NASA CR-159,111

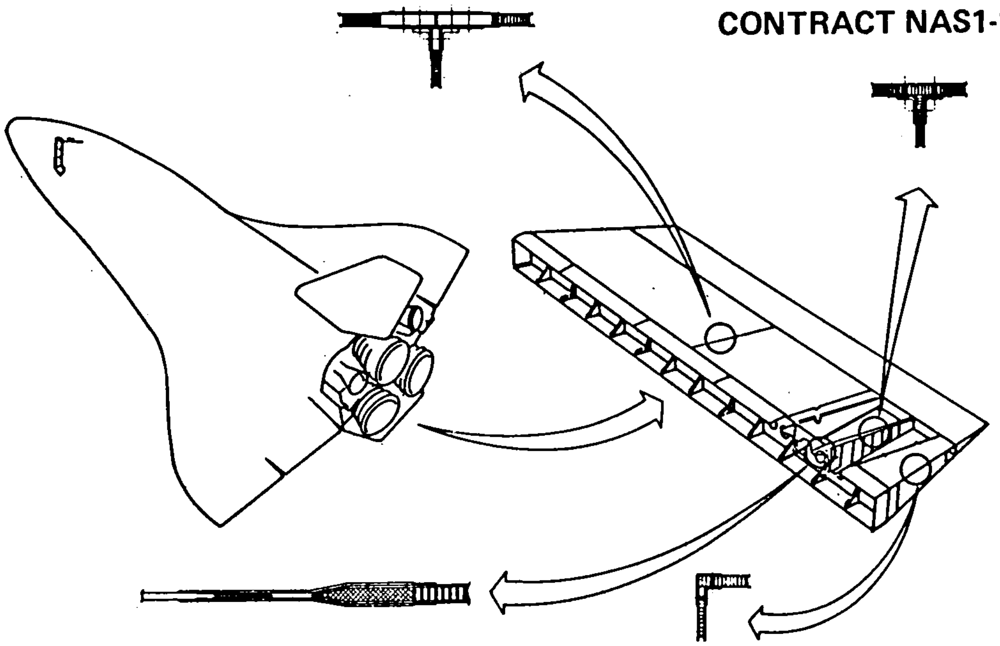
NASA-CR-159111
19800022941

NASA Contractor Report Number 159111

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

QUARTERLY TECHNICAL PROGRESS REPORT NO. 4
COVERING THE PERIOD FROM
OCTOBER 1, 1979 THROUGH JANUARY 31, 1980

CONTRACT NAS1-15644



PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665

FEBRUARY 15, 1980

BOEING AEROSPACE COMPANY
ENGINEERING TECHNOLOGY
POST OFFICE BOX 3999
SEATTLE, WASHINGTON 98124

NASA Contract Report Number 159111

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

QUARTERLY TECHNICAL PROGRESS REPORT NO. 4

CONTRACT NAS1-15644

February 15, 1980

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Langley Research Center
Hampton, Virginia 23665

BOEING AEROSPACE COMPANY

Engineering Technology
Post Office Box 3999
Seattle, Washington 98124

N80-31447#

FOREWORD

This report summarizes the work performed by the Boeing Aerospace Company (BAC) under NASA Contract NAS1-15644 during the period October 1, 1979 through January 31, 1980.

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.

Prepared by: D. E. Skoumal
D. E. Skoumal
Technical Leader

Approved by: J. L. Arnquist
J. L. Arnquist
Program Manager

TABLE OF CONTENTS

SUMMARY

This document reports on activities from October 1, 1979, through January 31, 1980, 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 data base 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, principal program activities dealt with the literature survey, design of joint concepts, assessment of GR/Pi material quality, fabrication of test panels, design allowables testing, definition of test matrices and specimens, and study of finite element modeling and analysis of joint adhesive fillets. Bonded and bolted designs are presented for each of the four major attachment types. Prepreg processing problems are discussed and quality control (QC) data presented for Lots 2W4604, 2W4632 and 2W4643. Preliminary design allowables test results for tension tests of $0°_{16}$, $90°_{30}$, $(0,\pm45,90)_{4S}$ and $\pm45°_{8S}$ laminates, and compression tests of $(90,\pm45,0)_{4S}$ laminates are presented. The final small specimen test matrix is defined and the configuration of symmetric step-lap joint specimens are shown. Finite element modeling studies of a double lap joint were performed to evaluate the number of elements required through the adhesive thickness to assess effects of various joint parameters on stress distributions. Results of finite element analyses assessing the effect of an adhesive fillet on the stress distribution in a double lap joint are also presented.

SECTION 1.0

INTRODUCTION

This is the 4th quarterly report covering results of activity during the period October 1, 1979, through January 31, 1980.

The purpose of this program is to provide a data base 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 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 were designed and analyzed for each bonded and each bolted attachment type and reported in reference 8. Concurrent with this task a series of design allowable and small specimen tests are being 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, a maximum of two of the most promising concepts for each joint type will be fabricated, tested, and evaluated. The evaluation will yield

