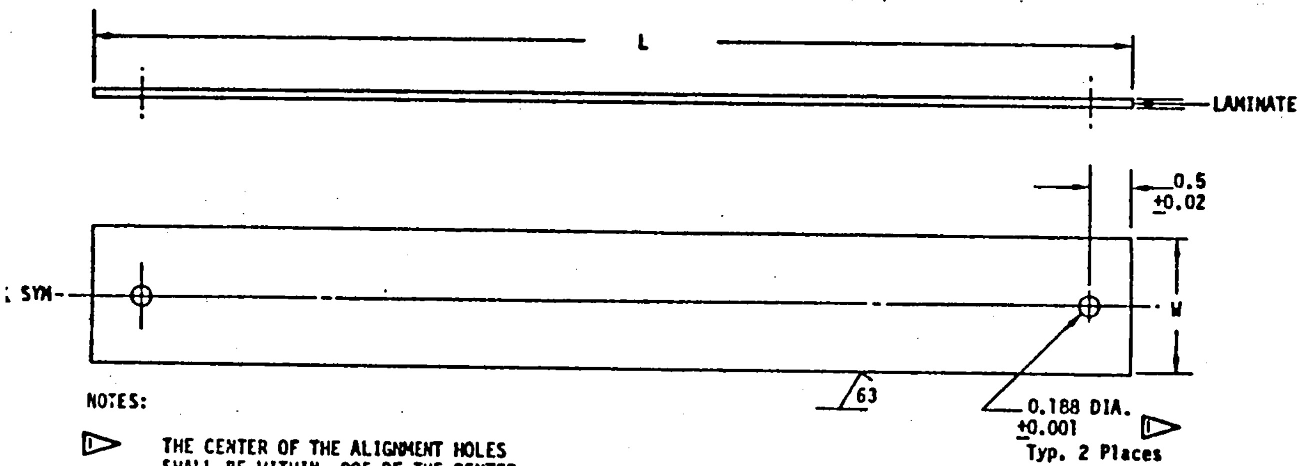
General note

• Determine and record dry weight of each specimen immediately after post cure.

• Determine and record weight of each specimen immediately prior to test.

• All prepreg is Celion/PMR-15 .063 mm (.0025 in) per ply

Figure 2-21 TEST MATRIX 1 - DESIGN ALLOWABLES



NOTES:

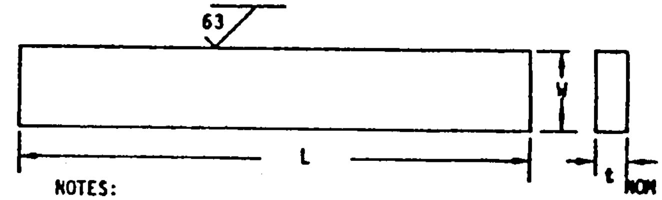
1. THE CENTER OF THE ALIGNMENT HOLES SHALL BE WITHIN .005 OF THE CENTER LONGITUDINAL AXIS.

SPECIMEN	W	L
2-21A	0.5 ± 0.01	12.00 ± 0.33
2-21B	1.00 ± 0.01	12.00 ± 0.33
2-21C	1.00 ± 0.01	12.00 ± 0.03

Figure 2-21A: TENSION SPECIMEN

Figure 2-21B: TENSION SPECIMEN

Figure 2-21C: TENSION SPECIMEN



NOTES:

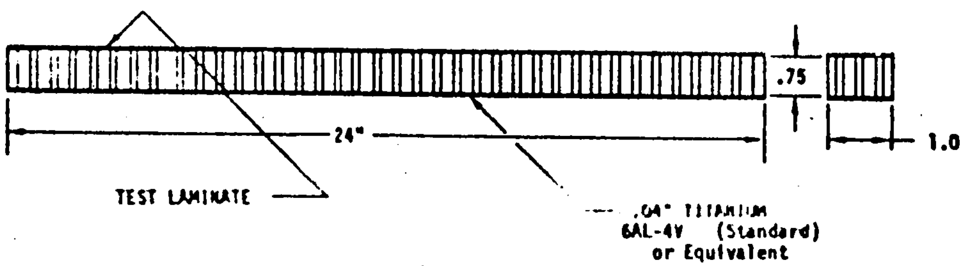
1. EDGES SHALL BE FLAT AND PARALLEL TO EACH OTHER WITHIN 0.005 TIR.

2. ENDS SHALL BE FLAT AND PARALLEL TO EACH OTHER WITHIN 0.001 TIR AND AT 90° ±0.25° TO THE ADJACENT FACES.

TABULATED DIMENSIONS

SPECIMEN	W	L
2-21D	1.00 ±0.01	(5.50 + 3t) ±.01

Figure 2-21D: RECTANGULAR COMPRESSION SPECIMEN



TEST LAMINATE $(0,\pm45,90)_s$
(.0025") CELION 3000 TAPE

CORE - HRH 327 - 3/16 - 8.0
(HEXCEL DESIGNATION)

Figure 2-21E: SANDWICH BEAM SPECIMEN

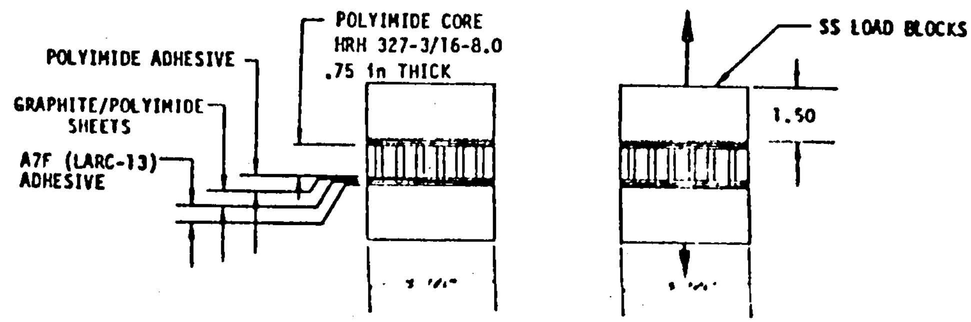


Figure 2-21G: FLATWISE TENSILE SPECIMEN

NOTE: All dimensions are in inches

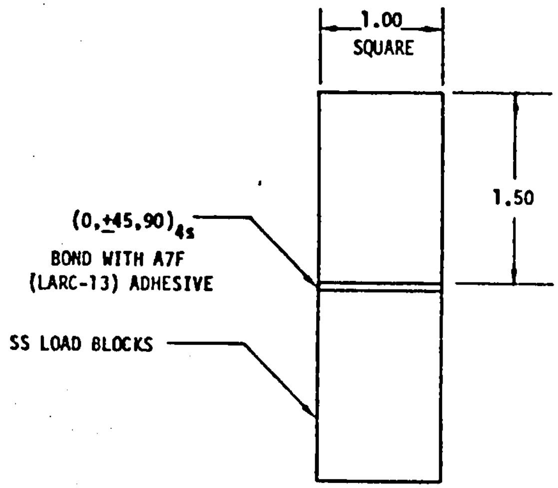


Figure 2-21F: FLATWISE TENSION SPECIMENS

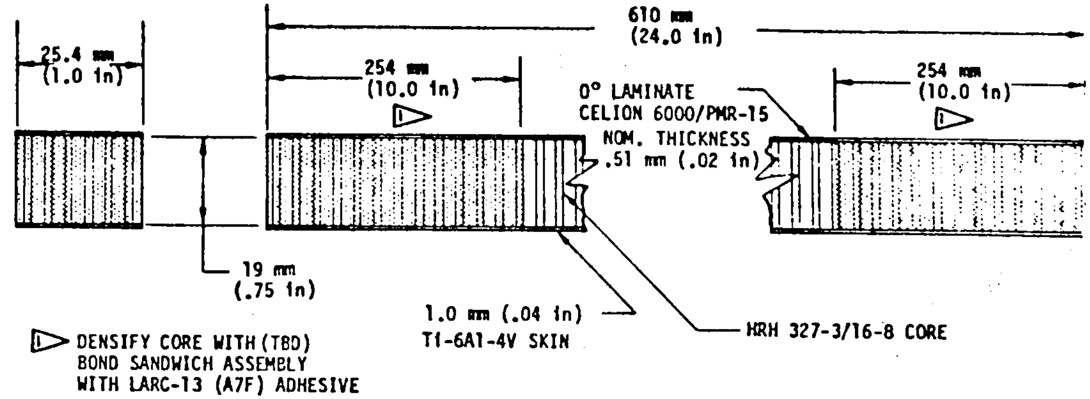


Figure 2-21H: SANDWICH BEAM COMPRESSION SPECIMEN

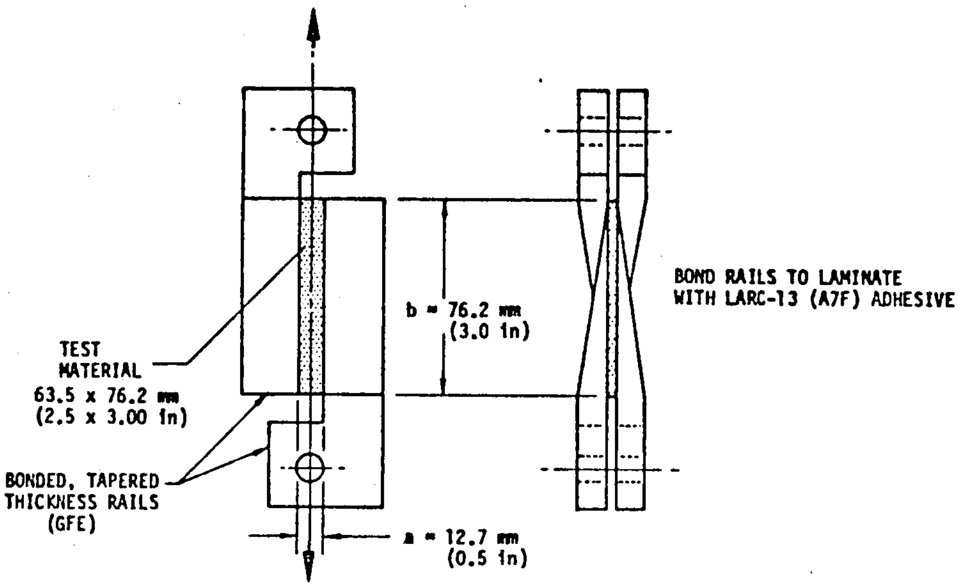


Figure 2-21J: BONDED RAIL SHEAR SPECIMEN

Figure 2-22 DESIGN ALLOWABLES PANEL FABRICATION STATUS

PANEL NO.	LAYUP	SIZE mm* (in.)	ROLL NO.	LAYUP DATE	CURE DATE	PC*** DATE	C-SCAN DATE	FOR USE IN TEST NO.: **
2W4582-1R	$(0)_{24}$	305x152 (12x6)	1	9/6	9/6	9/6	9/7	(QC)
2W4582-2R	$(0)_{24}$	305x152 (12x6)	3	9/6	9/6	9/6	9/7	(QC)
2W4582-3	$(0)_{8}$	635x279 (25x11)	3	9/5	9/7	9/27	10/2	12
2W4582-4	$(0)_{16}$	330x965 (13x38)	3	9/10	9/11	9/27	10/2	1
2W4582-5	$(\pm45)_{3S}$	229x660 (9x26)	3	9/11	9/12	9/27	10/2	13
2W4582-6	$(0/\pm45/90)_{S}$	635x330 (25x13)	3	9/17	9/18	9/27	10/2	5
2W4582-7	$(0/\pm45/90)_{2S}$	635x330 (23x13)	3	9/17	9/19	9/27	10/2	7 & 8
2W4582-8	$(0)_{30}$	559x330 (22x13)	3 & 2	9/18	9/19	9/27	10/2	2
2W4582-9	$(0)_{30}$	686x330 (27x13)	3	9/12	9/14	9/27	10/2	2
2W4582-10	$(\pm45)_{8S}$	559x330 (22x13)	2	9/21	9/25	9/27	10/2	6
2W4582-11	$(\pm45)_{8S}$	686x330 (27x13)	3	9/14	9/17	9/27	10/2	6
2W4582-12	$(\pm45/90/0)_{4S}$	178x559 (7x22)	2	9/20	9/21	9/27	10/2	4
2W4582-13	$(\pm45/90/0)_{4S}$	178x686 (7x27)	2	9/21	9/21	9/27	10/2	4
2W4582-14	$(0/\pm45/90)_{4S}$	330x533 (13x21)	2	9/25	9/26	9/27	10/2	3 & 11
2W4582-15	$(0/\pm45/90)_{4S}$	330x762 (13x30)	2	9/21	9/24	10/4	10/5	3 & 11

* 0° direction listed first (does not apply to ±45 panels)

** Refer to Figure 2-21

*** PC Post Cure

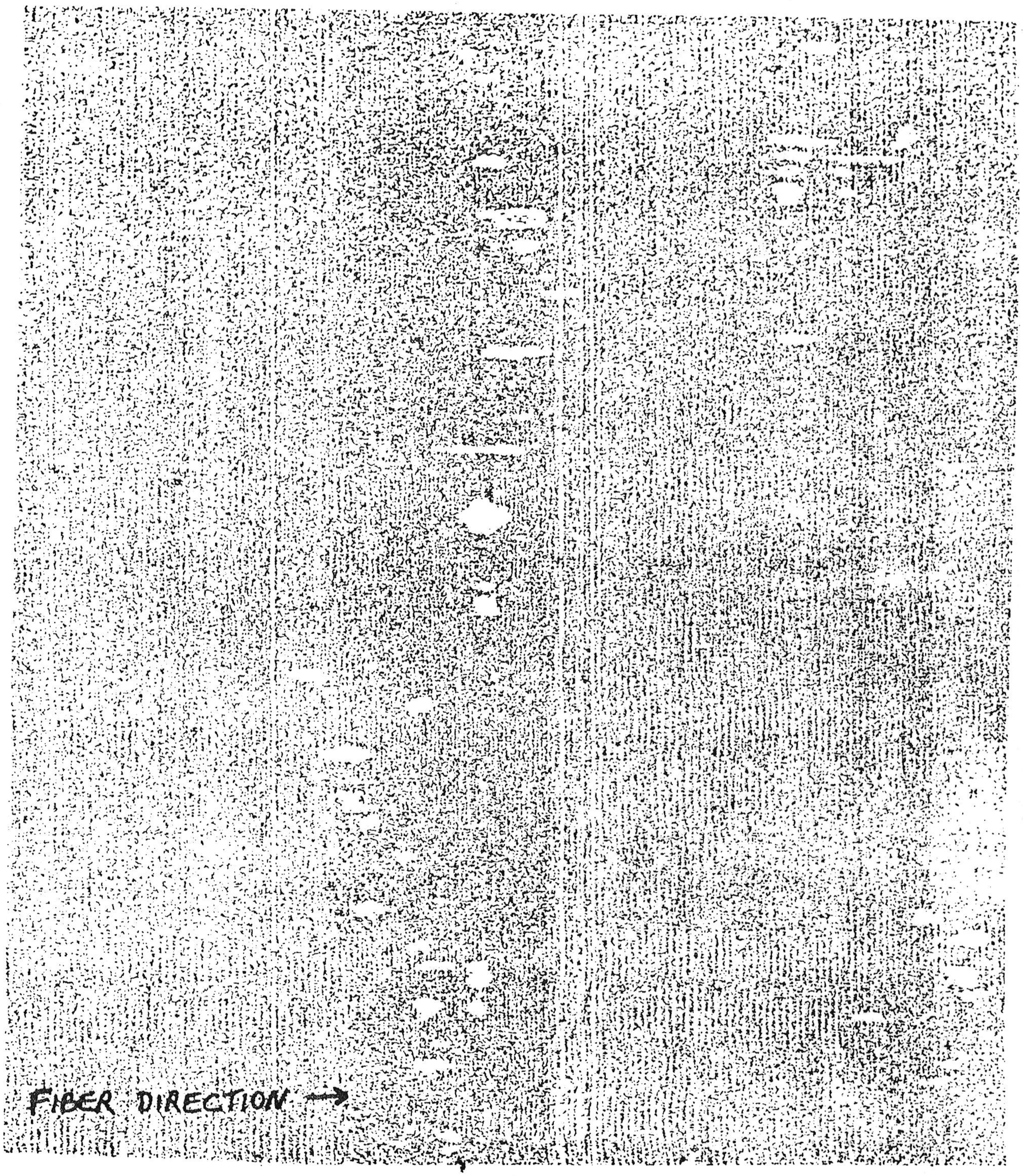


Figure 2-23 REPRESENTATIVE AREA OF C-SCAN OF PANEL 2W4582-9 (SCALE IS 1:1)

2.2.3 TASK 1.2.2 - Small Specimen Tests

The small specimen tests have been established to give initial data regarding basic joint component behavior. Two test matrices, designated 4A & 4B, will examine bearing, shear-out and net tension strength of GR/PI laminates as well as pad-up and transition capability. The test series are shown in Figure 2-24 and Figure 2-25. The data developed in test series 4B-1 and 4B-2 will define the local laminate and joint geometry for the sandwich tests in test series 4B-3.

Additional small specimen tests will be conducted to evaluate attachment angles and honeycomb close-out designs. Test matrices and specimen configurations will be defined after further detail joint design and analysis has been completed.

2.3 TASK 1.3 - Preliminary Evaluation of Attachment Concepts

The test matrix for the preliminary evaluation of the attachment concepts will be developed considering the small specimen test matrix and the results from the third cut screening (see Fig. 2-2). Ambient and elevated static tests to failure will be performed on a minimum of one concept for each joint type. The results from these tests will be used to finalize the designs of the specimens for the TASK 1.4 static strength and fatigue evaluation tests.

Figure 2-24. TEST MATRIX 4A - SMALL SPECIMEN TESTS (Bolted Joint Allowables)

Test No.	W mm (in.)	e mm (in.)	Laminate	Condition ▷1	Specimen* Type	No. of Tests @ RT	No. of Tests @ 561K(550°F)	Total Specimens
1a	63.5(2.5)	19.0 (.75)	$(0_2 \pm 45_2 90_2)_{4s}$	1	4A-1	3	3	6
1b	63.5(2.5)	19.0 (.75)	$(0_2 \pm 45_2 90_2)_{4s}$	2	4A-1	3	3	6
1c	63.5(2.5)	19.0 (.75)	$(0_2 \pm 45_2 90_2)_{4s}$	3	4A-1	3	3	6
2a	63.5(2.5)	33.3 (1.31)	$(0_2 \pm 45_2 90_2)_{4s}$	1	4A-1	3	3	6
2b	63.5(2.5)	33.3 (1.31)	$(0_2 \pm 45_2 90_2)_{4s}$	2	4A-1	3	3	6
2c	63.5(2.5)	33.3 (1.31)	$(0_2 \pm 45_2 90_2)_{4s}$	3	4A-1	3	3	6
3a	33.3 (1.31)	33.3 (1.31)	$(0_2 \pm 45_2 90_2)_{4s}$	1	4A-1	3	3	6
3b	33.3 (1.31)	33.3 (1.31)	$(0_2 \pm 45_2 90_2)_{4s}$	2	4A-1	3	3	6
3c	33.3 (1.31)	33.3 (1.31)	$(0_2 \pm 45_2 90_2)_{4s}$	3	4A-1	3	3	6
4a	47.8 (1.88	-	$(0_2 \pm 45_2 90_2)_{4s}$	1	4A-2	3	3	6
4b	47.8 (1.88)	-	$(0_2 \pm 45_2 90_2)_{4s}$	2	4A-2	3	3	6
4c	47.8 (1.88)	-	$(0_2 \pm 45_2 90_2)_{4s}$	3	4A-2	3	3	6

▷1 CONDITION CODE

1 - As cured/postcured

2 - Soaked for 450 ks (125 hrs) at 589K (600°F) in a one (1) atmosphere environment (air).

3 - Thermally cycled 125 times in a temperature range from 116K to 589K (-250°F to 600°F) and in a one (1) atmosphere environment (air).

The cryogenic temperature of 116K (-250°F) shall be held for 1800 sec (1/2 hr) and the maximum temperature of 589K (600°F) shall be held for 3600 sec (1 hr) per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min).