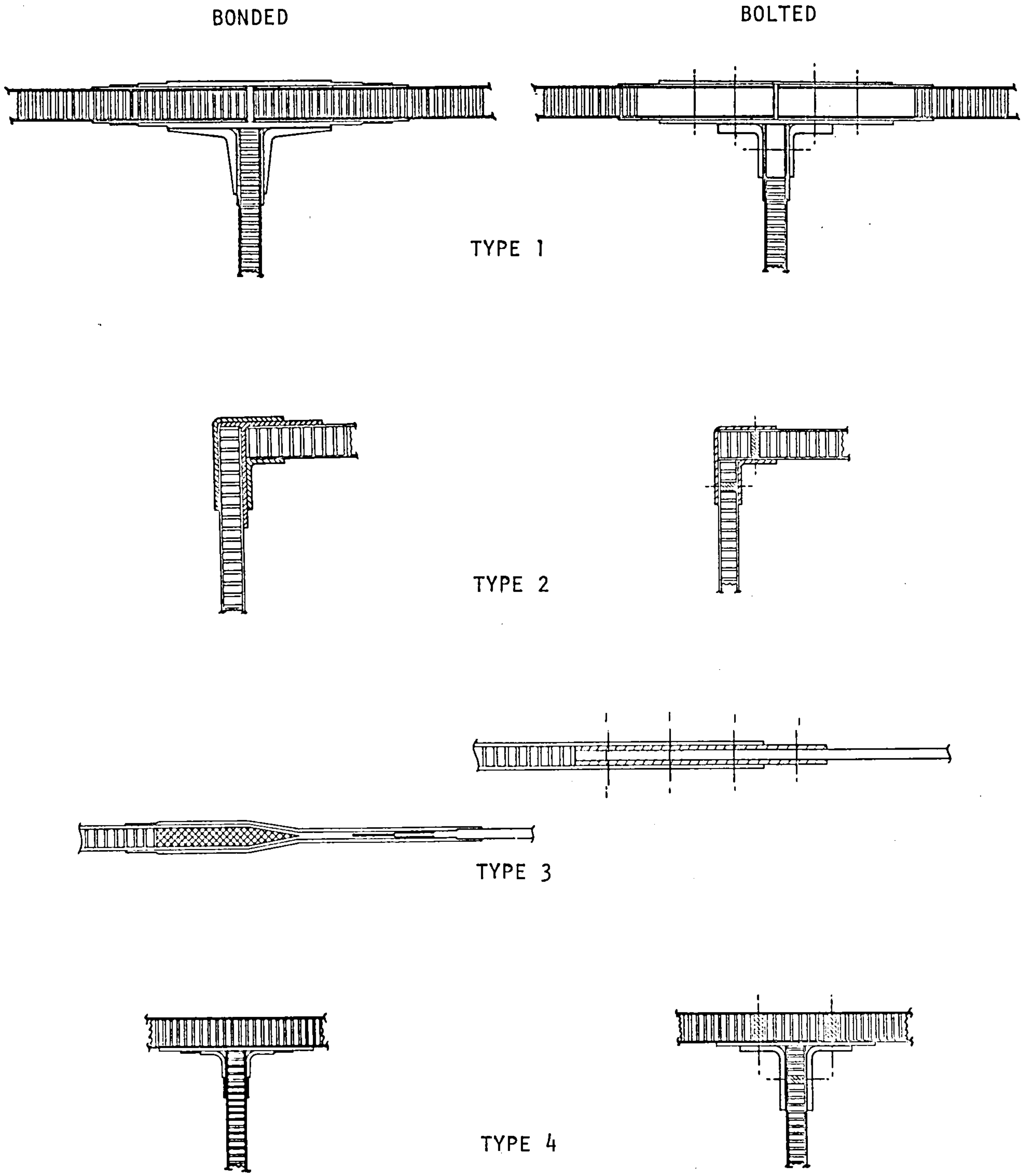


Figure 1-1: Generic Joint Concepts for 4 Attachment Types

NASA CONTRACT NAS1-15644

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

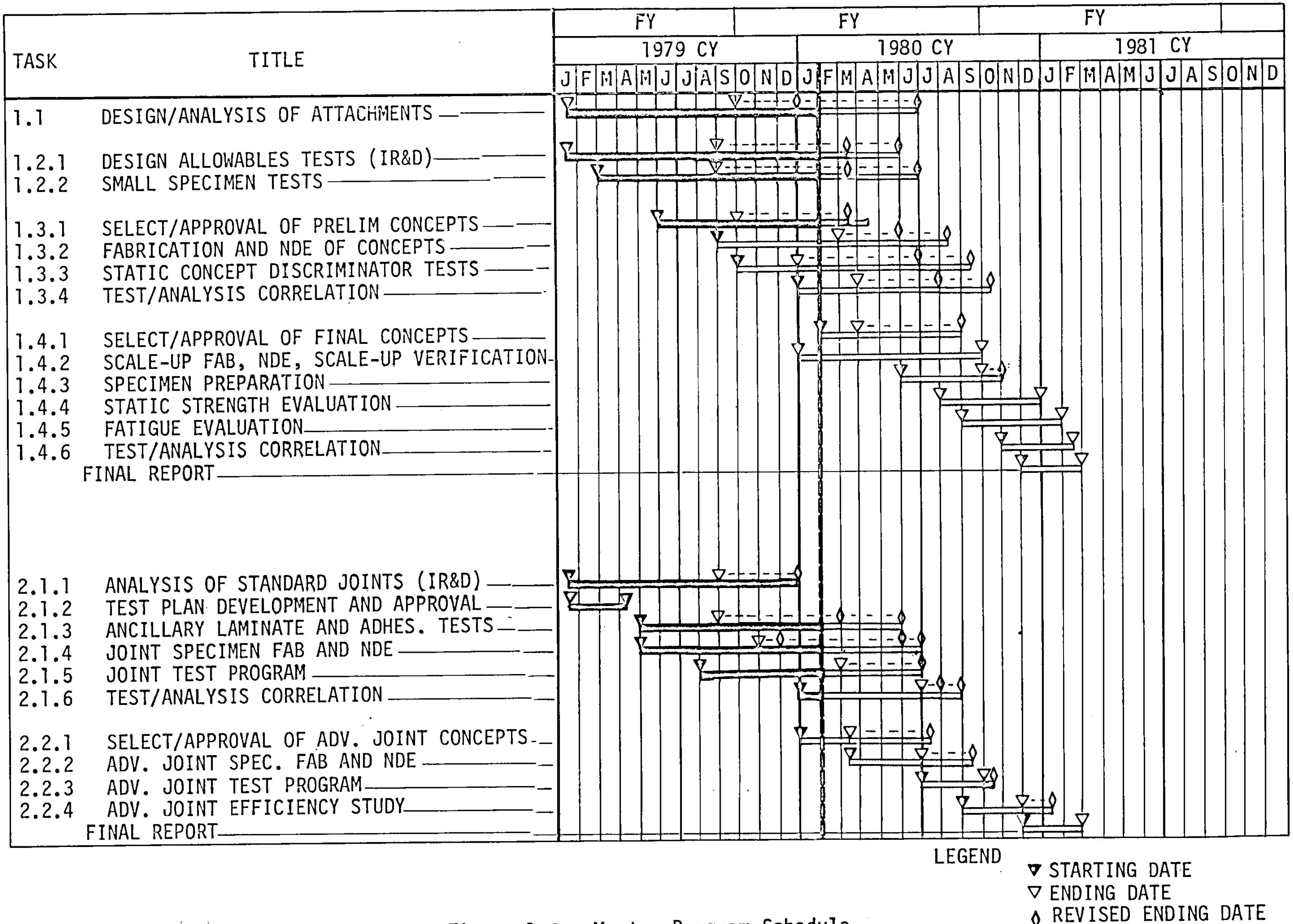


Figure 1-2: Master Program Schedule

the preferred joint concepts and will be based on weight efficiency, ease of fabrication, detail part count, inspectability and predicted fatigue behavior.

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 data base 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.

This report summarizes the literature survey, presents joint concepts selected in TASK 1.1 and presents preliminary results of design allowables testing completed during this reporting period.

Additional small specimen tests to evaluate specific joint details are defined in Matrix 4C. Materials and processing work to prepare composite panels for specimen fabrication and LARC-13 amide-imide modified (A7F) adhesive for specimen bonding are discussed. Results of finite element modeling studies and analyses to assess effects of adhesive fillets are presented.

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 7 and is summarized below.

References 3 compares results of an approximate nonlinear finite element analysis of a single lap joint with results of a linear finite-element analysis. The geometric nonlinear effects due to load-path eccentricities on the adhesive stress distribution are also determined. Analysis results are compared with the classical Goland-Reissner analysis. It is shown that geometric nonlinearity has sizable effects on the stress distribution in the adhesive. The Goland-Reissner analysis predicts adhesive midplane stresses sufficiently accurate for qualitative evaluation of various joint parameters. Internal moments in the adherend based on Goland-Reissner analyses are quite accurate even near the region of overlap for adhesives that are soft compared to the adherend. Detailed adhesive and adherend stress distributions are presented for comparison with other solution techniques.

Results of testing to characterize the static strength and creep performance of Celion 6000/PMR-15 graphite/polyimide bolted joints are presented in Reference 4. Two laminates, one fiber dominated and one matrix dominated, were tested at temperatures from 294K (70°F) to 589K (600°F). Bearing strengths of the matrix controlled laminate suggests a failure mechanism similar to local plastic yielding of metals. Bearing failures in the fiber controlled laminate indicate an instability phenomenon. Shearout strengths for the two laminates were the same indicating that shearout strength is governed by the $\pm 45°$ plies.

Reference 5 discusses testing of simple bolted joints in multi-direction composite fiber reinforced plastic (cfrp) for a range of laminate configurations, hole sizes and clamping pressures. Failure modes are discussed and single-hole data are used to design multi-hole joints. Test results show no significant interaction between holes for normal bolt spacings.

Reference 6 presents results of an experimental investigation of the IITRI test method for determining compressive properties of composite materials at room and elevated temperatures [589K (600°F)]. Four symmetric laminates of HTS-1/PMR-15 and HTS-2/PMR-15 graphite/polyimide were tested. Specimen widths were varied from 6.35 mm (0.25 in) to 25.4 mm (1.0 in). Test scatter and back to back strain variations were very low and no specimen failed by instability. Variation of specimens width had a negligible effect on measured results. It is concluded that the IITRI test method is a viable means for obtaining compressive properties of composite materials up to 589K (600°F).

Results of analytical and experimental investigations of thermal microcracking in Celion 6000/PMR-15 graphite/polyimide laminates are presented in Reference 7. Six laminates were exposed to five different thermal loads. The laminates tested were free of cracks after curing; however, cooling from 602K (625°F) to 78K (-320°F) by LN_2 quench produced microcracking in five of six laminates. A layup of $[\pm 45,0,90]_S$ was very resistant to microcracking. This laminate was free of microcracks for all five of the thermal loadings tested. The density of microcracks is dependent on fiber orientation, stacking sequence, edge effects and rate of cooling. The microcracks extended across the full width of 25.4 mm (1.0 inch) square specimens. The thermal load required to initiate microcracking, as determined by analysis, compared reasonably well with test results.

2.1.2 Design and Analysis

The design/analysis procedure used to develop the joint designs is shown in Figure 2-1,