* See Figure 2-26

Figure 2-25 : TEST MATRIX 4B - SMALL SPECIMEN TESTS (Bonded Doublers)

TEST NO.	La mm (in)	t_1 mm (in)	t_2 or t_3 mm (in)	Laminate		Condition [1]	Specimen* Type	No. of Tests @		Total Specimens
				1	2			RT	561°F(550°F)	
1a	63.5(2.5)	.51(.02)	1.52(.06)	$(0,+45,90)_s$	$(0,\pm45,90)_{3s}$	1	4B-1	3	3	6
1b	63.5(2.5)	.51(.02)	1.52(.06)	$(0,\pm45,90)_s$	$(0,\pm45,90)_{3s}$	2	4B-1	3	3	6
1c	63.5(2.5)	.51(.02)	1.52(.06)	$(0,\pm45,90)_s$	$(0,\pm45,90)_{3s}$	3	4B-1	3	3	6
2a	63.5(2.5)	.51(.02)	2.04(.08)	$(0,\pm45,90)_s$	See Fig. 2-26	1	4B-2	3	3	6
2b	63.5(2.5)	.51(.02)	2.04(.08)	$(0,\pm45,90)_s$	See Fig. 2-26	2	4B-2	3	3	6
2c	63.5(2.5)	.51(.02)	2.04(.08)	$(0,\pm45,90)_s$	See Fig. 2-26	3	4B-2	3	3	6
3a	33.0(1.3)	.51(.02)	See Fig. 2-26	$(0,\pm45,90)_s$	See Fig. 2-26	1	4B-3	3	3	6
3b	33.0(1.3)	.51(.02)	See Fig. 2-26	$(0,\pm45,90)_s$	See Fig. 2-26	2	4B-3	3	3	6
3c	33.0(1.3)	.51(.02)	See Fig. 2-26	$(0,\pm45,90)_s$	See Fig. 2-26	3	4B-3	3	3	6
4a	45.7(1.8)	.51(.02)	See Fig. 2-26	$(0,\pm45,90)_s$	See Fig. 2-26	2	4B-3	3	3	6

[1] CONDITION CODE

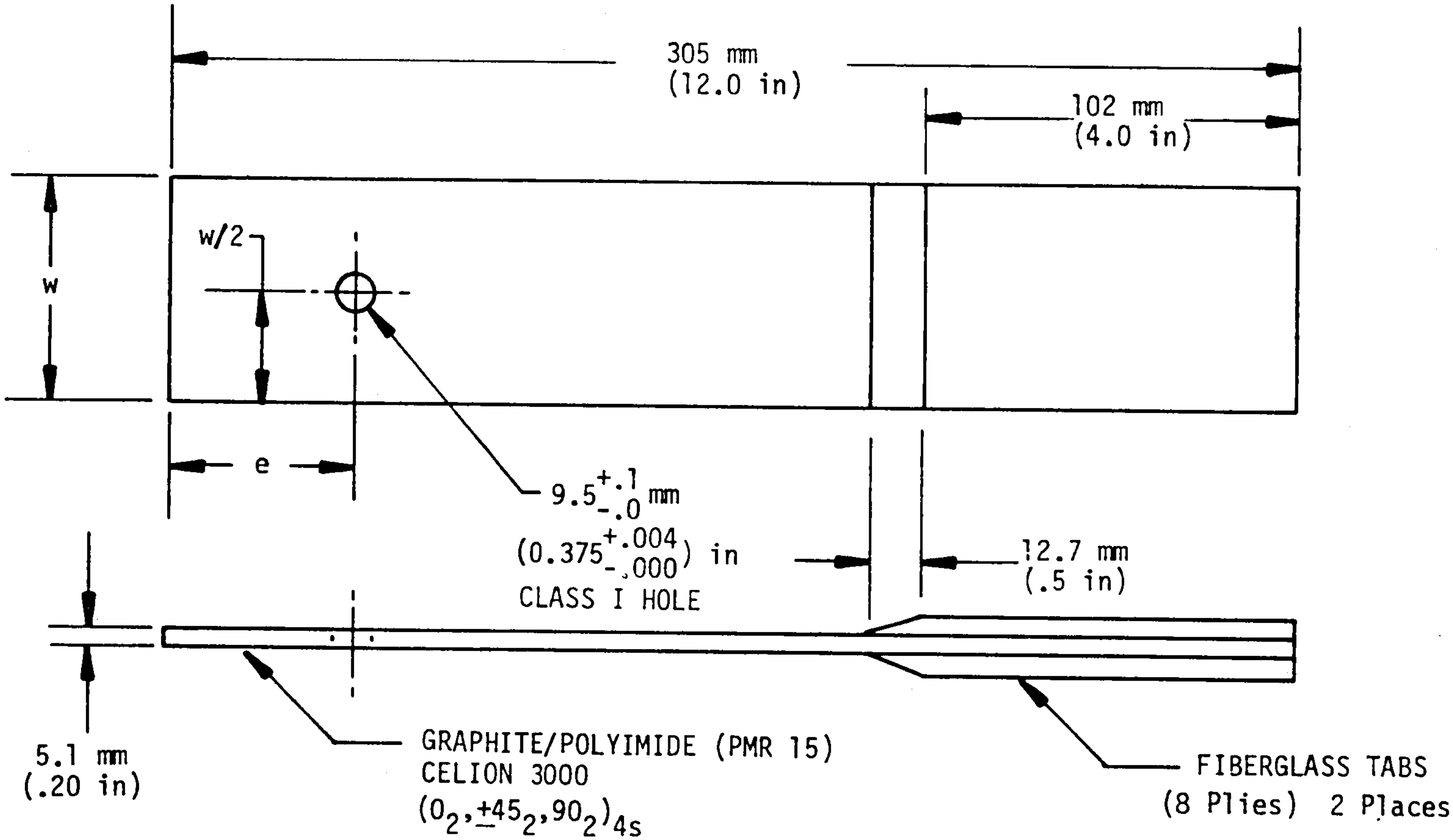
1 - As cured/postcured

2 - Soaked for 450 ks (125 hrs) at 589K (600°F) in a one (1) atmosphere environment (air).

3 - Thermally cycled 125 times in a temperature range from 116K to 589K (-250°F to 600°F) and in a one (1) atmosphere environment (air).

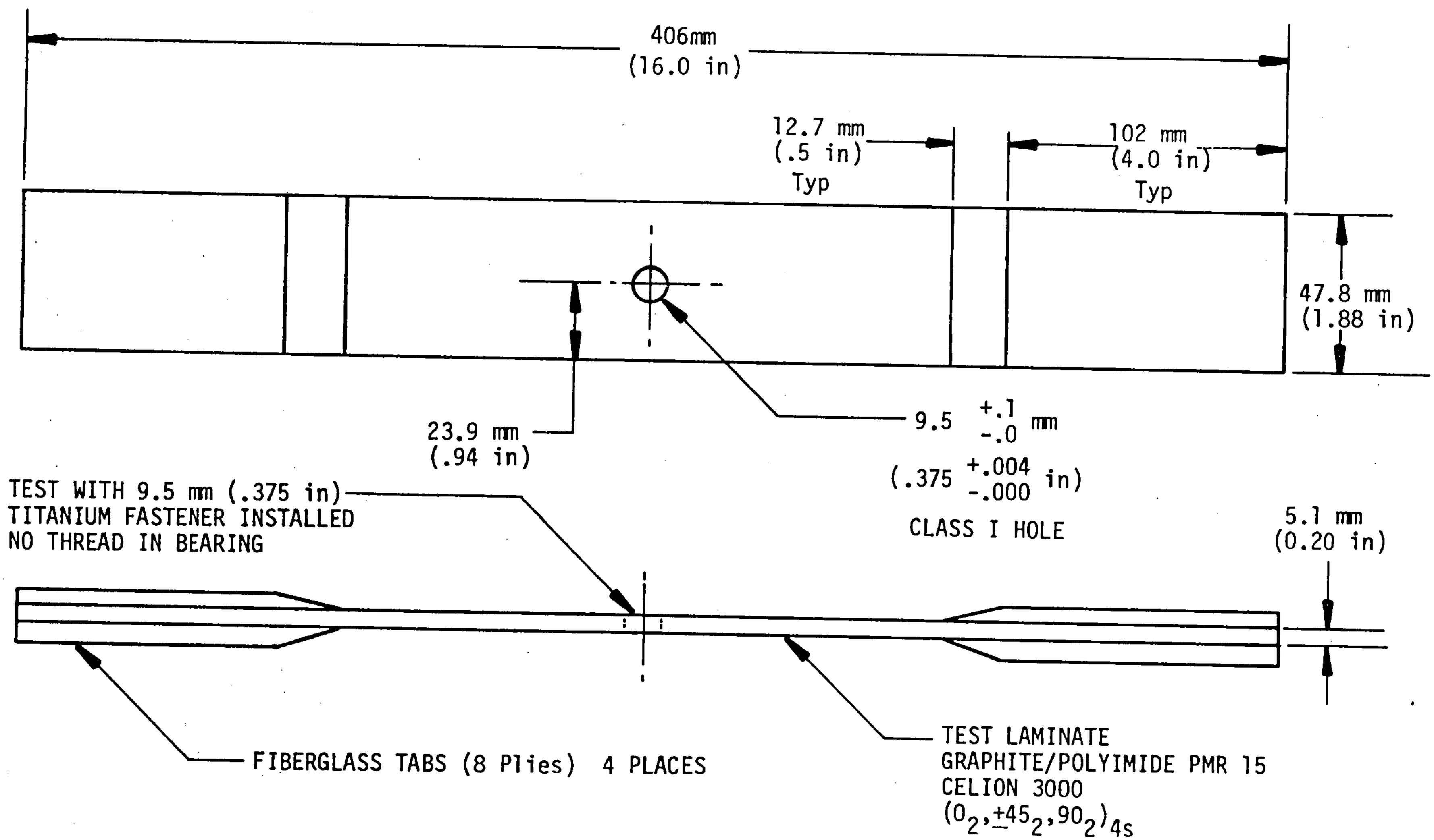
The cryogenic temperature of 116K (-250°F) shall be held for 1800 sec (1/2 hr). and the maximum temperature of 589K (600°F) shall be held for 3600 sec (1 hr) per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min).

* See Figure 2-26



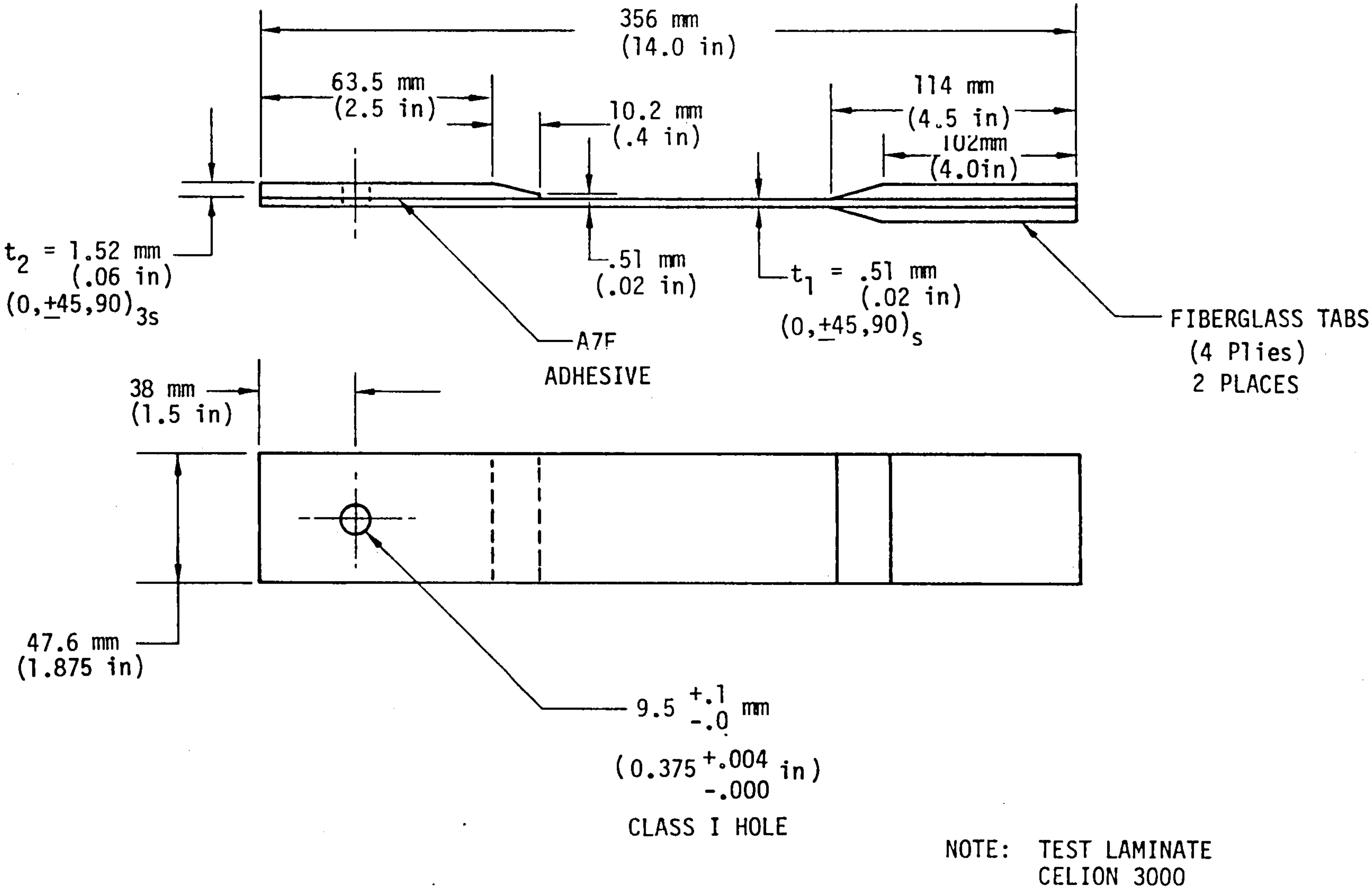
SPEC 4A-1

Figure 2-26 SMALL SPECIMEN TESTS



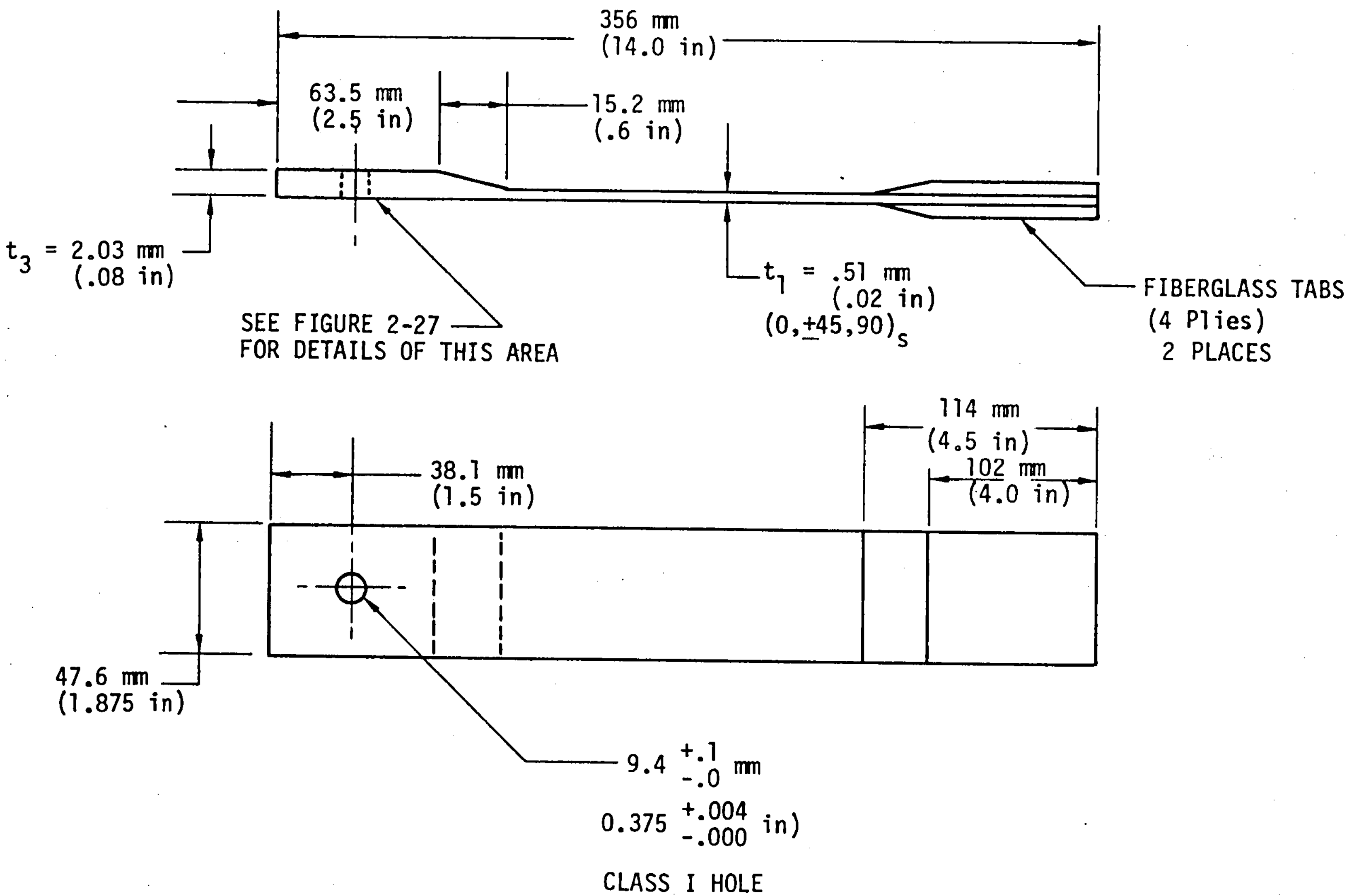
SPEC. 4A-2

Figure 2-26 SMALL SPECIMEN TESTS (Cont.)



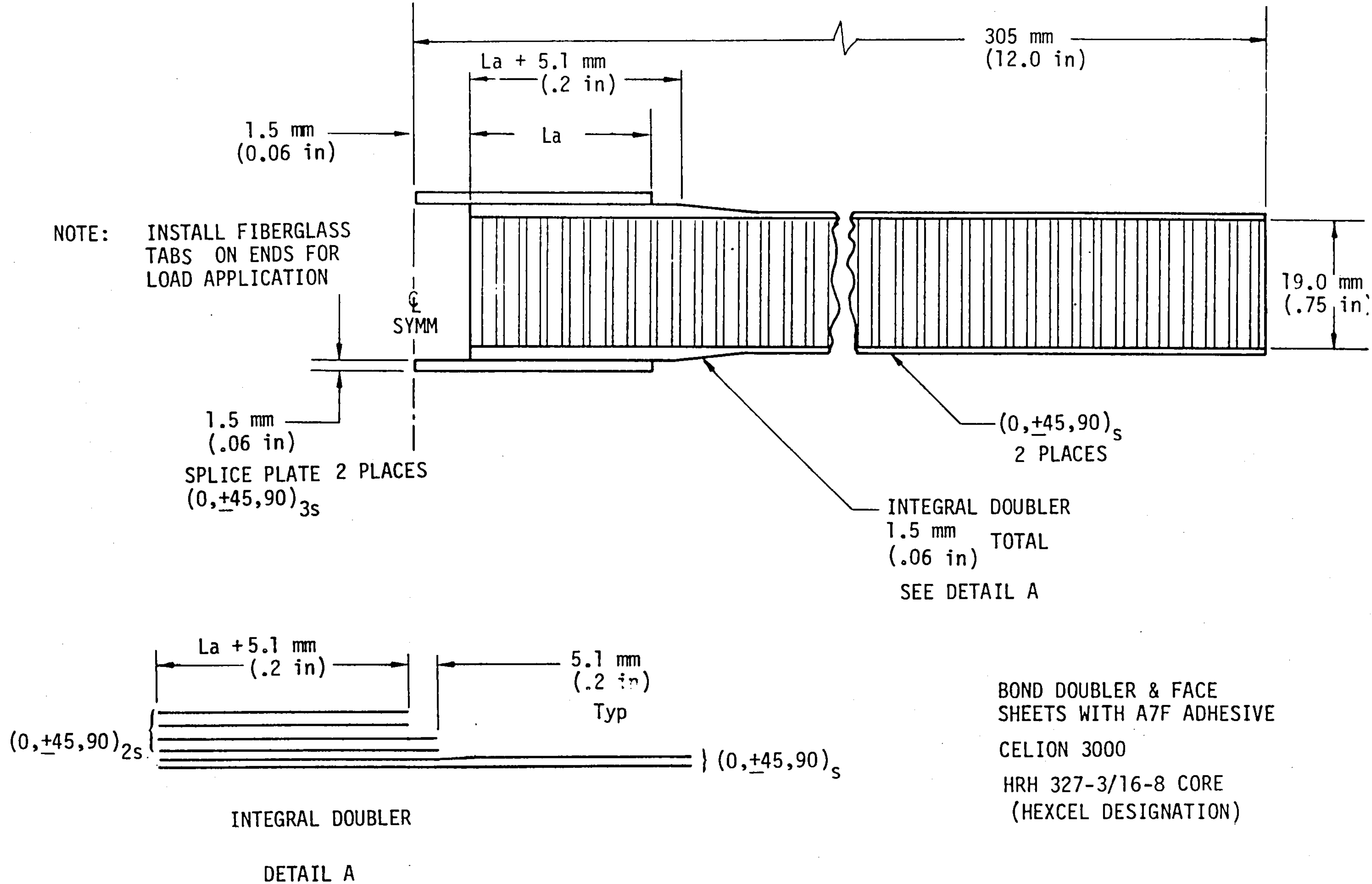
SPEC 4B-1

Figure 2-26 SMALL SPECIMEN TESTS (Cont.)



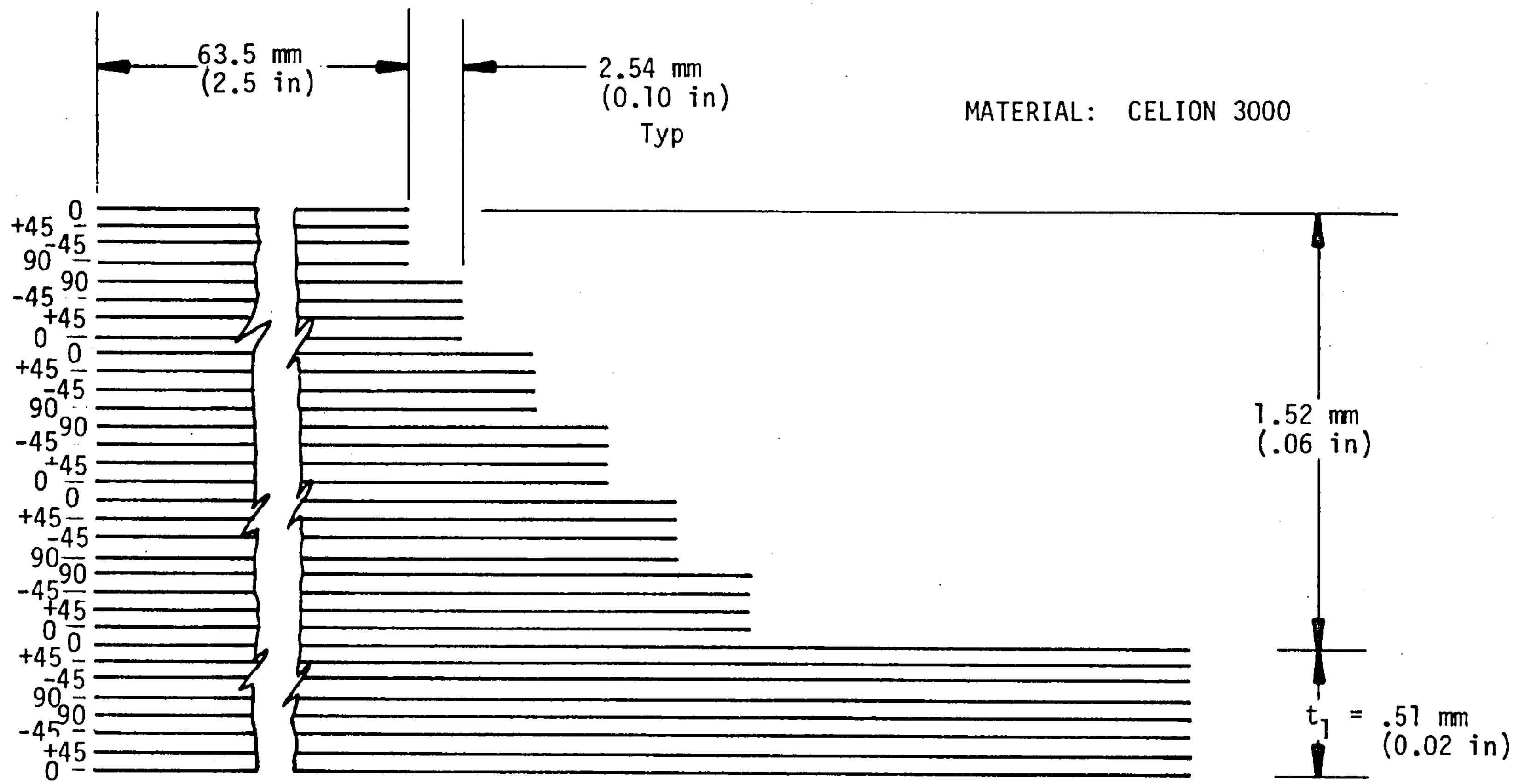
SPEC 4B-2

Figure 2-26 SMALL SPECIMEN TESTS (Cont.)



SPEC. 4B-3

Figure 2-26 SMALL SPECIMEN TESTS (Cont.)



SPEC. 4B-2

Figure 2-27 SMALL SPECIMEN TESTS

SECTION 3.0

TASK 2 - BONDED JOINTS

3.1 TASK 2.1 - Standard Bonded Joints

This task includes the analysis, fabrication and static strength determination of several standard bonded joint configurations. The theoretical influence of geometric and material parameters are being investigated and a test/analysis correlation performed to determine the relative efficiencies of the various joint configurations. The relationships of the sub-task activities are shown in Figure 3-1.

This section discusses analysis of standard joints, test plan development, ancillary laminate and adhesive tests, joint specimen fabrication and NDE, and joint test program.

3.1.1 TASK 2.1.1 - Analysis of Standard Joint Specimens

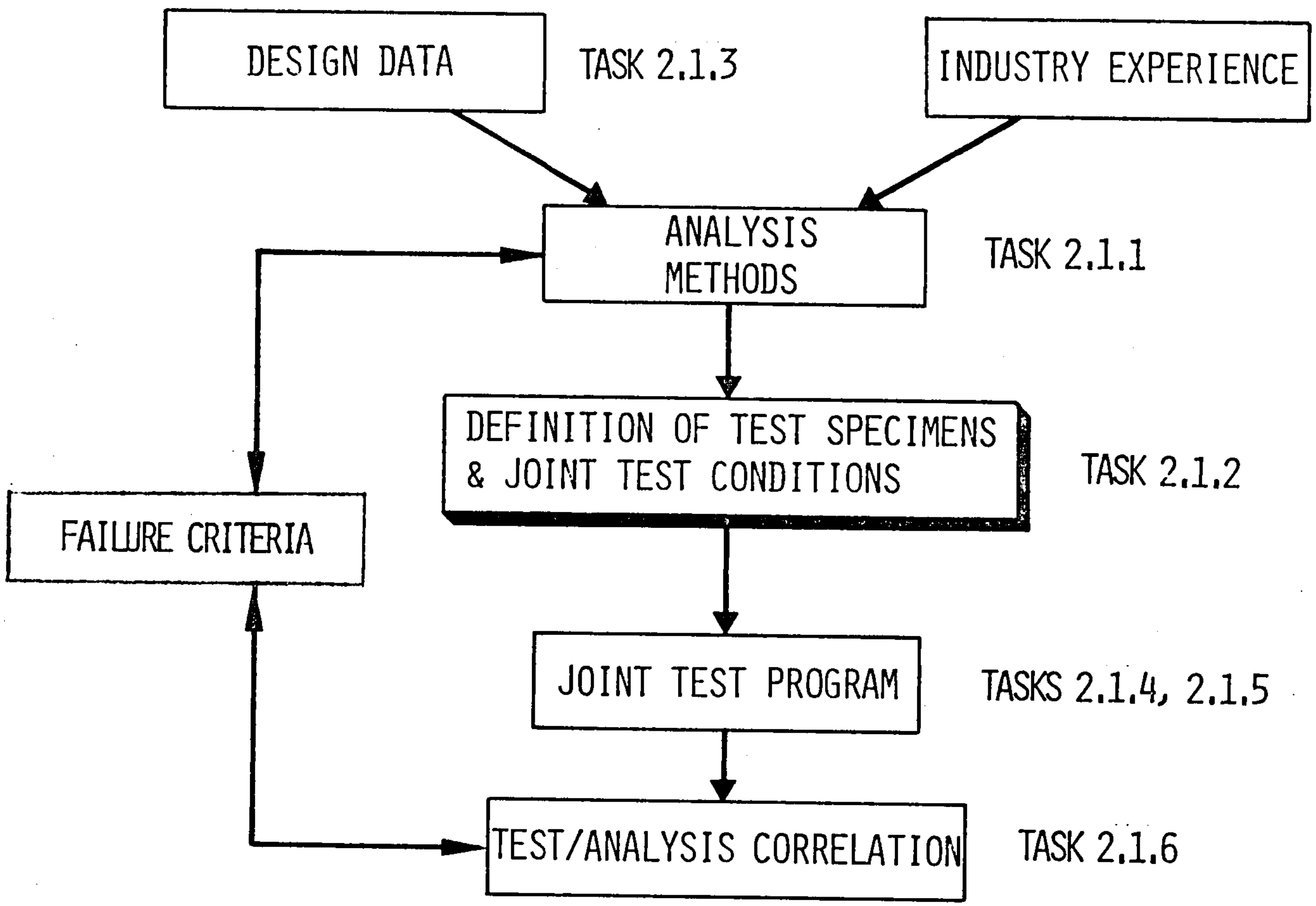
As reported in Reference 1 the joint analyses under this task are being performed using the Boeing BOPACE computer program. This is a finite element program with plastic analysis capability. It allows a detailed study of local stresses and deformations to be made without the need to incorporate simplifying assumptions regarding cross-ply and other three-dimensional effects and imposed beam-type behavior of laminates or lamina.

Percentage increases given in this section for shear stresses (τ_{xy}) or transverse stress (σ_y) are increases in peak values unless otherwise noted. Values of σ_y for lamina adjacent to the adhesive are for particular lamina in the adherend unless otherwise noted.

<u>Study of Modeling Techniques</u> - The study of modeling techniques to determine sensitivity of stress levels to changes in grid size continued during this reporting period. The purpose of this study is to construct an adequate stress analysis model of a composite double-lap adhesive bonded joint.

The basic joint chosen for study was a graphite/polyimide composite with a pseudo-isotropic, $(0,\pm45,90)_s$, layup. Material properties, joint configuration,

Figure 3-1: TASK 2 BONDED JOINT SUBTASKS



boundary and loading conditions are shown in Figure 3-2. The analysis was linear elastic with plain strain conditions assumed.

After an initial study of the joint, the critical areas appeared to be τ_{xy} in the adhesive and σ_y in the lamina adjacent to the adhesive near the edge of the lap. The following discussion focuses on these two areas. Effects of y-grid changes with the x-grid fixed are discussed first, followed by effects of x-grid changes with the y-grid fixed. A summary of the models used is shown in Figure 3-3.

Models 2A to 2E kept x-direction grid size unchanged while changing the lamina and adhesive representation. The coarsest model, 2A, used 1 element to represent the adhesive, 1 element to represent the 0° lamina, and 1 element to represent the ($\pm 45, 90_2, \pm 45$) lamina. The finest model, 2E, used 3 elements through the thickness of the adhesive, represented the ± 45 and 90_2° lamina separately, and used 2 elements through the thickness of the 0° lamina nearest the adhesive.

Changing from 1 element to 3 elements in the adhesive, Figure 3-4 and 3-5, changed the peak adhesive shear stress, τ_{xy}, by less than 4%. [45.28 MPa (6568 psi) to 47.09 MPa (6830 psi)].

The normal stress, σ_y, in both the adhesive and the lamina adjacent to the adhesive increased significantly as the adhesive representation was changed. Changing from 1 to 2 elements, Figures 3-6 and 3-7, changed σ_y in the adjacent lamina by nearly 12% [8.31 MPa (1205 psi) to 9.3 MPa (1345 psi)]. Changing from 2 to 3 elements, Figures 3-7 and 3-8, changed σ_y by an additional 2% [9.3 MPa (1345 psi) to 9.45 MPa (1370 psi)].

A summary of τ_{xy} and σ_y stresses as a function of model changes is shown in Figure 3-9. Increasing the 0° lamina nearest the adhesive from 1 to 2 elements, Model 2D to 2E, (the number of adhesive elements remain constant at three) did not appreciably change σ_y. The σ_y stress in the adhesive, however, is still increasing as the number of adhesive elements is changed from 1 to 3 (Models 2B to 2D).

It is concluded that using two elements through the adhesive and one to represent the nearest lamina will economically represent τ_{xy} in the adhesive and σ_y

in the adherend. The σ_y stress in the adhesive, however, appears to still be increasing. An additional model with more adhesive elements will be run to see if σ_y in the adhesive continues to increase or finally reaches an equilibrium point.

Models 1A to 1D kept Y-direction modeling constant and changed the X-direction grid size (see Figure 3-3). All stresses in the areas of stress concentration increased with decreasing grid size, but again τ_{xy} in the adhesive, and σ_y in the lamina adjacent to the adhesive near the edge of the lap are of greatest interest.

Between the 3rd and 4th models, Figures 3-10 and 3-11, τ_{xy} increased and the peak of the curve moved closer to the edge of the lap. Plots of τ_{xy}-vs-x show little divergence between the 2 models up to within 1-1/2 adhesive thicknesses .381 mm (.015 in) of the edge of the lap (see Figure 3-12).

Figures 3-13 and 3-14 show σ_y in the lamina adjacent to the adhesive increased significantly from the 3rd to the 4th models. Plots of σ_y-vs-x, (Figure 3-15) show that σ_y does not diverge appreciably from Model 1C to 1D until 1 adhesive thickness .254 mm (.01 in) from the edge of the lap. (At 1 adhesive thickness, σ_y differs by 4%, at 1-1/2 times the thickness, σ_y differs less than 2%.) A distance of 1 adhesive thickness in from the edge of the lap appears to be a good basis of comparison of σ_y from one layup to another (see Figure 3-16). The sensitivity of σ_y at this location to an adhesive fillet is not knows at this time and will be studied.

Standard Double Lap Bonded Joints - BOPACE finite element analyses of three double-lap bonded joints have been completed during this reporting period. The first had a very stiff zone, three 0° lamina adjacent to the adhesive, the second, one 0° lamina adjacent to the adhesive, and the third, a very soft zone, ±45° lamina nearest the adhesive. Figure 3-17 shows the general characteristics of the three models. Initial results show that it is advantageous to place the ±45° lamina next to the adhesive. Load was transferred more slowly and peak shear stress in the adhesive was reduced by approximately 9%.

The three double lap joints were chosen from the standard joint Task 2.1.3 test matrix 3D; 3D-4a - $(0_3,\pm45_3,90_3)_{2S}$, 3D-2b - $(0,\pm45,90)_{6S}$, 3D-5a - $(\pm45,0,90)_{6S}$. Data from the analyses of these joints can be used to predict trends or to compare stress levels in one joint with another, however, joint strength or failure load was not predicted.

Modeling studies show it is important to keep x-direction grid size constant. Y-direction grid size is somewhat less important. The representation of the adhesive by two elements in the y-direction was kept constant for each joint, but y-direction grid for the laminates was dictated by individual group.

Model 3D-4a has 408 quadrilateral plate elements and both 3D-2b and 3D-5a have 512 elements. The x-direction grid remained unchanged from model to model. The width of the smallest element in areas of stress concentration was .254 mm (.01 in). The thickest element in model 3D-2b was .381 mm (.015 in) in height which represented ($\pm 45°, 90_2, \pm 45°$) lamina. The 0° lamina were represented individually. The thickest element in 3D-4a was also .381 mm (.015 in) and represented both $\pm 45_3$ and 90_6 lamina. Again, the 0° lamina were represented individually. The thickest element in 3D-5a was .254 mm (.01 in) and represented the ($0°, 90°_2, 0°$) lamina. Both of the two 0° lamina nearest the adhesive were represented individually.

The analysis assumed geometrically linear and elastic material and a plain strain condition. Boundary conditions are as shown in Figure 3-2.

The joint was loaded by displacing the free end by .254 mm (.01 in) in the +x-direction, [$\sigma_x \simeq$ 268 MPa (38.9 ksi)], [$P \simeq$ 10.39 KN (2,335 lb)]. This loading overstresses the adhesive, but as these analyses are elastic, the displacements and stresses may be ratioed as necessary.

A comparison of the three joints show that all have the same extensional stiffness, but the flexural stiffness is quite different. Bending stiffness however is a far less important parameter for the double lap joint than the single lap.

Each of the joints studied was designed to fail in the joint rather than outside the joint in the laminate. Thus, the basic laminate is lightly loaded and the critical stresses are the shear stress in the adhesive and perhaps σ_y in the lamina adjacent to the adhesive near the edge of the lap. The latter becomes increasingly important as the adherend becomes thicker.

Approximately a 4% drop [53.12 MPa (7705 psi) to 51.0 MPa (7397 psi)] in peak shear stress in the adhesive was achieved by changing the three 0° lamina nearest the adhesive to one 0° lamina. Another 4.5% [51.0 MPa (7397 psi) to 48.88 MPa (7090 psi)] in the peak adhesive shear stress was achieved by placing the $\pm 45°$ lamina next to the adhesive (see Figures 3-18, 3-19 and 3-20).

A very stiff zone, such as the three 0° lamina next to the adhesive, together with the condition of equal strain, ε_x, in the adherend and the doubler requires extremely rapid transfer of load between the stiff three 0° lamina resulting in a very high peak shear stress in the adhesive. A soft buffer next to the adhesive, i.e., the $\pm 45°$ lamina, transfers load more slowly with lower shear stress in the adhesive. This is accomplished by allowing additional shear strain across this soft zone softening the condition of equal strain, ε_x, in the adherend and the doubler.

The σ_y stress in the lamina nearest the adhesive can also be an important parameter. Changing from a stiff zone, three 0° lamina, to a soft zone, the $\pm 45°$ lamina, increased σ_y by approximately 6% [50.08 MPa (7264 psi) to 53.07 MPa (7697 psi)] as shown in Figures 3-21, 3-22 and 3-23.

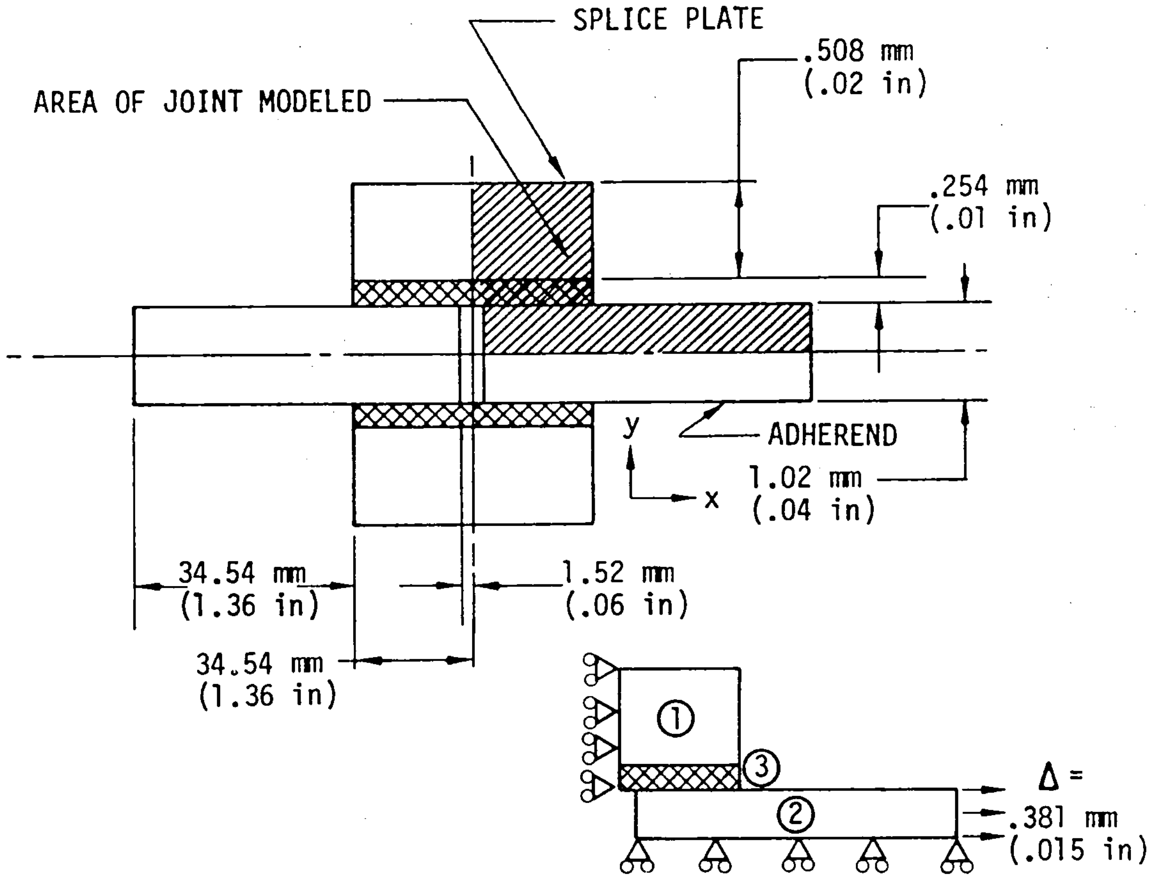
In conclusion, it appears advantageous to place a soft zone adjacent to the adhesive. This produced a decrease in adhesive shear stress. The drop in shear stress could directly increase the joint strength provided the σ_y strength of the laminate has not been exceeded.

3.1.2 TASK 2.1.2 - Test Plan Development

This task complete. See Reference 2.

3.1.3 TASK 2.1.3 - Ancillary Laminate and Adhesive Tests

Additional testing will be conducted during this task to supplement the design allowables and small specimen tests of Tasks 1.2.1 and 1.2.2. This testing will characterize the LARC-13 adhesive system through a series of tension and shear specimens. Testing is planned over the range of 116 to 561K (-250°F to 550°F). The test matrix is shown in Figure 3-24. Work on this task has begun.