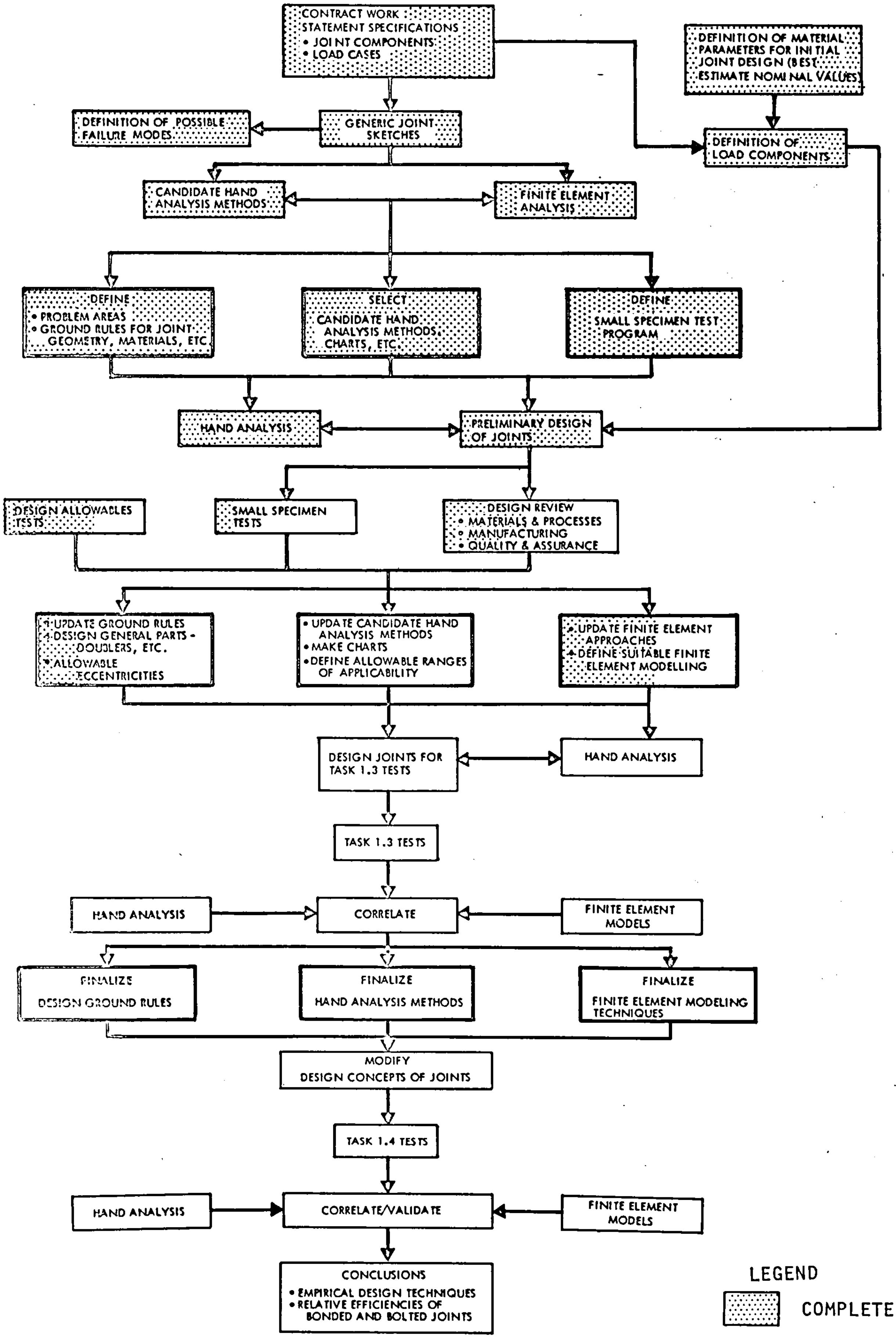


Figure 2-1: Task 1 Design/Analysis/Test Flow Diagram

which illustrates the interaction between design, analysis and test. Shaded areas identify approximate percent completion.

Preliminary design and analysis of joint concepts selected during the second cut screening (Ref. 8) has continued during this reporting period. Results of preliminary sizing that has been completed are shown in Figures 2-2 through 2-9. These designs are based on best estimates of material properties and are subject to change as results of design allowables and small specimen testing become available.

2.2 TASK 1.2 - Material and Small Component Characterization

This section discusses design allowables testing, panel fabrication and small specimen tests.

2.2.1 TASK 1.2.1 - Design Allowables

A limited design allowables test program is being conducted by Boeing under Independent Research and Development funding. Results of this testing will develop a data base of laminate material properties which will support joint design, failure prediction and analysis correlation in subsequent tasks.

All panels for the design allowables test matrix have been fabricated and conditioned. Specimens not requiring adhesive bonding or moisture conditioning have been cut and delivered to the test labs. Testing started on 19 December 1979, and is scheduled for completion in May 1980, except for moisture conditioned specimens. All moisture conditioning for the design allowables specimens will be done simultaneously and specimens tested later.

All panels used for the design allowables specimens were made from prepreg lot 2W4582. After curing and conditioning, each panel was inspected by C-scan to detect voids or porosity. All the panels C-scanned "clean" except for the large area 16 or 30 ply unidirectional panels. The bad areas of these panels were marked and no specimens were cut from the defective zones. Details of all the quality control tests conducted on this prepreg lot are presented and discussed in Reference 8.