BOUNDARY CONDITIONS

MATERIAL PROPERTIES

① $(0/\underline{+}45/90)_s$	}	E_1 = 137 GPa ($20x10^6$ psi, For 0° Laminate
② $(0/\underline{+}45/90)_s$	}	E_2 = 11 GPa ($1.6x10^6$ psi) For 90° Laminate
		μ = .25
		G = 5.8 GPa ($.85x10^6$ psi) For $\underline{+}45°$ Laminate

ADHESIVE: ③ G = 2.1 GPa (.309 x 10^6 psi)
ASSUMED HOMOGENOUS AND ISOTROPIC

Figure 3-2: STUDY MODEL CONFIGURATION

SUMMARY OF MODELS USED IN STUDY OF
MODELING TECHNIQUES OF A DOUBLE-LAP
BONDED JOINT - $(0,\pm 45,90)_s$ LAMINATE

MODEL NO.	X-DIRECTION GRID REPRESENTATION	Y-DIRECTION GRID REPRESENTATION		
	DIM. OF SMALLEST ELEMENT IN AREAS OF HIGH STRESS	NO. OF ELEMENTS IN Y-DIRECTION		
		ADHESIVE	0° LAMINA	$(\pm 45,90)_s$
1A	1.52 mm (.06 in)	1	1	3
1B	0.762 mm (.03 in)	1	1	3
1C	0.254 mm (.01 in)	1	1	3
1D	0.127 mm (.005 in)	1	1	3
2A	0.762 mm (.03 in)	1	1	1
2B	0.762 mm (.03 in)	1	1	3
2C	0.762 mm (.03 in)	2	1	3
2D	0.762 mm (.03 in)	3	1	3
2E	0.762 mm (.03 in)	3	2	3

Figure 3-3: SUMMARY OF MODELS FOR STUDY

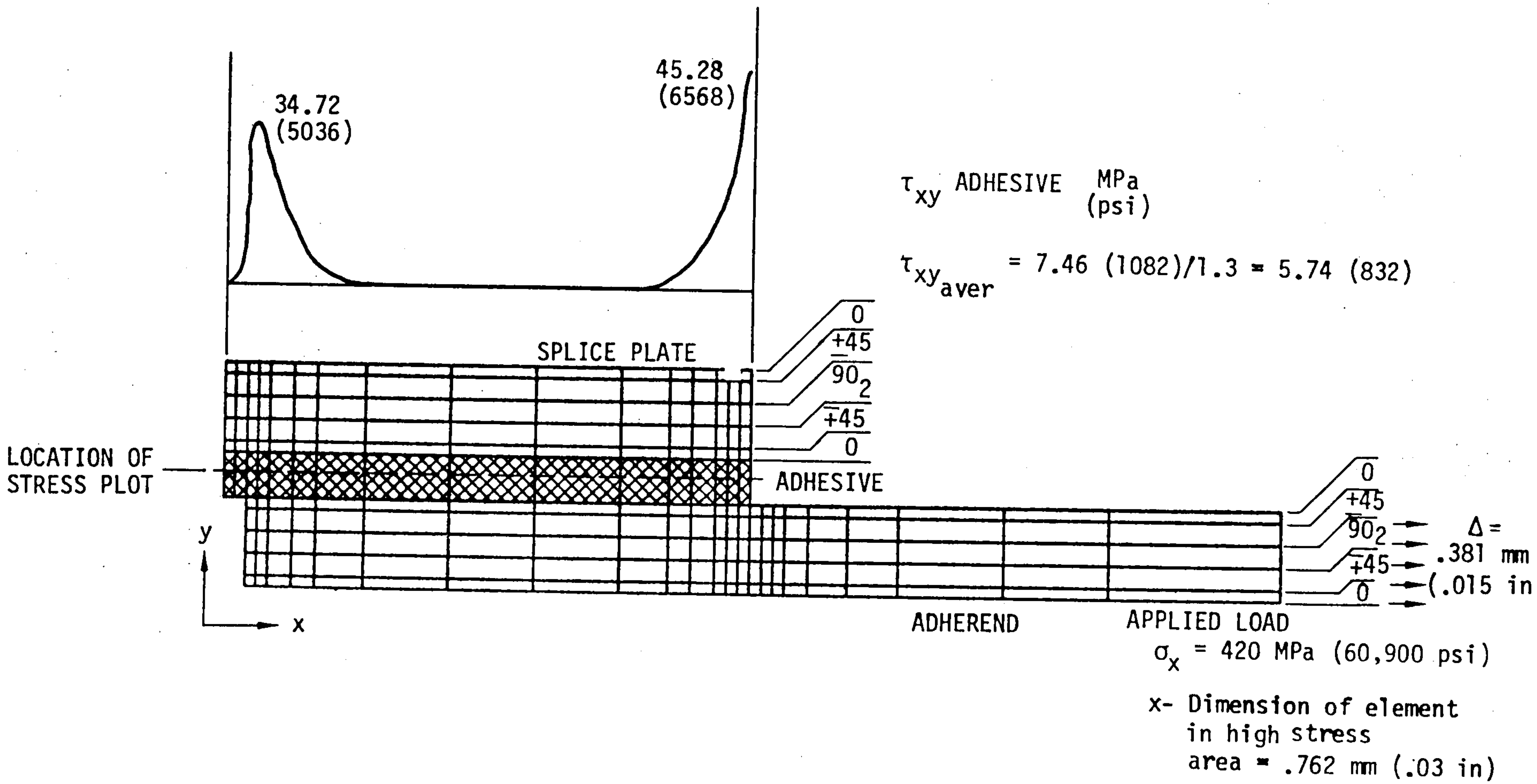


Figure 3-4: ADHESIVE SHEAR STRESS

- MODEL 1B-2B

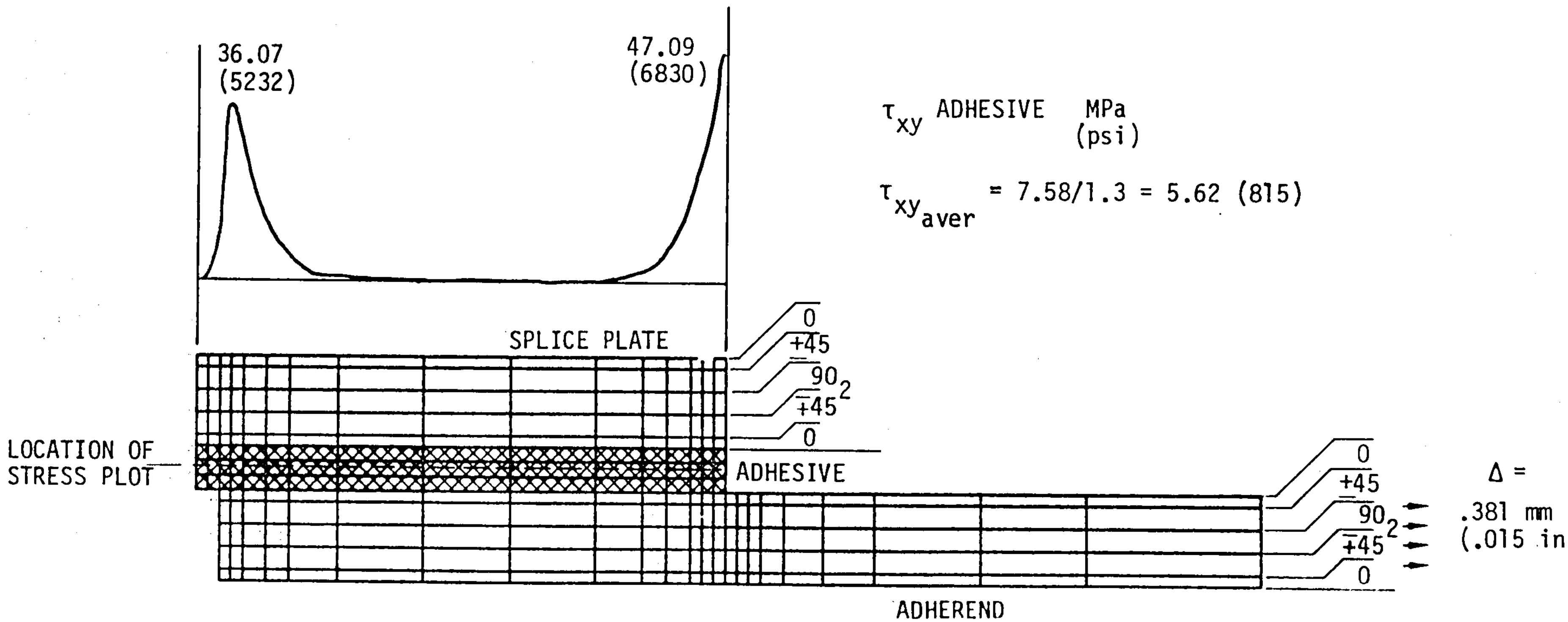
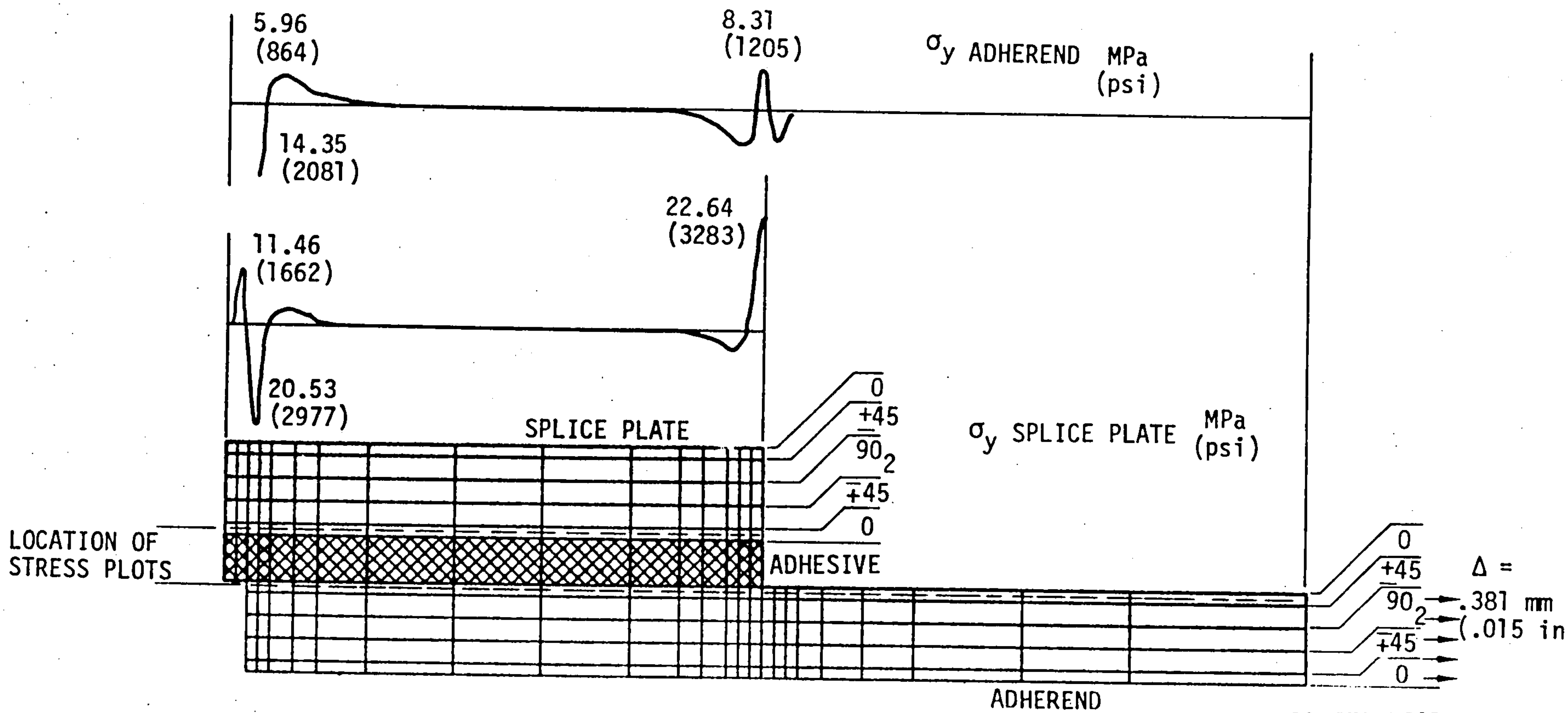


Figure [illegible] ADHESIVE SHEAR STRESS
- MODEL 2D



APPLIED LOAD

σ_x = 420 MPa (60,900 psi)

x-Dimension of smallest element in high stress area = .762 mm (.03 in)

Figure 3-6: σ_y IN 0° LAMINA NEAREST ADHESIVE - MODEL 1B-2B

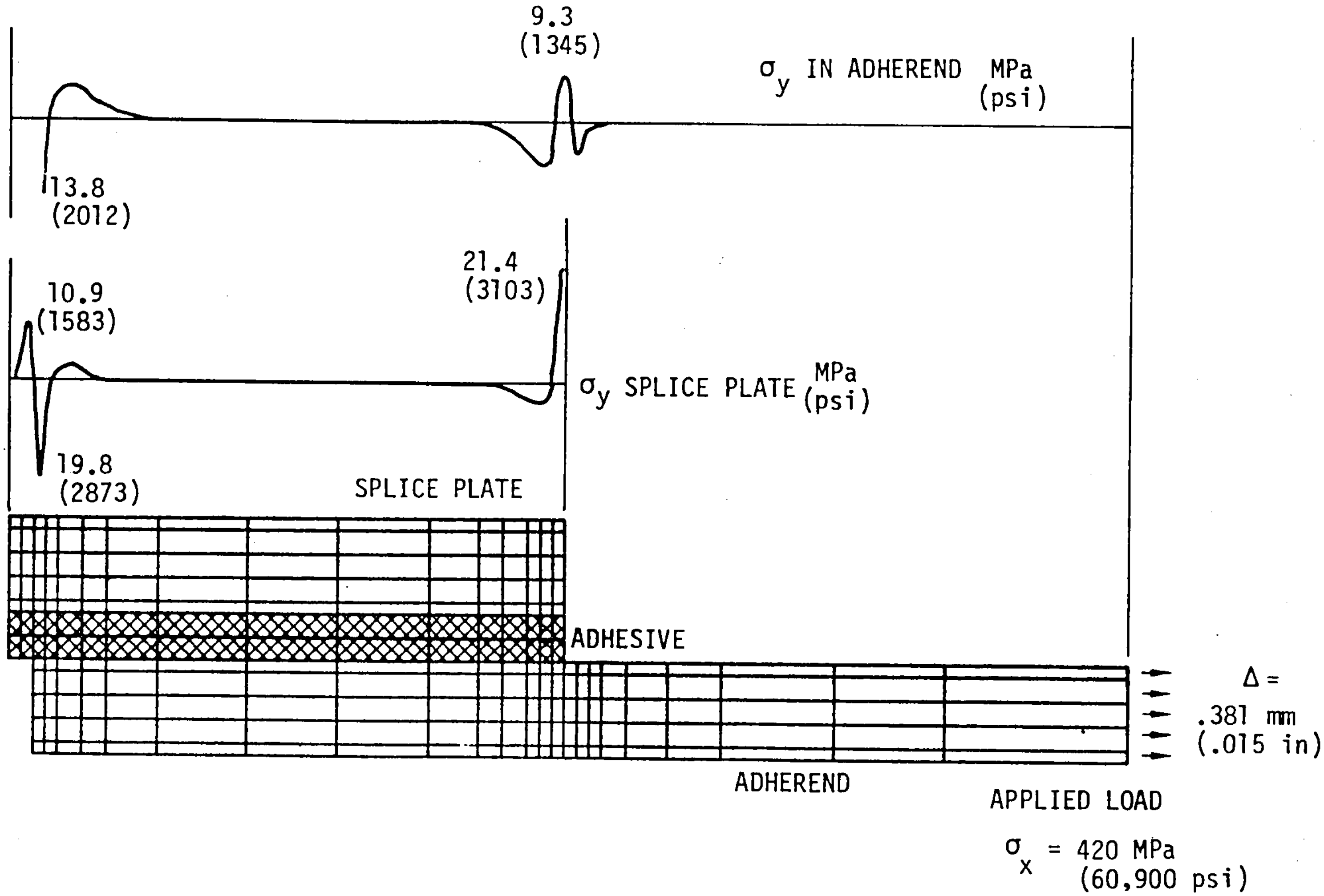


Figure 3-7: σ_y IN LAMINA NEAREST ADHESIVE

- MODEL 2C

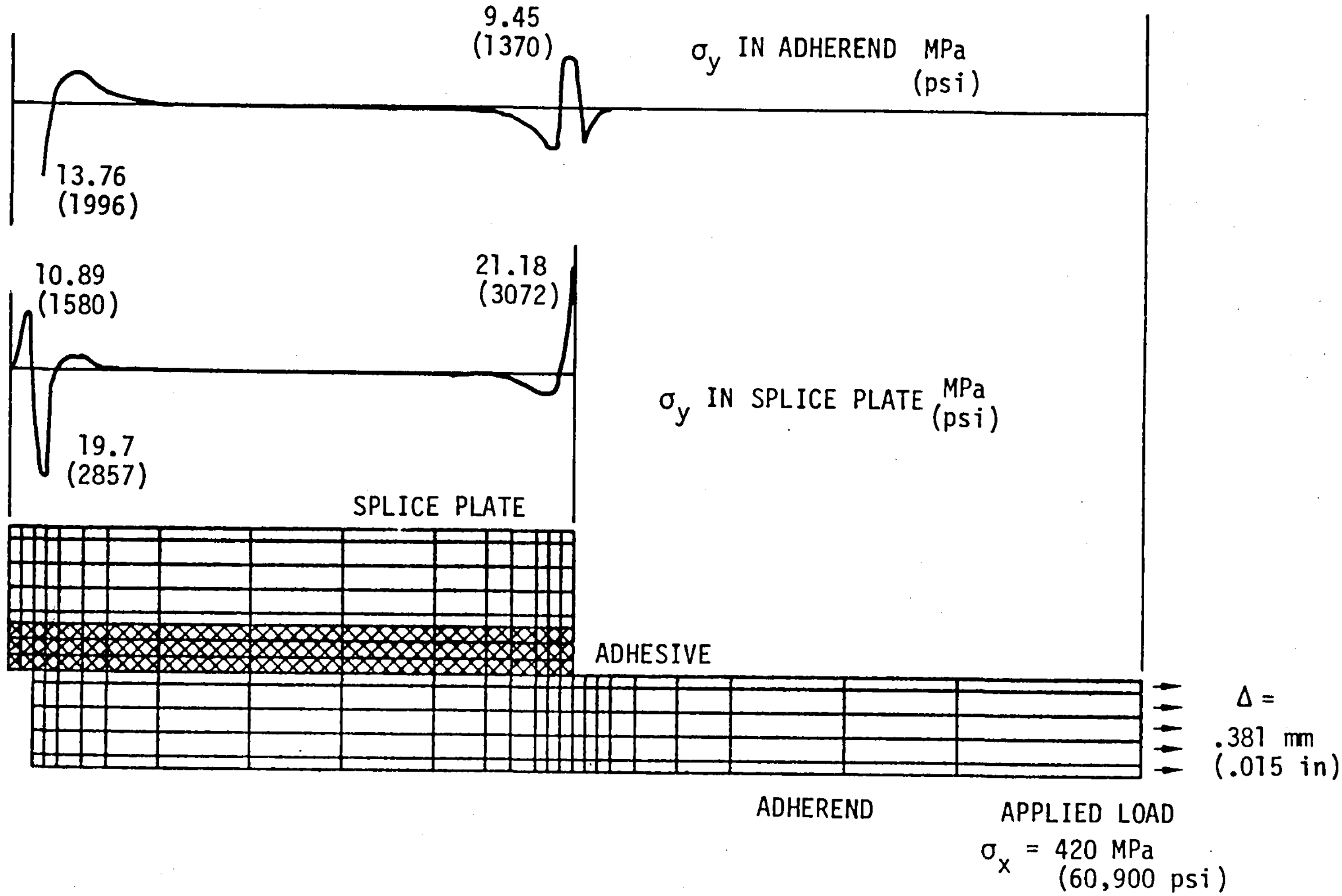


Figure 3-8: σ_y IN LAMINA NEAREST ADHESIVE
- MODEL 2D

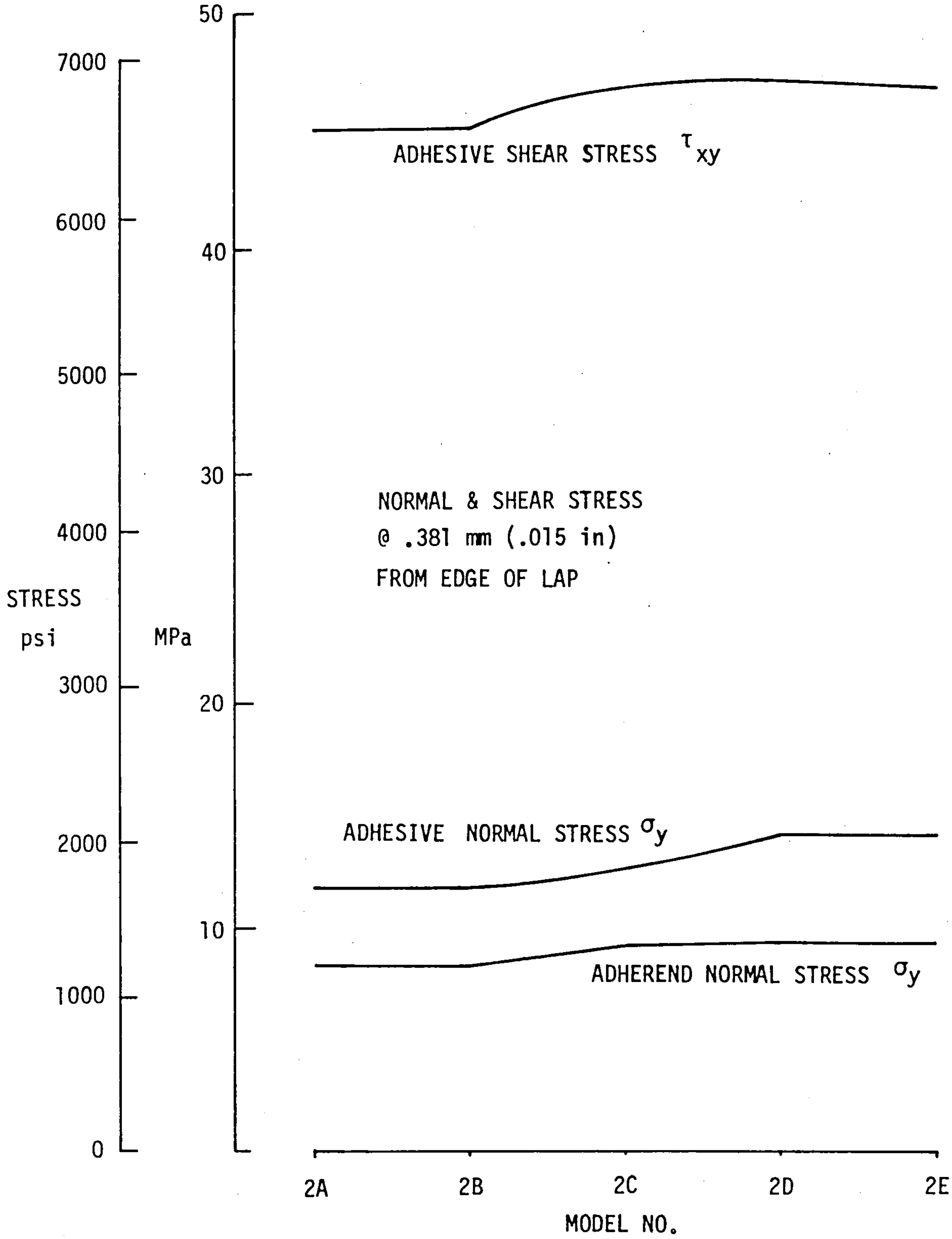


Figure 3-9: EFFECTS OF Y-GRID CHANGES ON STRESS LEVELS

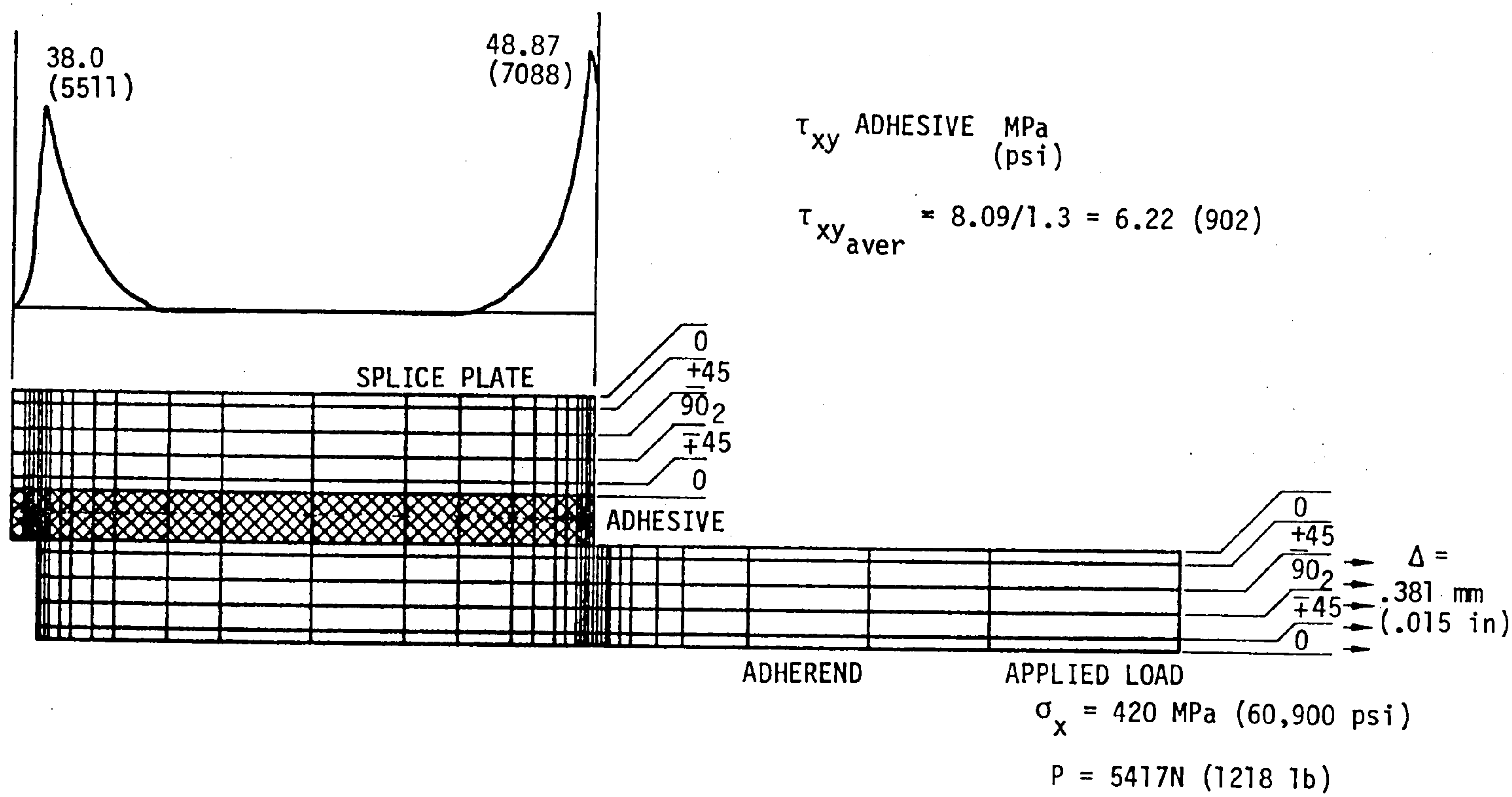
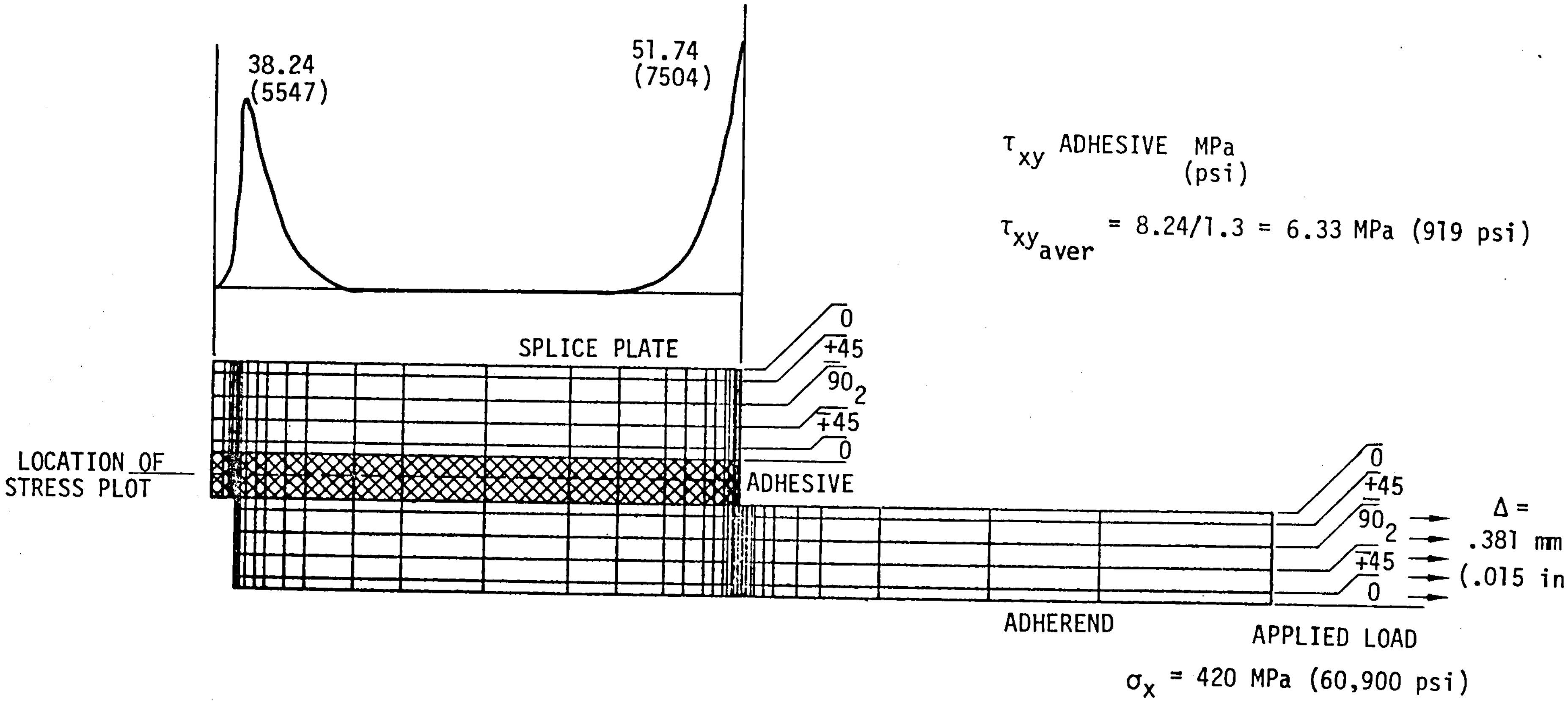


Figure 3-10: ADHESIVE SHEAR STRESS
- MODEL 1C



x- Dimension of element in high stress area = .127 mm (.005 in)

Figure 3-11: ADHESIVE SHEAR STRESS - MODEL 1D

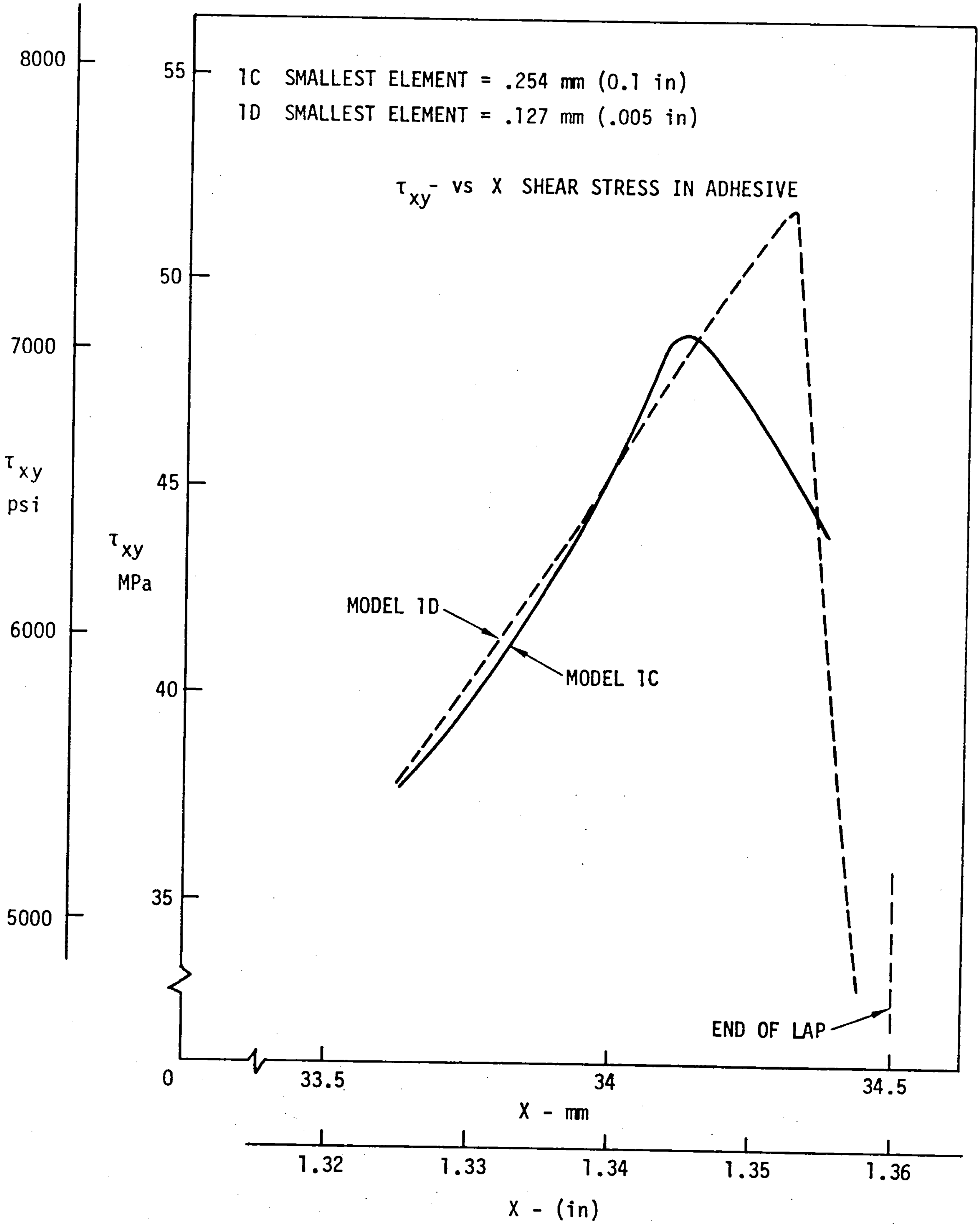
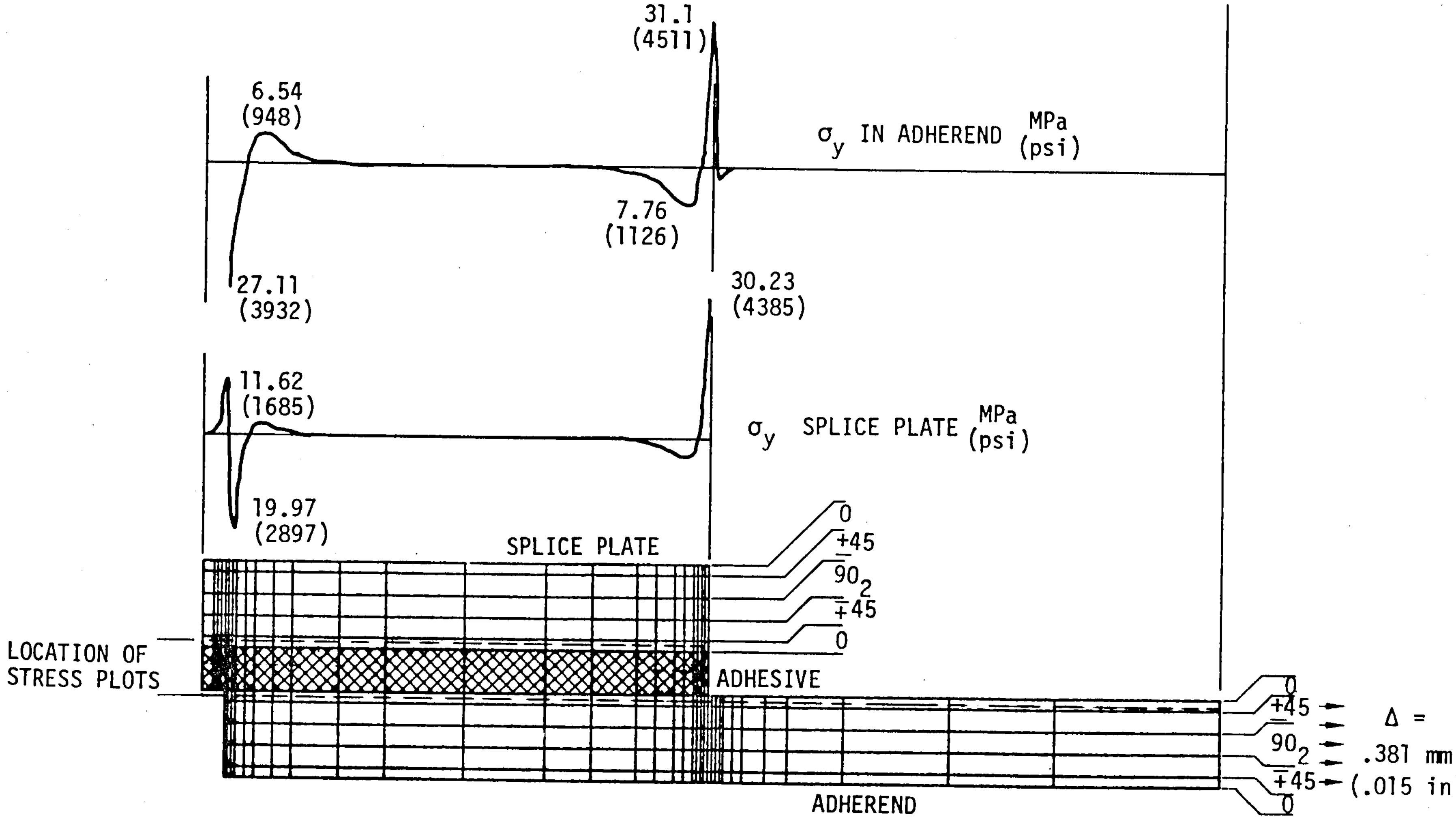


Figure 3-12: EFFECT OF X-GRID CHANGE ON τ_{xy} ADHESIVE



APPLIED LOAD

σ_x = 420 MPa (60,900 psi)