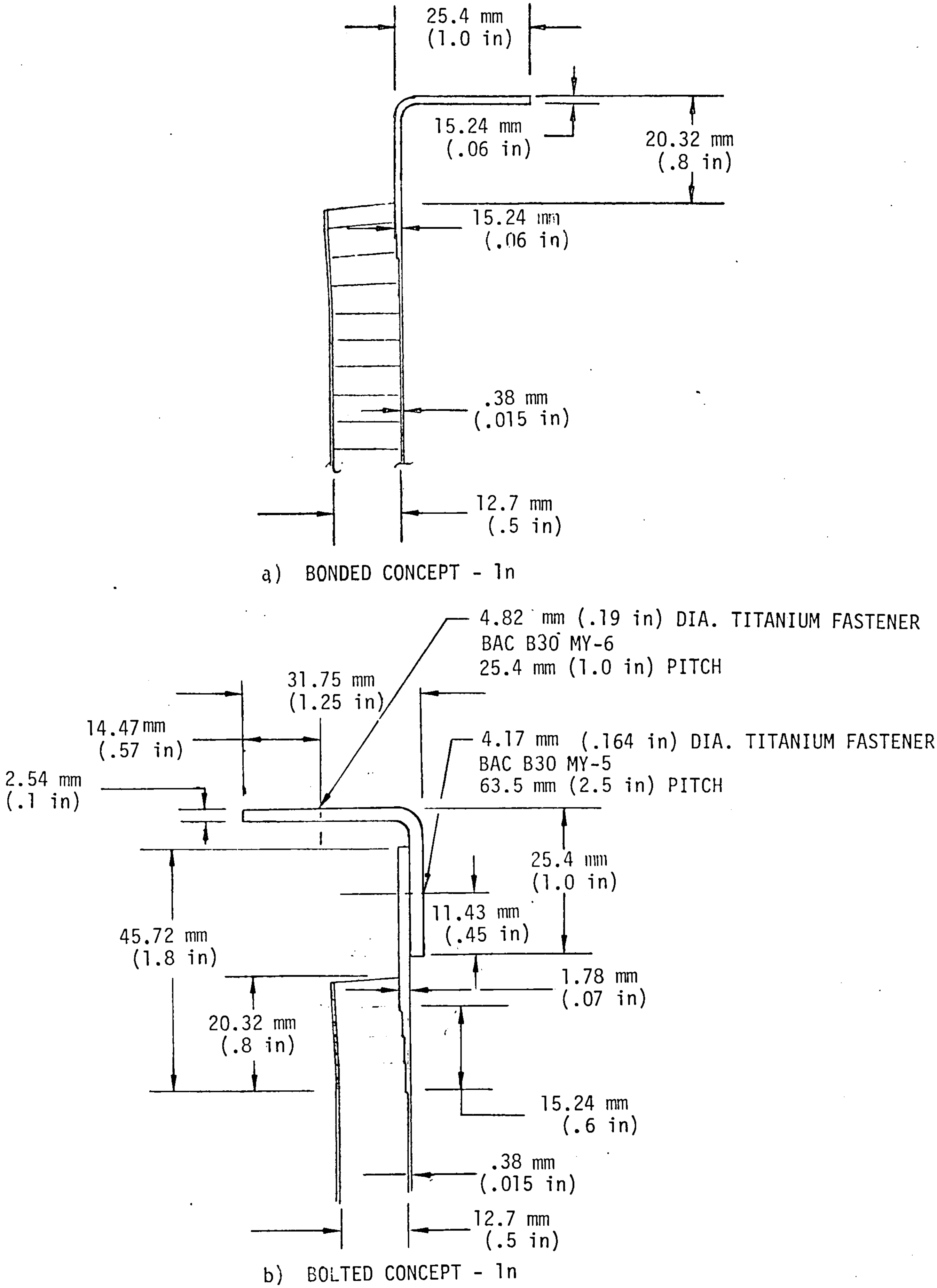


Figure 2-2: Type 1 Web to Cover Attachment Concepts

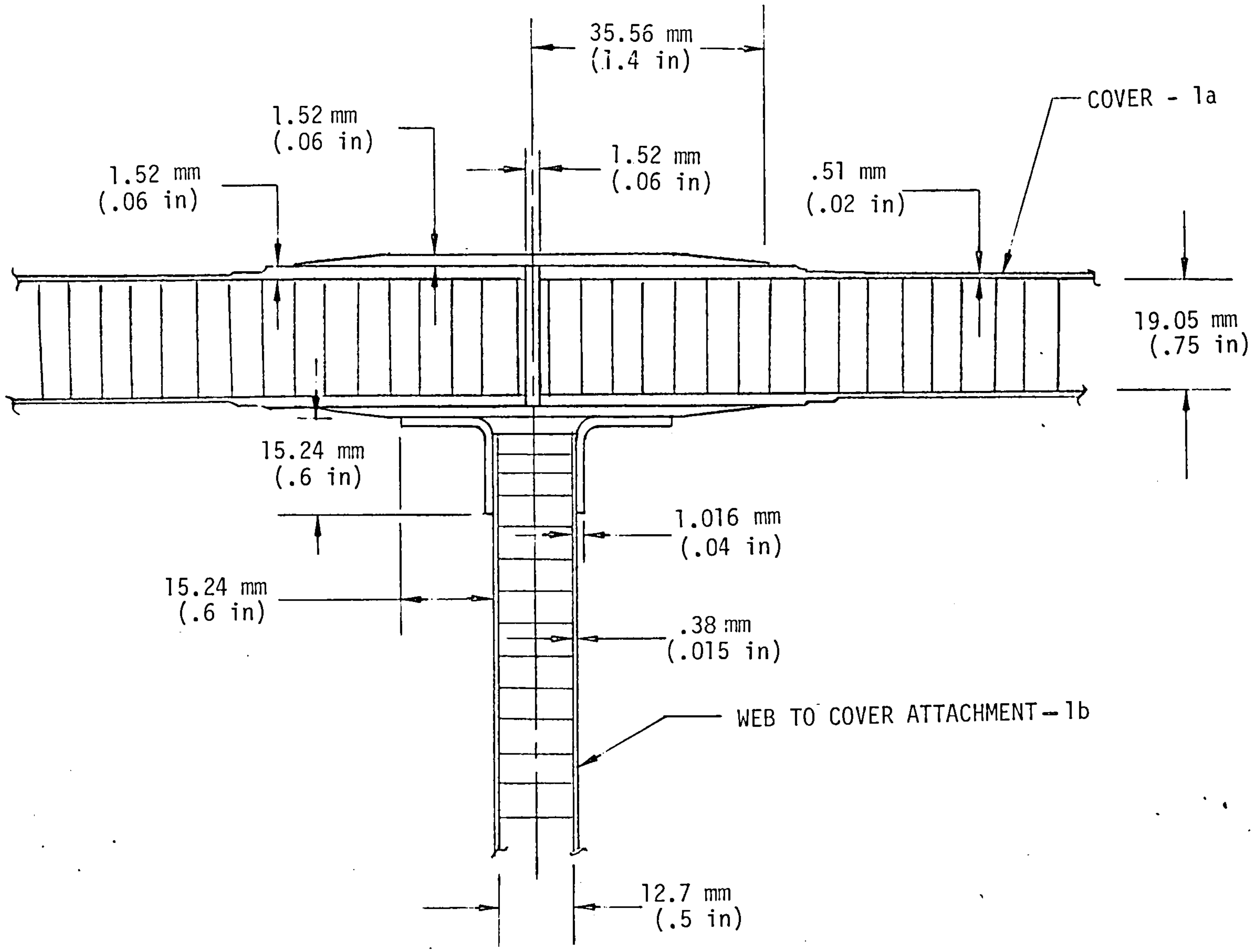


Figure 2-3: Type 1 Bonded Joint Concept

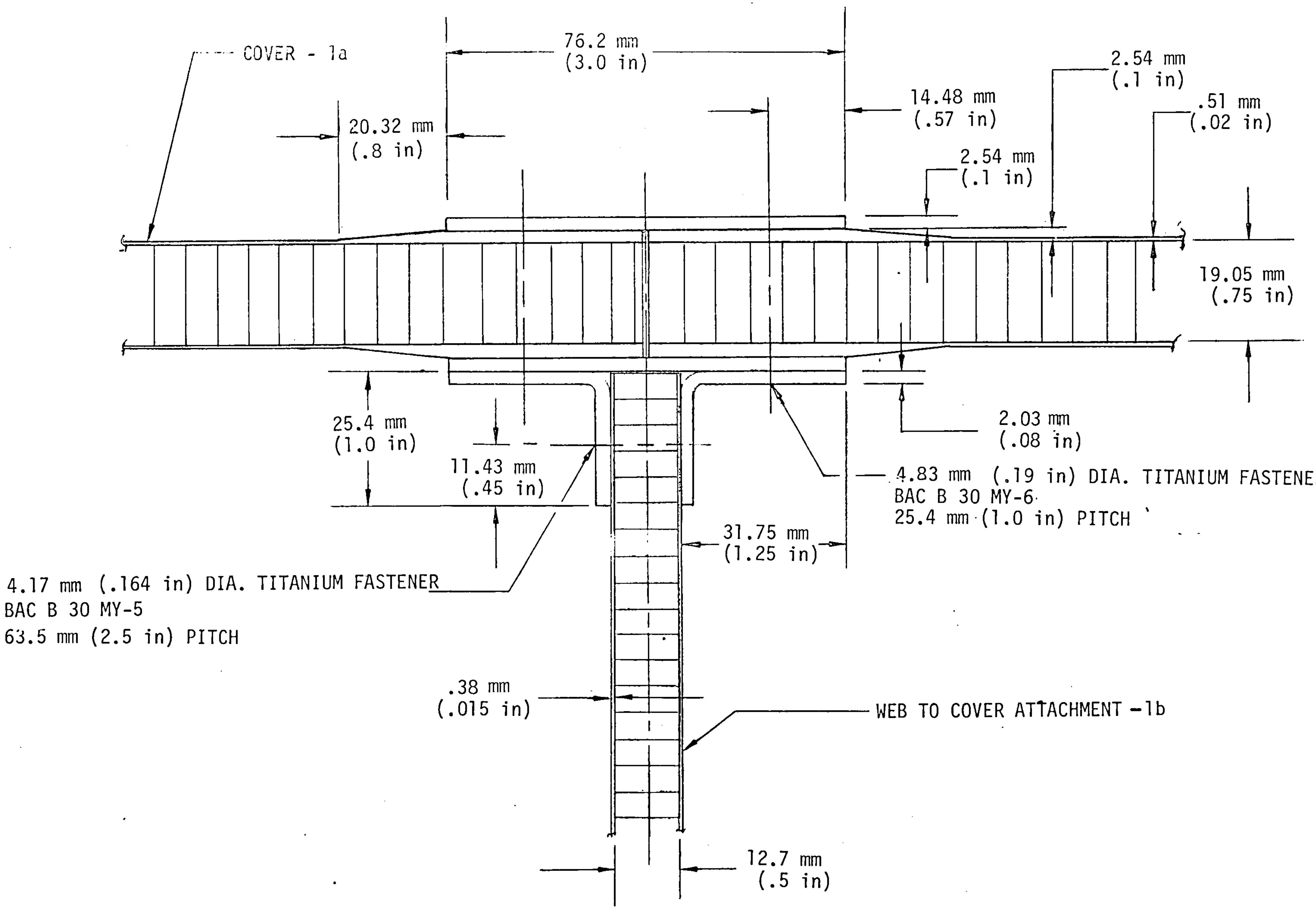