Figure 3-13: σ_y IN LAMINA NEAREST ADHESIVE - MODEL 1C

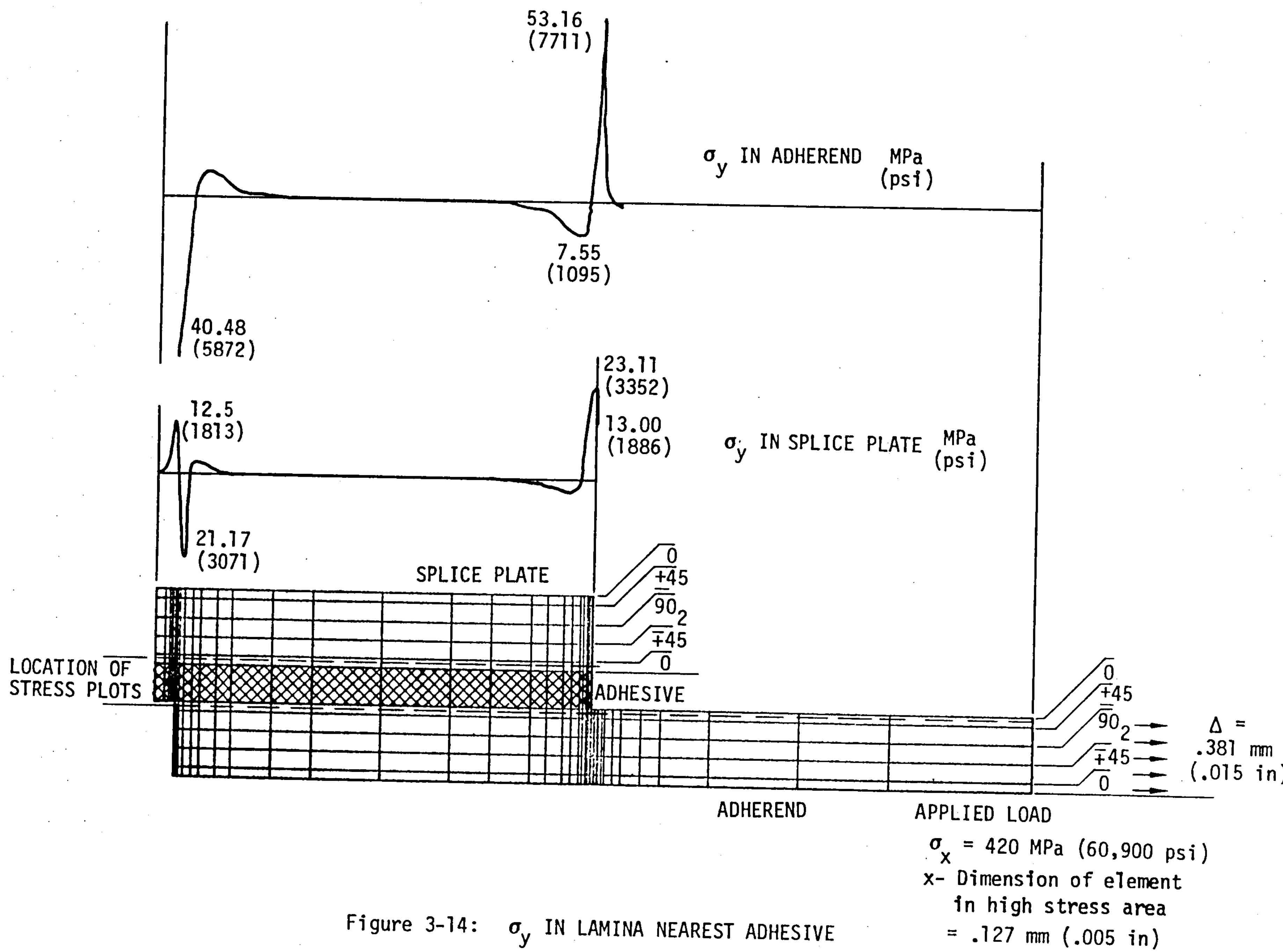


Figure 3-14: σ_y IN LAMINA NEAREST ADHESIVE
- MODEL 1D

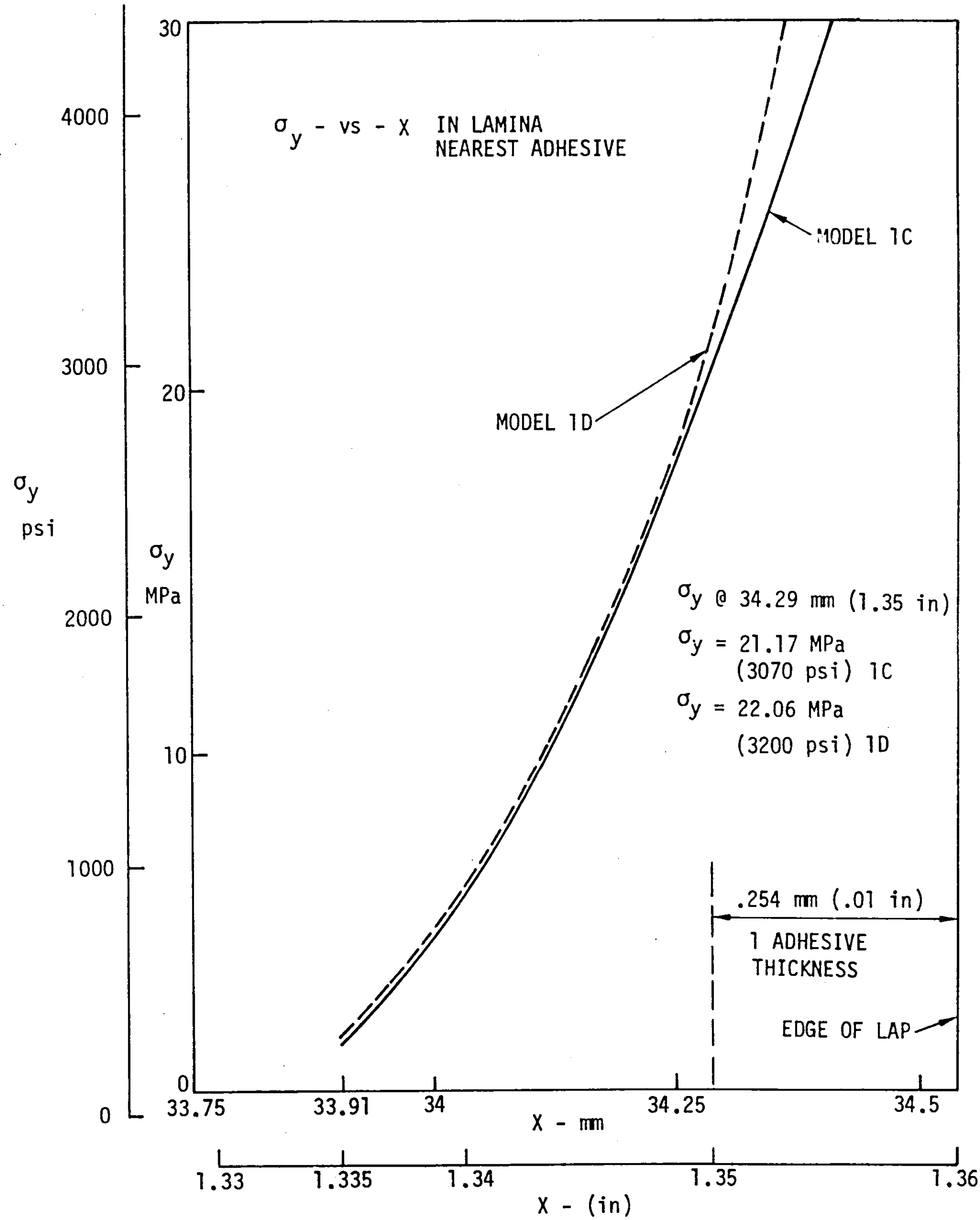


Figure 3-15: EFFECT OF X-GRID CHANGE ON σ_y IN LAMINATE

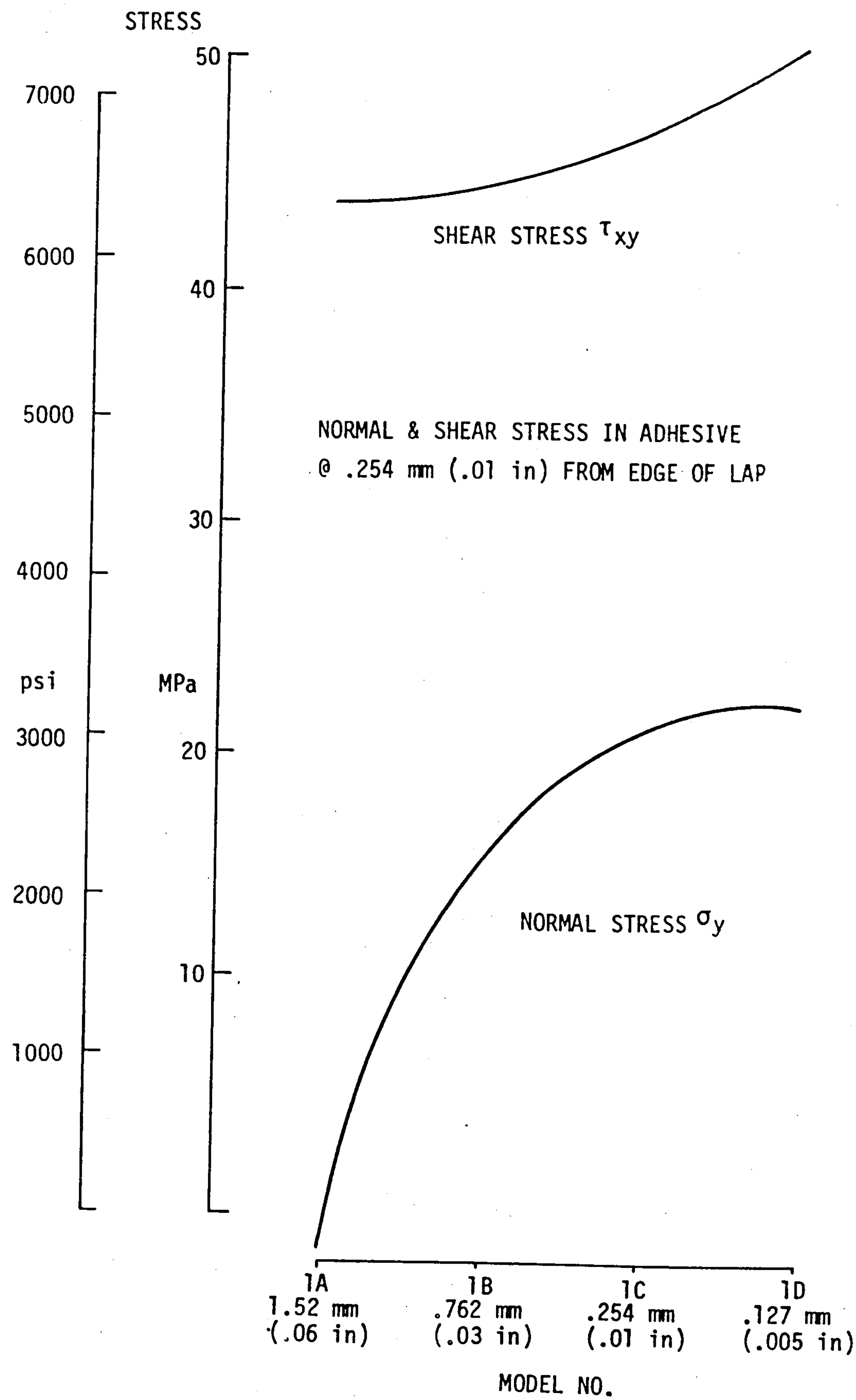
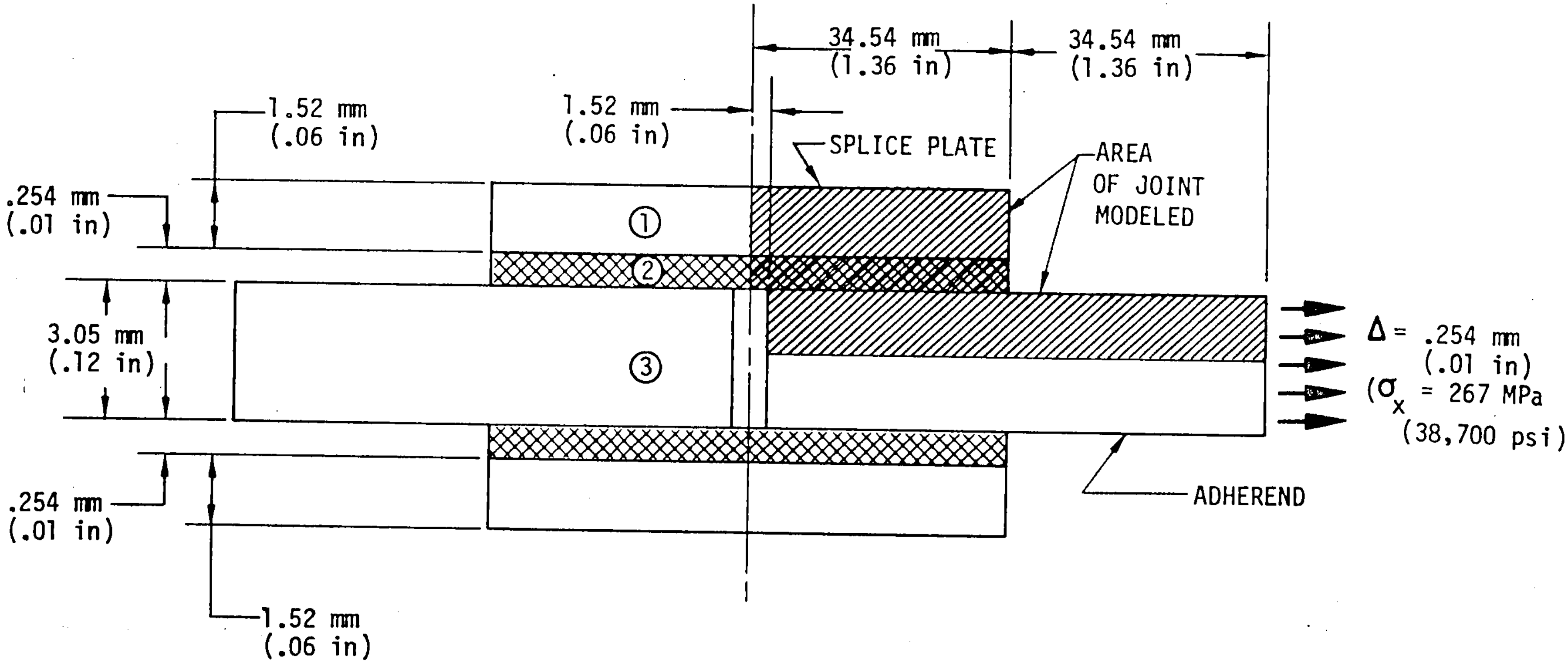