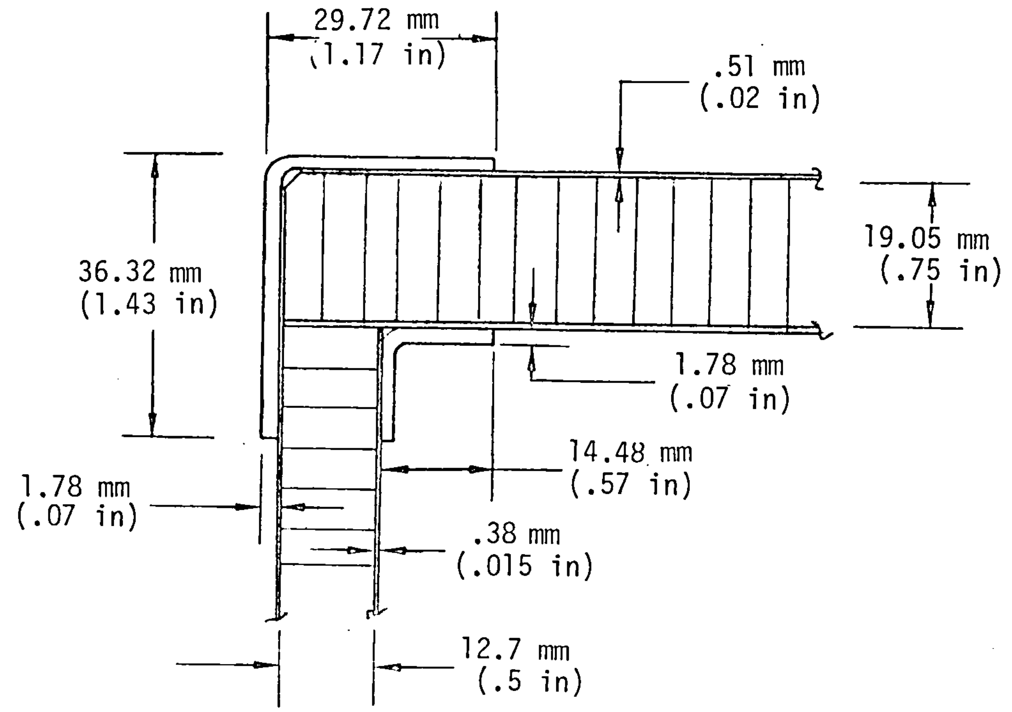
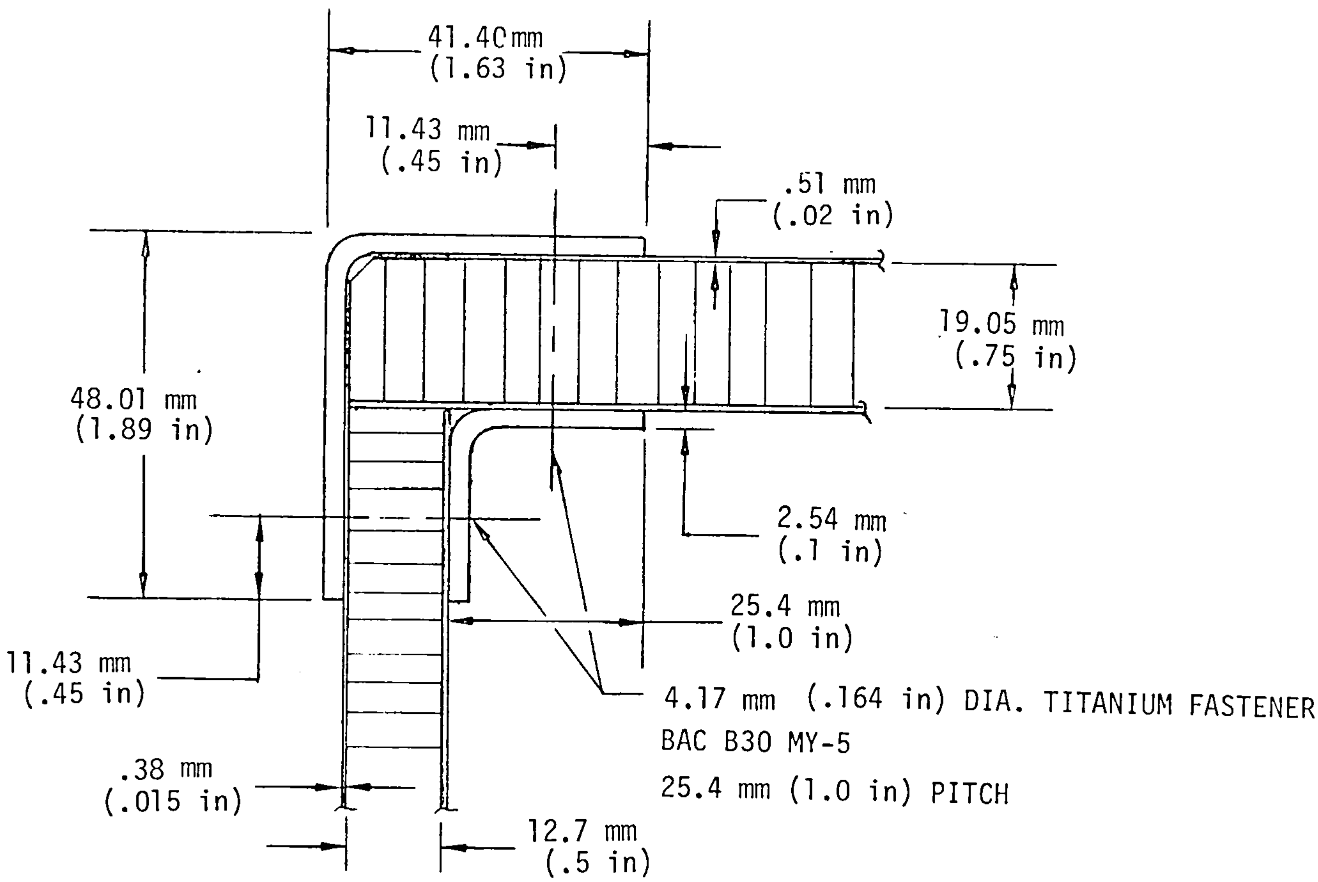