Figure 3-16: EFFECTS OF X-GRID CHANGES ON STRESS LEVELS IN ADHESIVE



MODEL 3D-2b

① $(0,\pm 45,90)_{3s}$

③ $(0,+45,90)_{6s}$

② Adhesive

MODEL 3D-4a

① $(0_3,\pm 45_3,90_3)_s$

③ $(0_3,+45_3,90_3)_{2s}$

② Adhesive

MODEL 3D-5a

① $(\pm 45,0,90)_{3s}$

③ $(+45,0,90)_{6s}$

② Adhesive

Figure 3-17: DOUBLE LAP BONDED JOINT CONFIGURATION

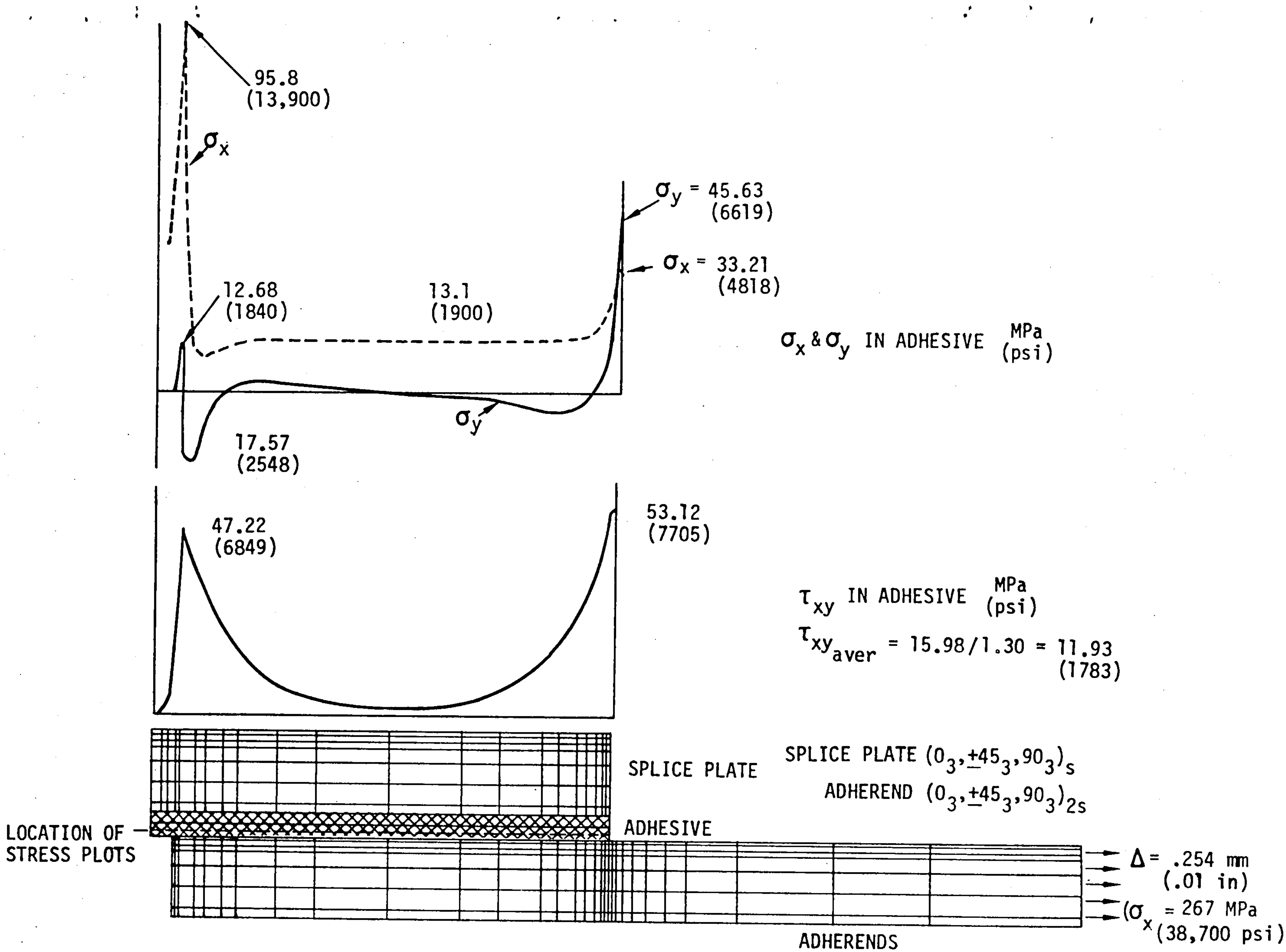


Figure 3-18: ADHESIVE SHEAR σ_x & σ_y STRESS MODEL 3D-4a

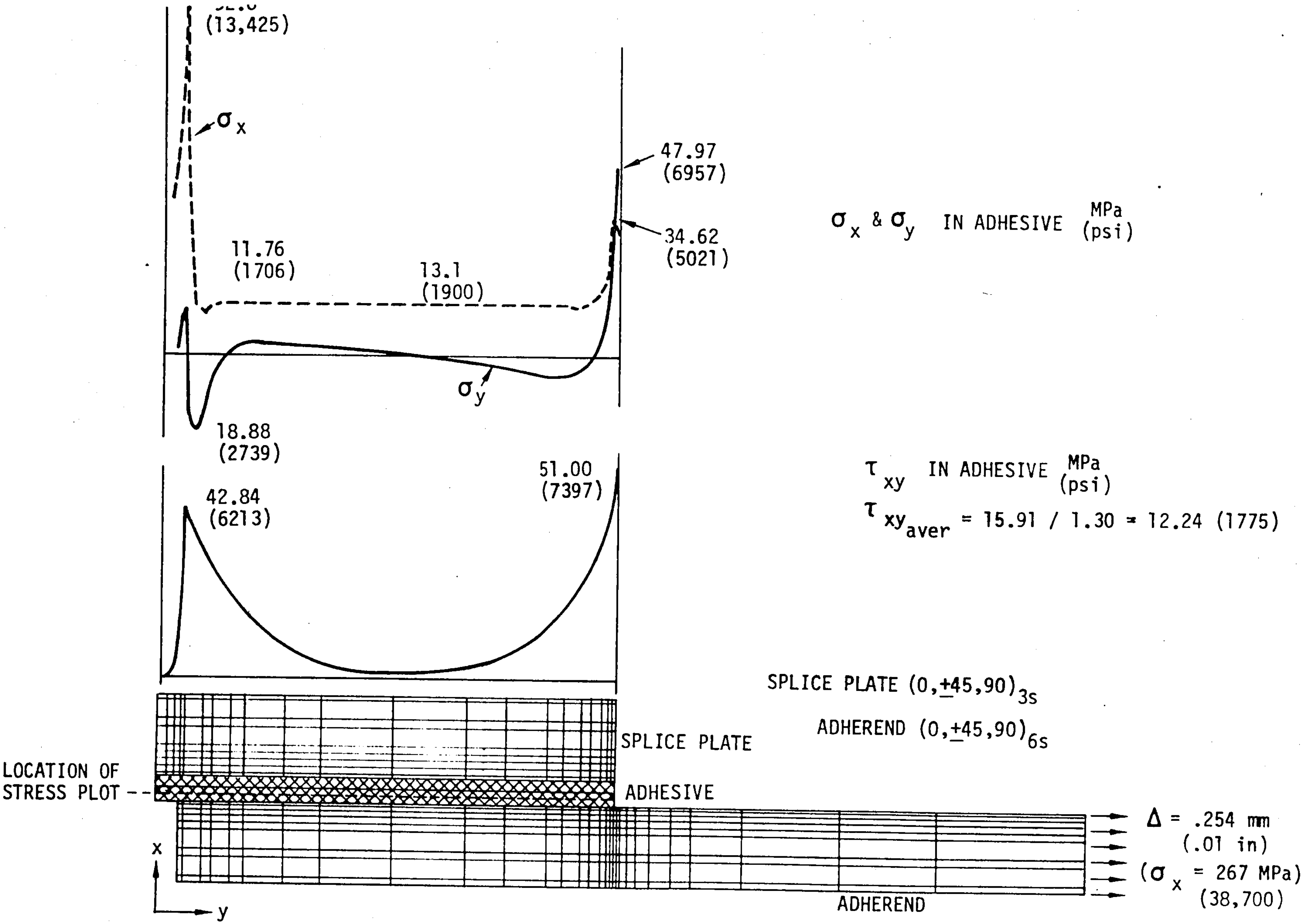


Figure 3-19: ADHESIVE SHEAR, σ_x & σ_y STRESS MODEL 3D-2b

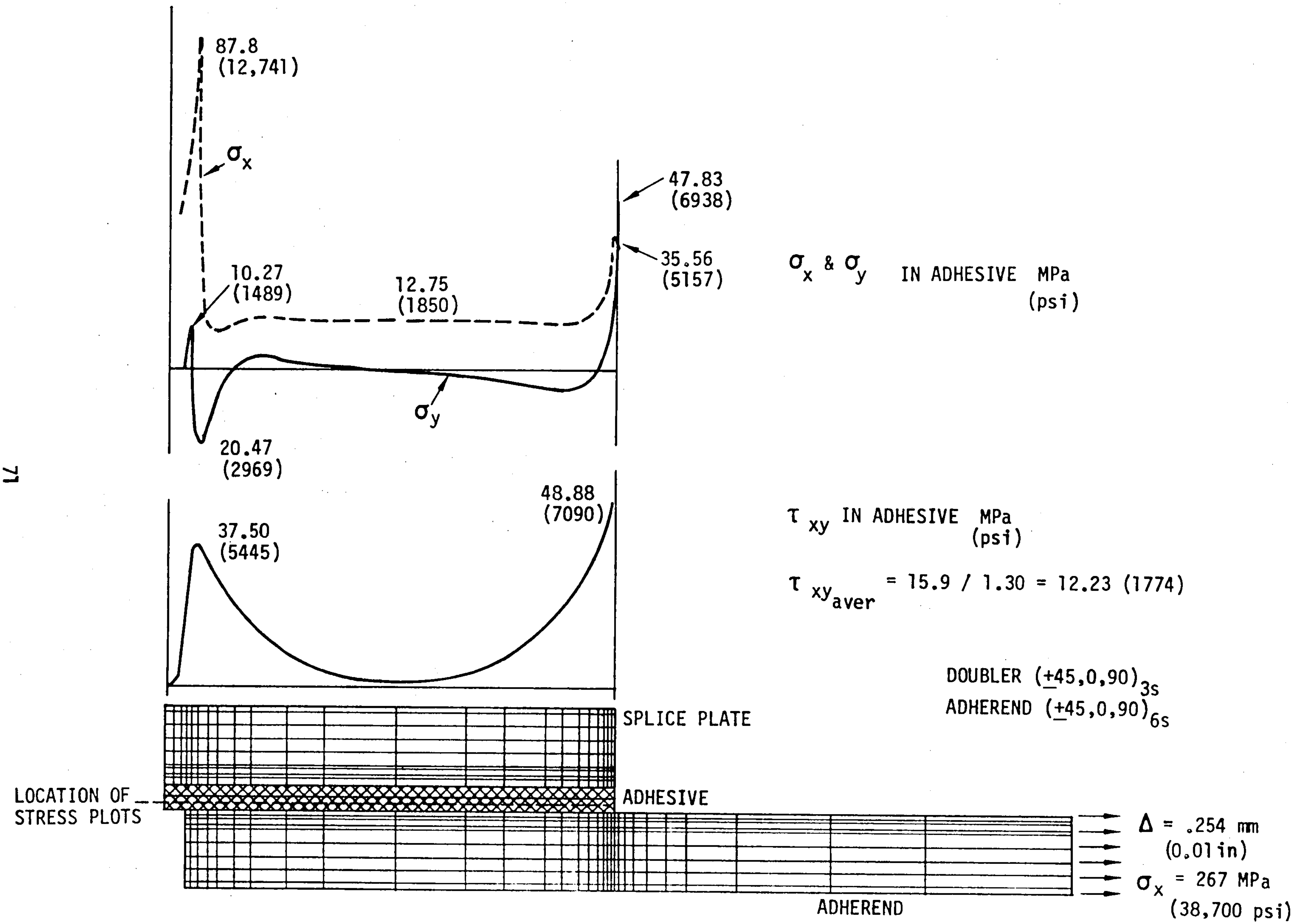


Figure 3-20: ADHESIVE SHEAR, σ_x & σ_y STRESS MODEL 3D-5a

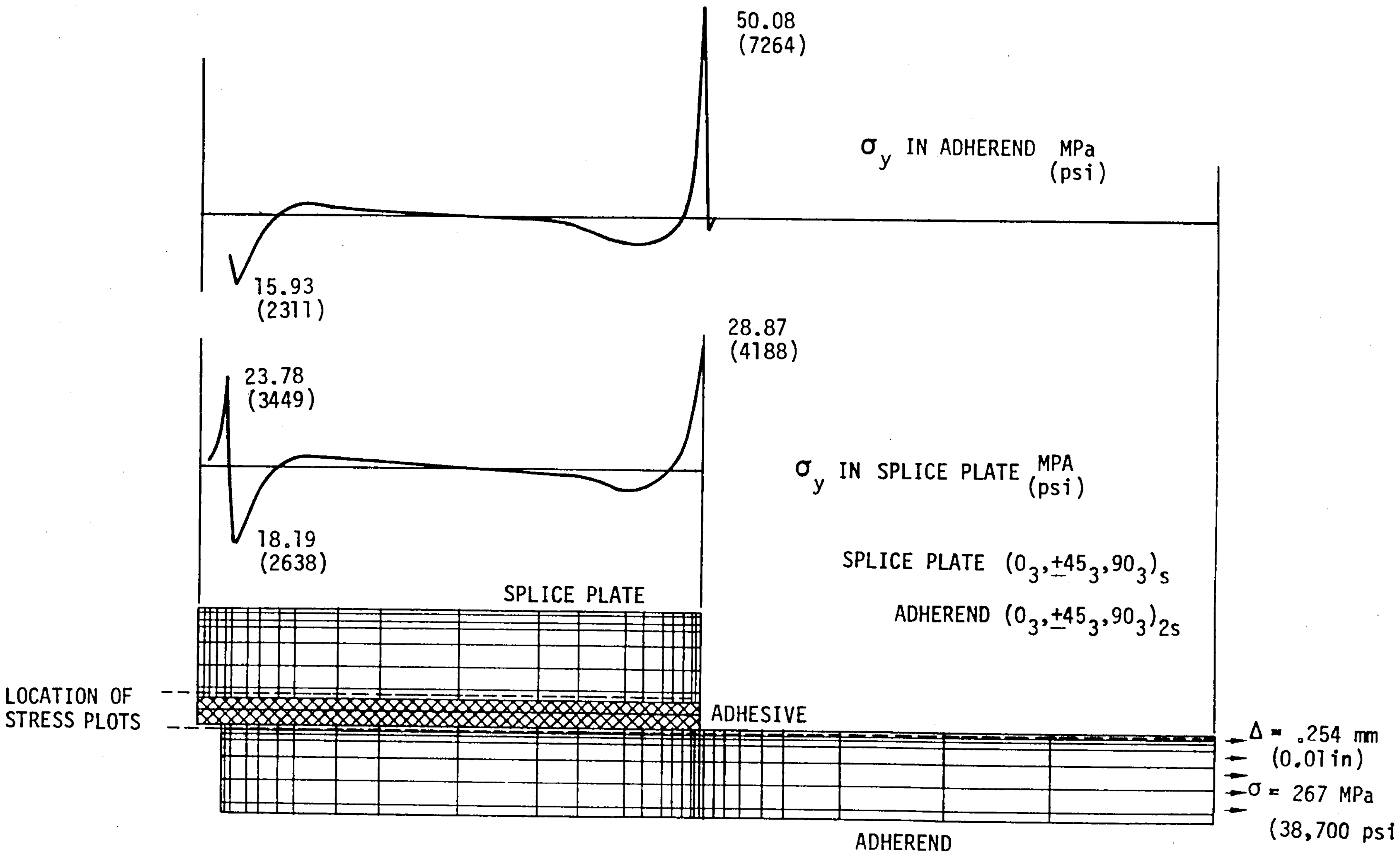


Figure 3-21: σ_y IN 0° LAMINA MODEL 3D-4a

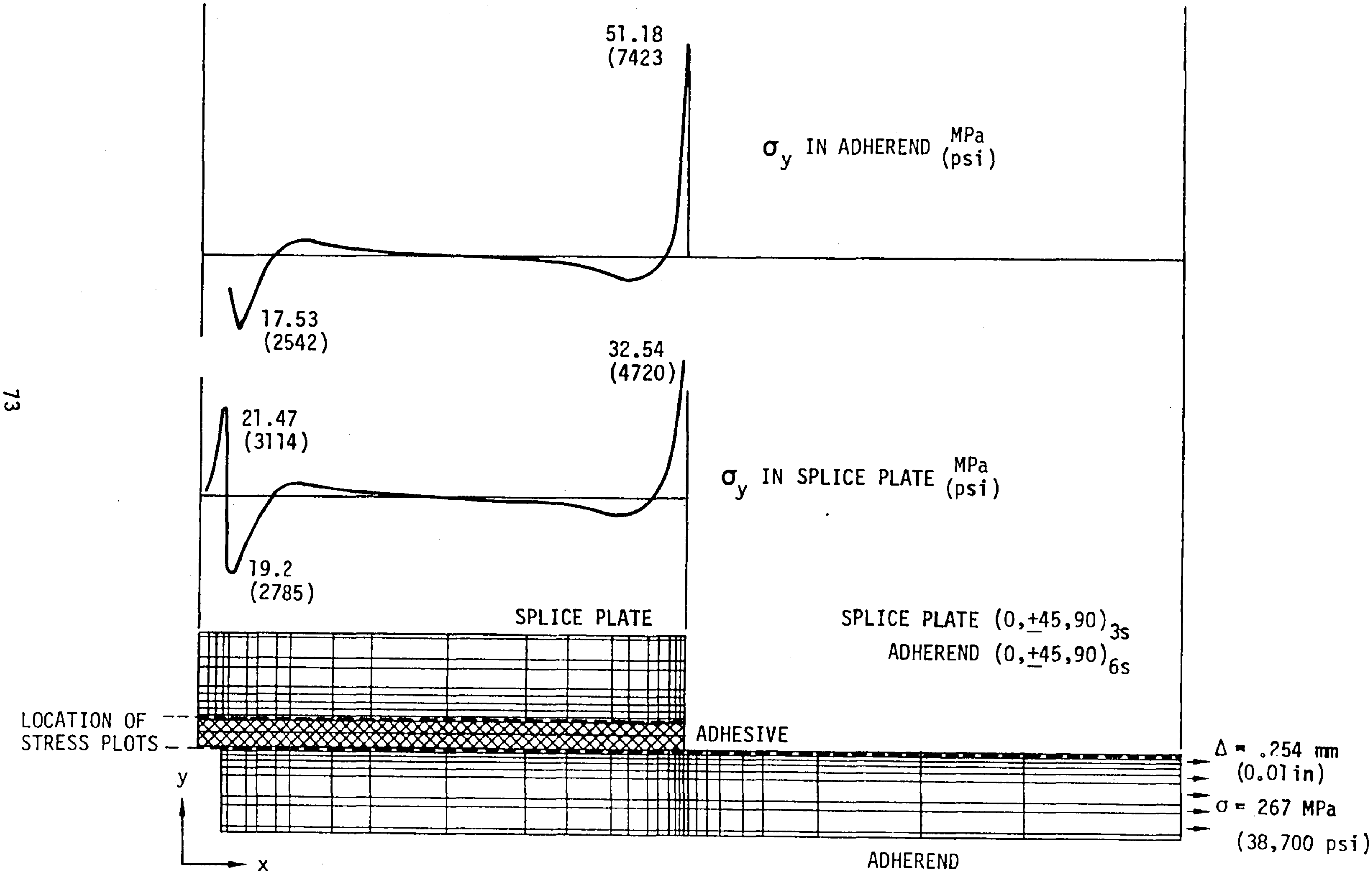


Figure 3-22: σ_y IN 0° LAMINA MODEL 3D-2b

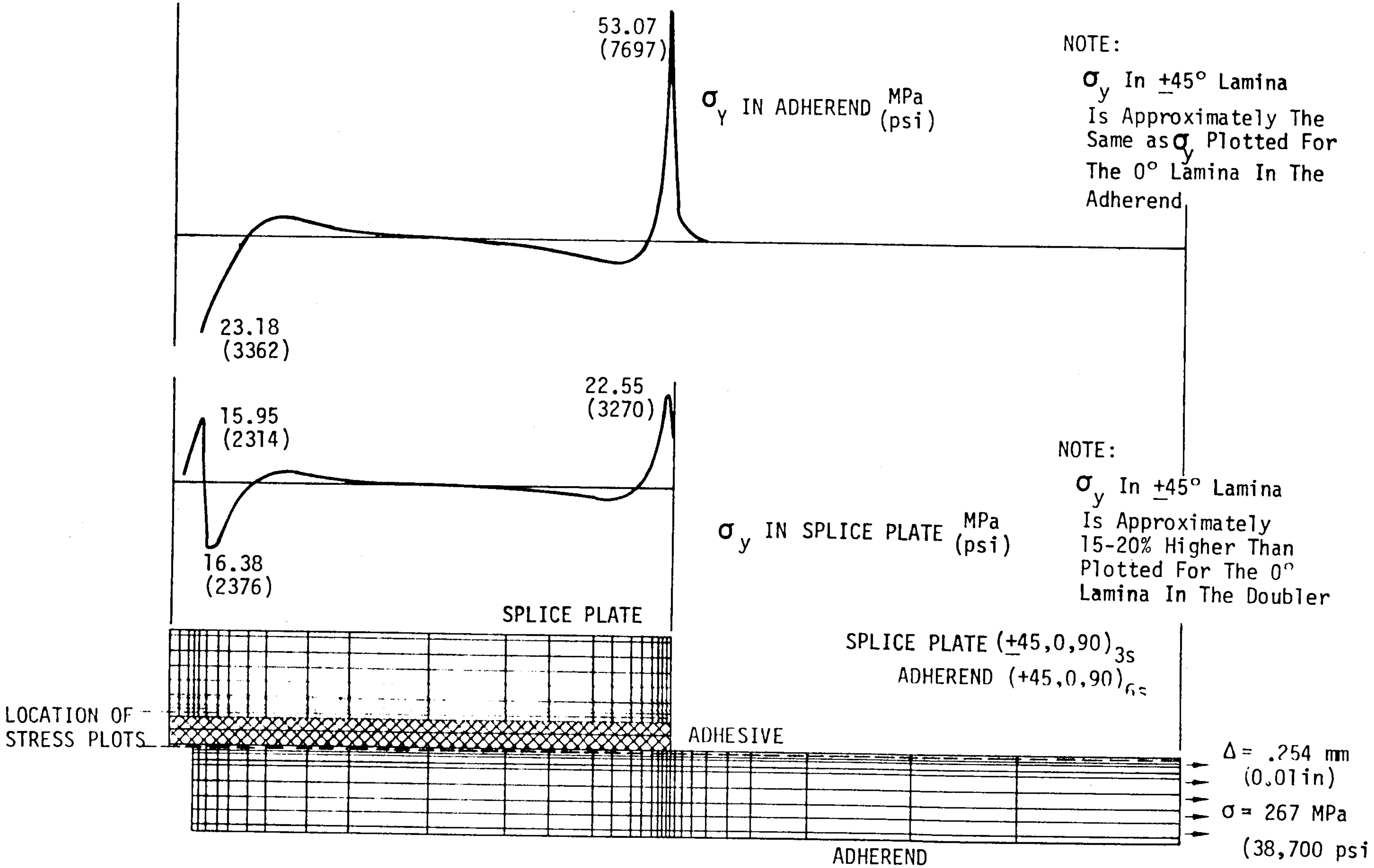


Figure 3-23: σ_y IN 0° LAMINA NEAREST ADHESIVE MODEL 3D-5a

Figure 3-24: TEST MATRIX 2 - A7F (LARC-13 AMIDE-IMIDE MODIFIED) ADHESIVE

TEST		CONDITIONING [1]	NUMBER OF TESTS AT			TOTAL NUMBER OF TESTS	TEST PROCEDURES	SPECIMEN CONFIGURATION	INSTRUMENTATION	DATA REQUIRED
NO.	TYPE		116K (-250°F)	RT	561K (550°F) [2]					
1	TENSION	1 2 4	3 3 -	3 3 -	3 3 3	9 9 3	ASTM D3039	FIGURE 3-24A	• EXTENSOMETER • T STRAIN GAGE	[2]
2	SHEAR	1 2	3 3	3 3	3 3	9 9		FIGURE 3-24B		ULTIMATE
3	SHEAR	1 2 3	3 3 3	3 3 3	3 3 3	9 9 9		FIGURE 3-24C		ULTIMATE
4	SHEAR	1 2	3 3	3 3	3 3	9 9	Thick Adherend	To Be Determined	• Displacement	ULTIMATE
5	TENSION	1 2	3 3	3 3	3 3	9 9	ASTM D2095	FIGURE 3-24E		ULTIMATE

[1] CONDITION CODE

1 - As cured/postcured

2 - Soaked for 125 hours at 589K (600°F) in a one (1) atmosphere environment (air)

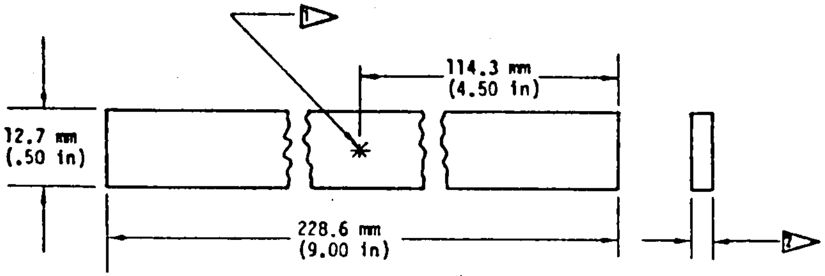
3 - Thermally cycled 125 times in a temperature range from 116K to 589K (-250°F to 600°F) and in a one (1) atmosphere environment (air)

The cryogenic temperature of 116K (-250°F) shall be held for one-half (1/2) hour and the maximum temperature of 589K (600°F) shall be held for one (1) hour per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min).

4 - Moisture conditioned

Condition in chamber at 75% RH at 353K (175°F) for two weeks. Follow by conditioning in chamber at 50% RH at RT for two months.

[2]
- Modulus
  - Test same specimen at all 3 temperatures
  - Strain to less than failure
- Ultimate
  - 1 each in conditions 1 and 2 at RT and 561K (550°F)
- Poisson's Ratio



1 INSTALL TFE STRAIN GAGE
(0-10,000 MICROSTRAIN RESOLUTION

2 MOLDED THICKNESS APPROX
3mm (.12 in) GRIND FLAT
AND PARALLEL

Figure 3-24A: NEAT RESIN TENSION SPECIMEN

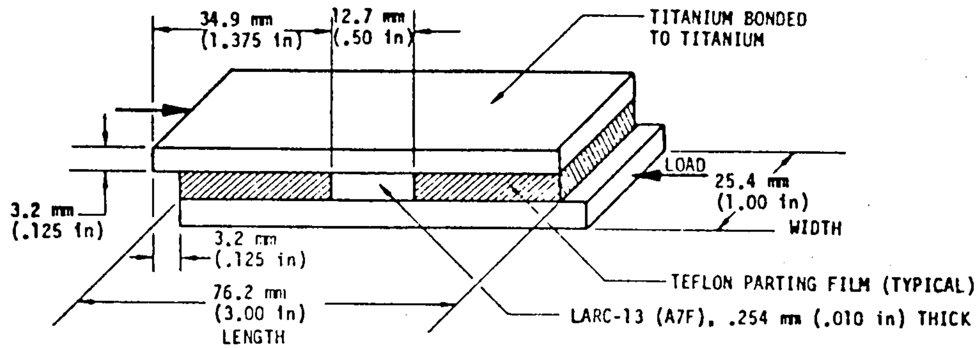
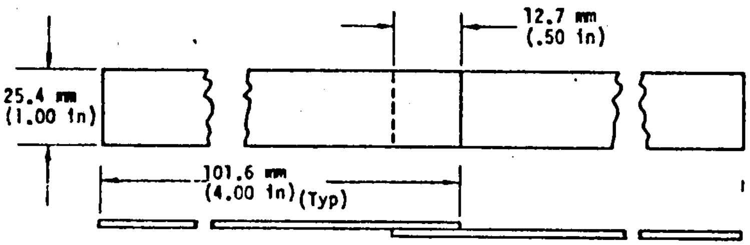
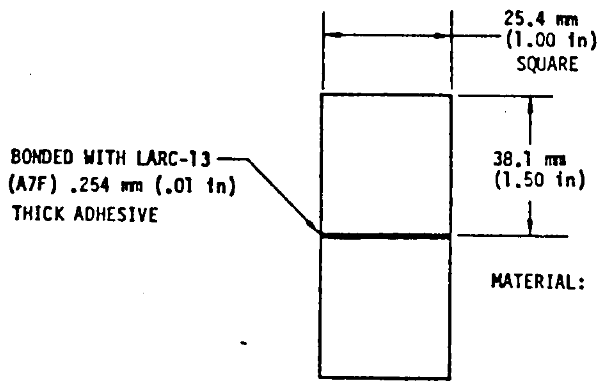


Figure 3-24B: SLIP PLANE SHEAR SPECIMEN



MATERIAL: TITANIUM 6A1-4V ANNEALED
1.6 mm (.063 in) NOM.
BOND WITH LARC-13 (A7F)
.254 mm (.01 in) THICK
(ASTM D1002 STANDARD)

Figure 3-24C: TITANIUM LAP SHEAR SPECIMEN



MATERIAL: LOADING BLOCKS SHALL BE 300 SERIES CRES STL,
PER ASTM D2094-69

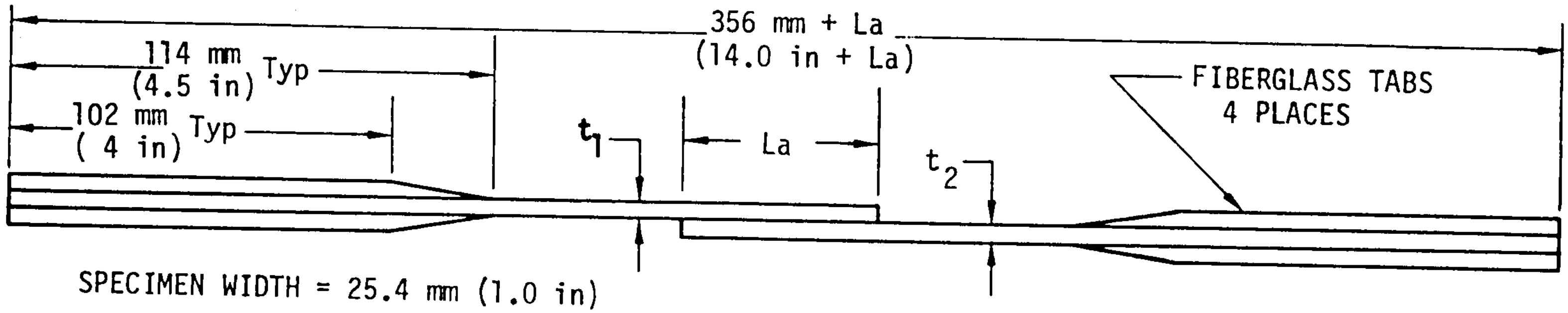
Figure 3-24E: FLATWISE TENSION ADHESIVE TEST SPECIMEN

3.1.4 TASK 2.1.4 - Joint Specimen Fabrication and Non-Destructive Evaluation

This task will accomplish the fabrication and inspection of the specimens as defined in Task 2.1.5. Visual observation of fabrication processes, inspection of completed test specimens for size and geometry, and nondestructive evaluation of each specimen will be made. In order to increase the database for designing the Task 1.3 joints and attachments, a series of test specimens from the Task 2.1.5 test matrix are being fabricated "out-of-sequence". Four laminates have been fabricated, using the remaining prepreg from Lot 2W4582. Celion 3000/PMR-15 prepreg [27 kg (60 lbs)] is on order to complete the laminate fabrication required for this task. In view of past problems with prepreg purchases, unusually stringent requirements are imposed for this purchase.

3.1.5 TASK 2.1.5 - Joint Test Program

Tentative test matrices for this task are shown in Figures 3-25 thru 3-31. Single lap, double lap and symmetrical step lap joints will be tested. Conditioning will consist of 450 ks (125 hour) soak at 589K (600°F) in a one atmosphere environment (air). Testing will cover the range of 116 to 561K (-250 to 550°F).



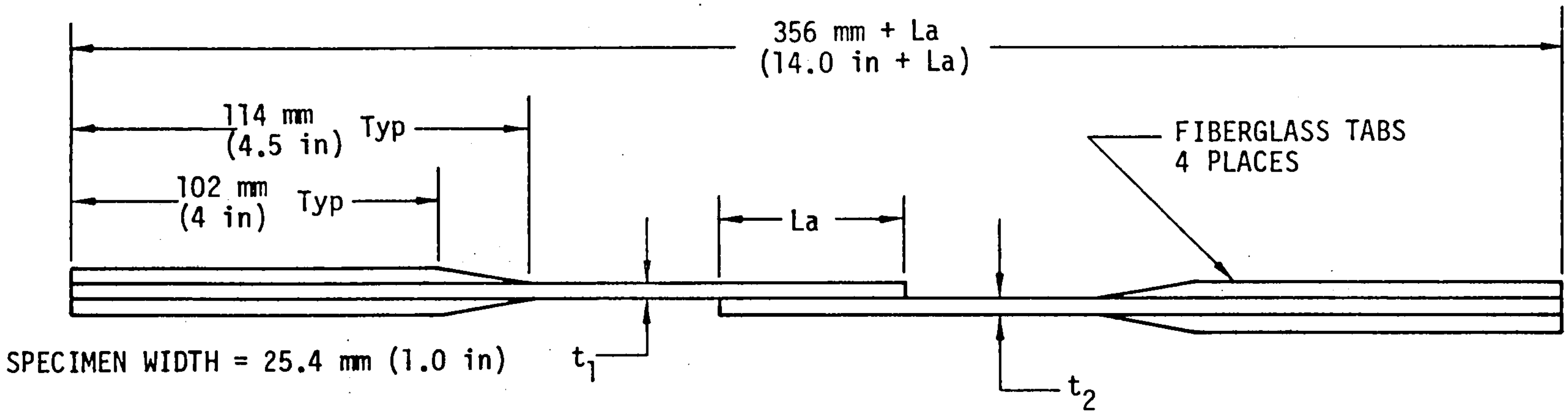
SPECIMEN WIDTH = 25.4 mm (1.0 in)

TEST NO	La mm (in)	t_1 mm (in)	t_2 mm (in)	LAMINATE t_1 & t_2	NUMBER OF TESTS AT 116K (-250°F)	RT	561K (550°F)	TOTAL NUMBER OF SPECIMENS
1a	25.4 (1.0)	1.52 (.06)	1.52 (.06)	$(0,\pm45,90)_{3s}$	6	6	6	18
1b	50.8 (2.0)	1.52 (.06)	1.52 (.06)	$(0,\pm45,90)_{3s}$	6	6	6	18
1c	76.2 (3.0)	1.52 (.06)	1.52 (.06)	$(0,\pm45,90)_{3s}$	6	6	6	18
2a	50.8 (2.0)	1.52 (.06)	1.52 (.06)	$(0,\pm45,0_3)_{2s}$	6	6	6	18
3a	50.8 (2.0)	1.52 (.06)	1.52 (.06)	$(\pm45,0,90)_{3s}$		6		6
4a	50.8 (2.0)	1.52 (.06)	1.52 (.06)	$(0_3,\pm45_3,90_3)_s$		6		6
5a	50.8 (2.0)	1.02 (.04)	2.03 (.08)	$(0,\pm45,90)_{2s}/(0,\pm45,90)_{4s}$ (t_1/t_2)	6	6	6	18
6a	50.8 (2.0)	2.54 (.10)	2.54 (.10)	$(0,\pm45,90)_{5s}$		6		6
7a	12.7(0.5)	1.52(.06)	1.52(.06)	$(0,\pm45,90)_{3s}$	6	6	6	18

TOTAL 126

1. Celion 3000 (NR150B2 Finish)/PMR-15 prepreg.
2. A7F (LARC-13, Amide-Imide modified) adhesive.
3. Condition specimens by soaking for 450 ks (125 hours) at 589K (600°F) in a one (1) atmosphere environment (air).

Figure 3-25: TEST MATRIX 3A, STANDARD JOINT, SINGLE LAP, GR/PI-GR/PI 1 2 3



TEST NO	La mm (in)	t_1 mm (in)	t_2 mm (in)	LAMINATE t_1	LAMINATE t_2	NUMBER OF TESTS AT 116K (-250°F)	RT	561K (550°F)	TOTAL NUMBER OF SPECIMENS
1a	25.4 (1.0)	1.52 (.06)	.76 (.03)	$(0,\pm45,90)_{3s}$	[4]	6	6	6	18
1b	50.8 (2.0)	1.52 (.06)	.76 (.03)	$(0,\pm45,90)_{3s}$	[4]	6	6	6	18
1c	76.2 (3.0)	1.52 (.06)	.76 (.03)	$(0,\pm45,90)_{3s}$	[4]	6	6	6	18

TOTAL 54

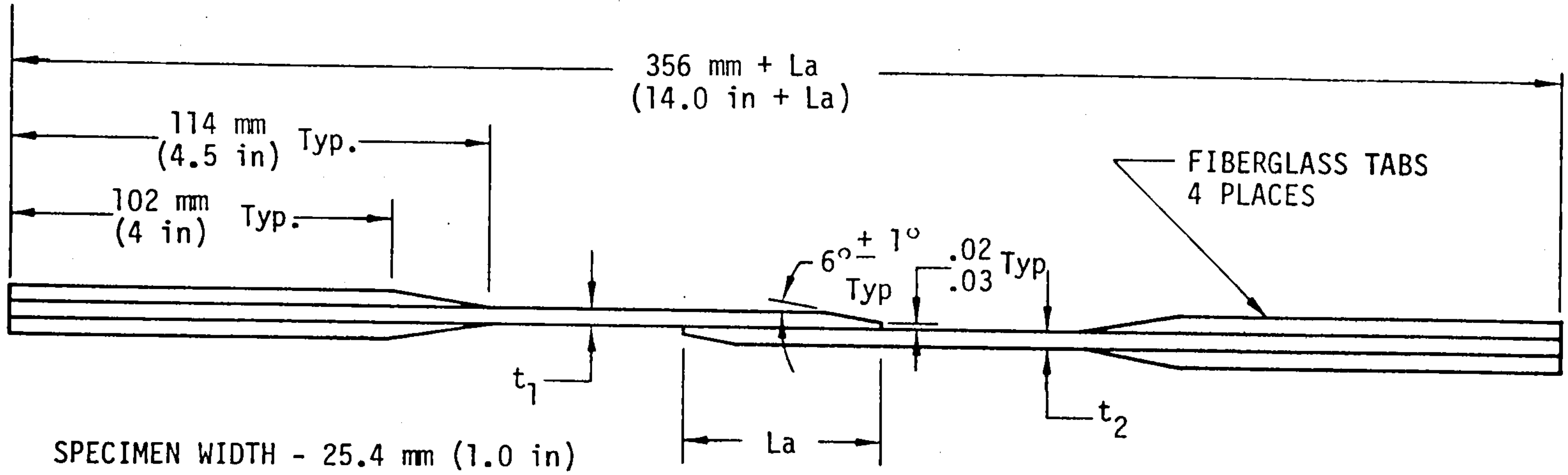
[1] Celion 3000 (NR150B2 Finish)/PMR-15 prepreg.

[2] A7F (LARC-13, Amide-Imide modified) adhesive.

[3] Condition specimens by soaking for 450 ks (125 hours) at 589K (600°F) in a one (1) atmosphere environment (air).

[4] Titanium 6Al-4V, Standard MIL-T-9046 Type III Annealed (or equivalent).

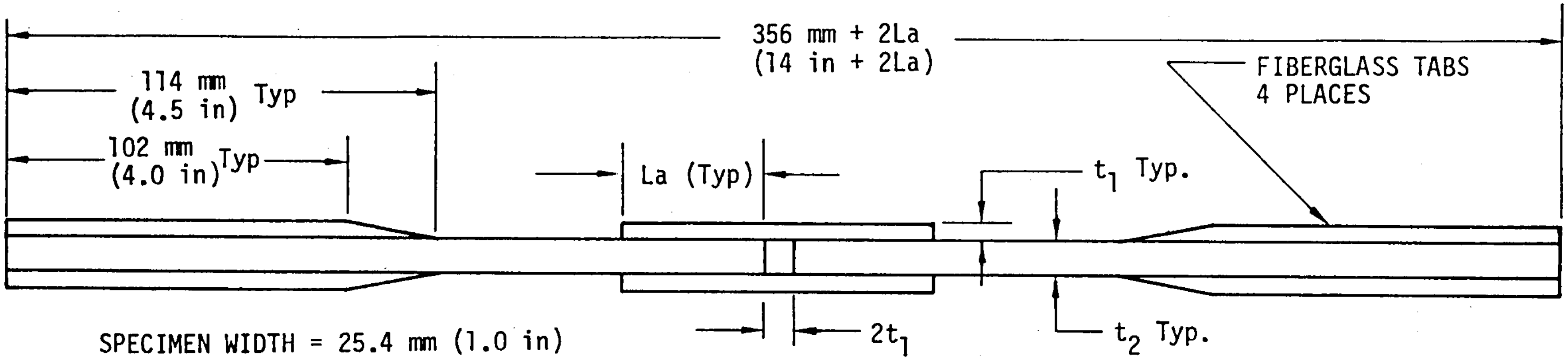
Figure 3-26: TEST MATRIX 3B, STANDARD JOINT, SINGLE LAP, GR/PI-Ti [1] [2] [3]



TEST NO	La mm (in)	t_1 mm (in)	t_2 mm (in)	LAMINATE t_1 & t_2	NUMBER OF TESTS AT 116K (-250°F)	RT	561K (550°F)	TOTAL NUMBER OF SPECIMENS
1a	50.8 (2.0)	2.54 (.10)	2.54 (.10)	$(0,\pm45,90)_{5s}$		6		6

1. Celion 3000 (NR150B2 Finish)/PMR-15 prepreg.
2. A7F (LARC-13, Amide-Imide modified) adhesive.
3. Condition specimens by soaking for 450ks (125 hours) at 589K (600°F) in a one (1) atmosphere environment (air).

Figure 3-27: TEST MATRIX 3C, STANDARD JOINT, SINGLE LAP TAPERED ADHERENDS, GR/PI-GR/PI 1 2 3



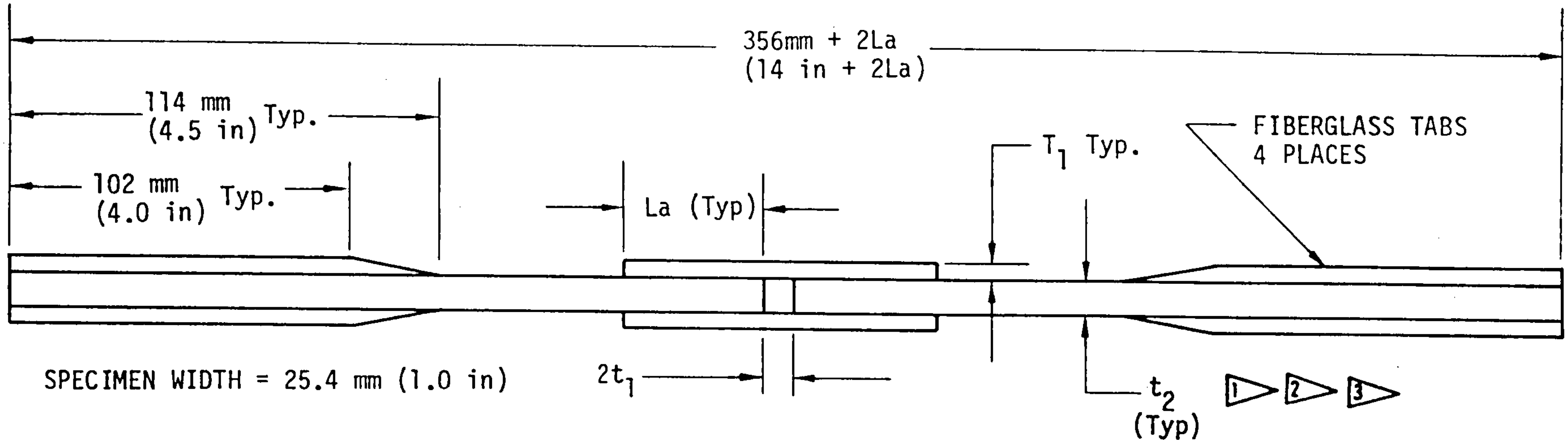
SPECIMEN WIDTH = 25.4 mm (1.0 in)

TEST NO	La mm (in)	t_1 mm (in)	t_2 mm (in)	LAMINATE t_1	LAMINATE t_2	NUMBER OF TESTS AT 116K (-250°F)	RT	561K (550°F)	TOTAL NUMBER OF SPECIMENS
1a	20.3 (.8)	1.02 (.04)	2.03 (.08)	$(0,\pm45,90)_{2s}$	$(0,\pm45,90)_{4s}$	6	6	6	18
1b	33.0 (1.3)	1.02 (.04)	2.03 (.08)	$(0,\pm45,90)_{2s}$	$(0,\pm45,90)_{4s}$	6	6	6	18
1c	45.7 (1.8)	1.02 (.04)	2.03 (.08)	$(0,\pm45,90)_{2s}$	$(0,\pm45,90)_{4s}$	6	6	6	18
2a	20.3 (.8)	1.52 (.06)	3.05 (.12)	$(0,\pm45,90)_{3s}$	$(0,\pm45,90)_{6s}$	6	6	6	18
2b	33.0 (1.3)	1.52 (.06)	3.05 (.12)	$(0,\pm45,90)_{3s}$	$(0,\pm45,90)_{6s}$	6	6	6	18
2c	45.7 (1.8)	1.52 (.06)	3.05 (.12)	$(0,\pm45,90)_{3s}$	$(0,\pm45,90)_{6s}$	6	6	6	18
3a	33.0 (1.3)	1.52 (.06)	3.05 (.12)	$(0,+45,0_2,-45,0)_{2s}$	$(0,+45,0_2,-45,0)_{4s}$	6	6	6	18
4a	33.0 (1.3)	1.52 (.06)	3.05 (.12)	$(0_3,\pm45_3,90_3)_s$	$(0_3,\pm45_3,90_3)_{2s}$	6	6	6	18
5a	33.0 (1.3)	1.52 (.06)	3.05 (.12)	$(\pm45,0,90)_{3s}$	$(\pm45,0,90)_{6s}$	6	6	6	18
6a	33.0 (1.3)	1.52 (.06)	2.03 (.08)	$(0,\pm45,90)_{3s}$	$(0,\pm45,90)_{4s}$	6	6	6	18
7a	33.0 (1.3)	3.05 (.12)	6.10 (.24)	$(0,\pm45,90)_{6s}$	$(0,\pm45,90)_{12s}$		6	6	12

TOTAL 192

1. Celion 3000 (NR150B2 Finish)/PMR-15 prepreg.
2. A7F (LARC-13, Amide-Imide modified) adhesive.
3. Condition specimens by soaking for 450 ks (125 hours) at 589K (600°F) in a one (1) atmosphere environment (air).

Figure 3-28: TEST MATRIX 3D, STANDARD JOINT, DOUBLE LAP, GR/PI-GR/PI 1 2 3



TEST NO	La mm (in)	t_1 mm (in)	t_2 mm (in)	LAMINATE t_1	t_2	NUMBER OF TESTS AT 116K (-250°F)	RT	561K (550°F)	TOTAL NUMBER OF SPECIMENS
1a	20.3 (.8)	1.52 (.06)	1.52 (.06)	$(0, \pm45, 90)_{3s}$	▷4	6	6	6	18
1b	45.7 (1.8)	1.52 (.06)	1.52 (.06)	$(0, \pm45, 90)_{3s}$	▷4	6	6	6	18
2a	45.7 (1.8)	1.52(.06)	1.52(.06)	$(\pm45, 0, 90)_{3s}$	▷4	6	6	6	18

TOTAL 54

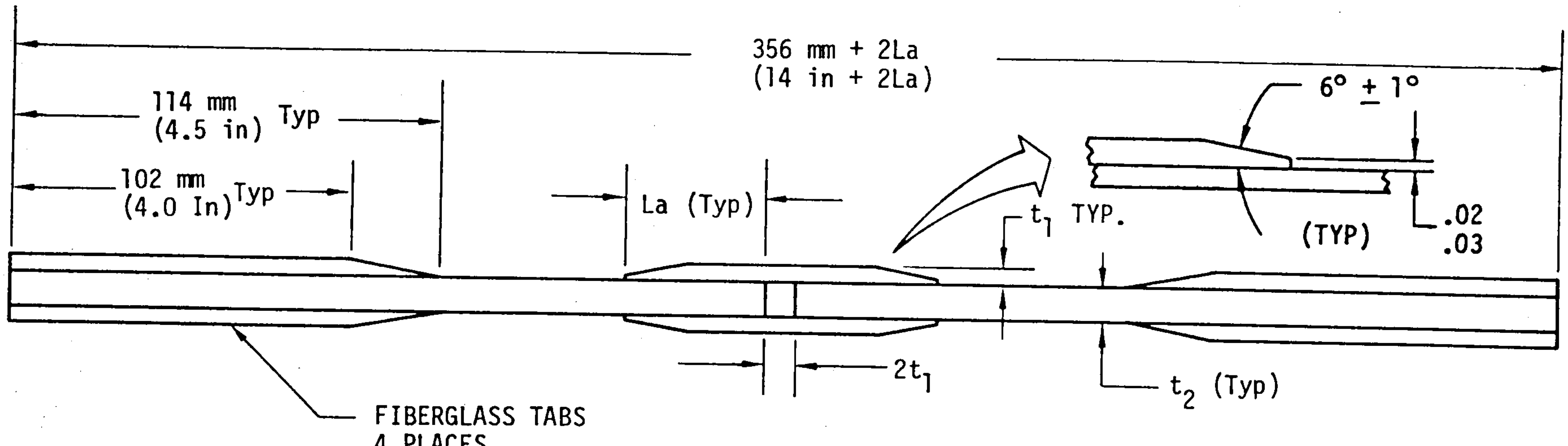
▷1 **Celion 3000 (NR150B2 Finish)/PMR-15 prepreg.**

▷2 **A7F (LARC-13, Amide-Imide modified) adhesive.**

▷3 **Condition specimens by soaking for** 450 ks (125 hours) **at 589K (600°F) in a one (1) atmosphere environment (air).**

▷4 **Titanium 6Al-4V, Standard MIL-T-9046 Type III Annealed (or equivalent.**

Figure 3-29: TEST MATRIX 3E, STANDARD JOINT, DOUBLE LAP, GR/PI-Ti



SPECIMEN WIDTH = 25.4 mm (1.0 in)

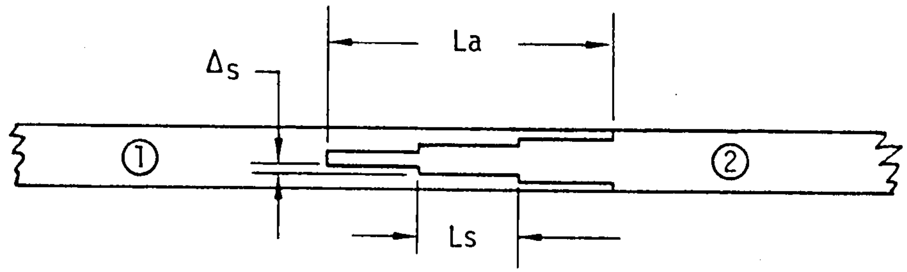
TEST NO	La mm (in)	t_1 mm (in)	t_2 mm (in)	LAMINATE t_1	LAMINATE t_2	NUMBER OF TESTS AT 116K (-250°F)	RT	561K (550°F)	TOTAL NUMBER OF SPECIMENS
1a	33.0 (1.3)	3.05 (.12)	6.10 (.24)	$(0,\pm45,90)_{6s}$	$(0,\pm45,90)_{12s}$		6	6	12

1 Celion 3000 (NR150B2 Finish)/PMR-15 prepreg.

2 A7F (LARC-13, Amide-Imide modified) adhesive.

3 Condition specimens by soaking for 125 hours at 589K (600°F) in a one (1) atmospheric environment (air).

Figure 3-30: TEST MATRIX 3F, STANDARD JOINT, DOUBLE LAP, TAPERED ADHERENDS, GR/PI-GR/PI 1 2 3



TEST NO.	La	MATERIAL ①	MATERIAL ②	NO. OF STEPS	Ls	Δ s	NUMBER OF TESTS AT 116K (-250°F)	ROOM TEMP.	561K (550°F)	TOTAL NO. OF SPECIMENS
1a	38.1 mm (1.5 in)	GR/PI 50% ± 45°	TITANIUM 6A-4V	3	12.7 mm (.5 in)	.51 mm (.02 in)	6	6	6	18
1b	63.5 mm (2.5 in)	GR/PI 50% ± 45°	TITANIUM 6A-4V	5	12.7 mm (.5 in)	.51 mm (.02 in)	6	6	6	18
2a	63.5 mm (2.5 in)	GR/PI 50% ± 45°	TITANIUM 6A-4V	5	12.7 mm (.5 in)	.51 mm (.02 in)	6	6	6	18

TOTAL 54

Figure 3-31: TEST MATRIX 3G, STANDARD JOINT, SYM. STEP LAP, GR/PI - TITANIUM

SECTION 4.0

FAILURE ANALYSIS

This section of the quarterly report will discuss failure criteria and key results of failure analysis investigations conducted during the reporting period. No significant conclusions were drawn during this reporting period.

SECTION 5.0

CONCLUDING REMARKS

During the period covered by this report the principal program activities dealt with joint concept screening, verification of GR/PI material, fabrication of design allowables panels, defining test matrices and analysis of bonded and bolted joints. A detailed screening to select the best 2 or 3 concepts for each attachment type has been completed. Resolution of prepreg processing problems resulted in successful fabrication of thirteen panels for design allowables testing. Test matrices and specimen configurations have been defined in detail for design allowables (Matrix 1), ancillary adhesive tests (Matrix 2), standard joints (Matrix 3) and small specimens (Matrix 4). Preliminary analysis of bonded and bolted type 3 joints was completed, as well as additional finite element and analysis of double lap bonded joints.

The results from the activity discussed in this report have led to the following conclusions:

- *Celion 3000/PMR-15 prepreg processing anomalies are attributable to resin changes resulting from the exotherm during formulation scale-up.*

- *It appears advantageous to place a "soft" zone, say a $\pm 45°$ laminate adjacent to the adhesive in a double lap bonded joint, to minimize stress concentrations in the critical zone near the edge of the adherend.*

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