Figure 2-4: Type 1 Bolted Joint Concept



a) BONDED CONCEPT - 2a



b) BOLTED CONCEPT - 2a

Figure 2-5: Type 2 Joint Concepts

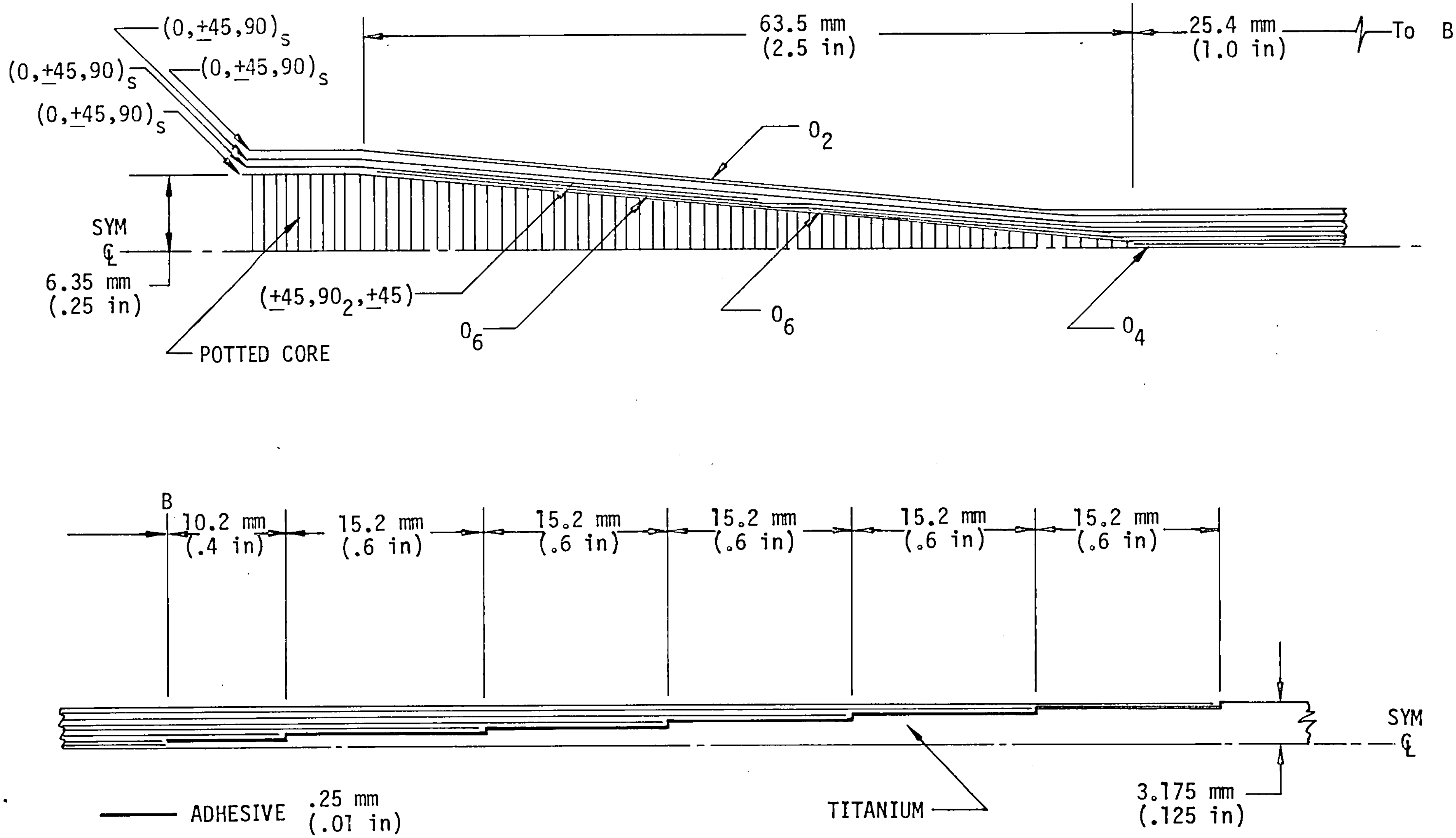


Figure 2-6: Type 3 Bonded Joint

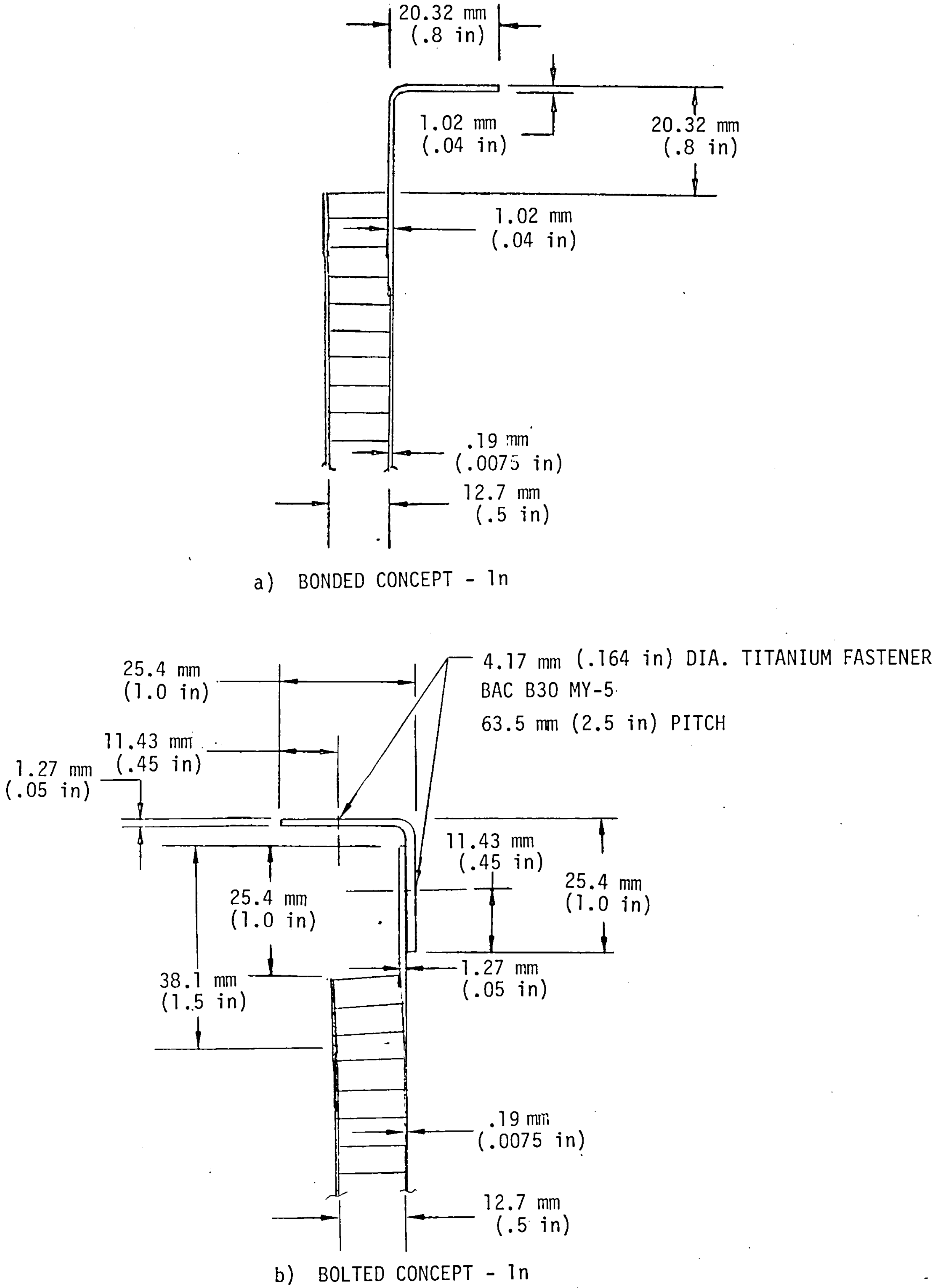


Figure 2-7: Type 4 Web to Cover Attachment Concepts

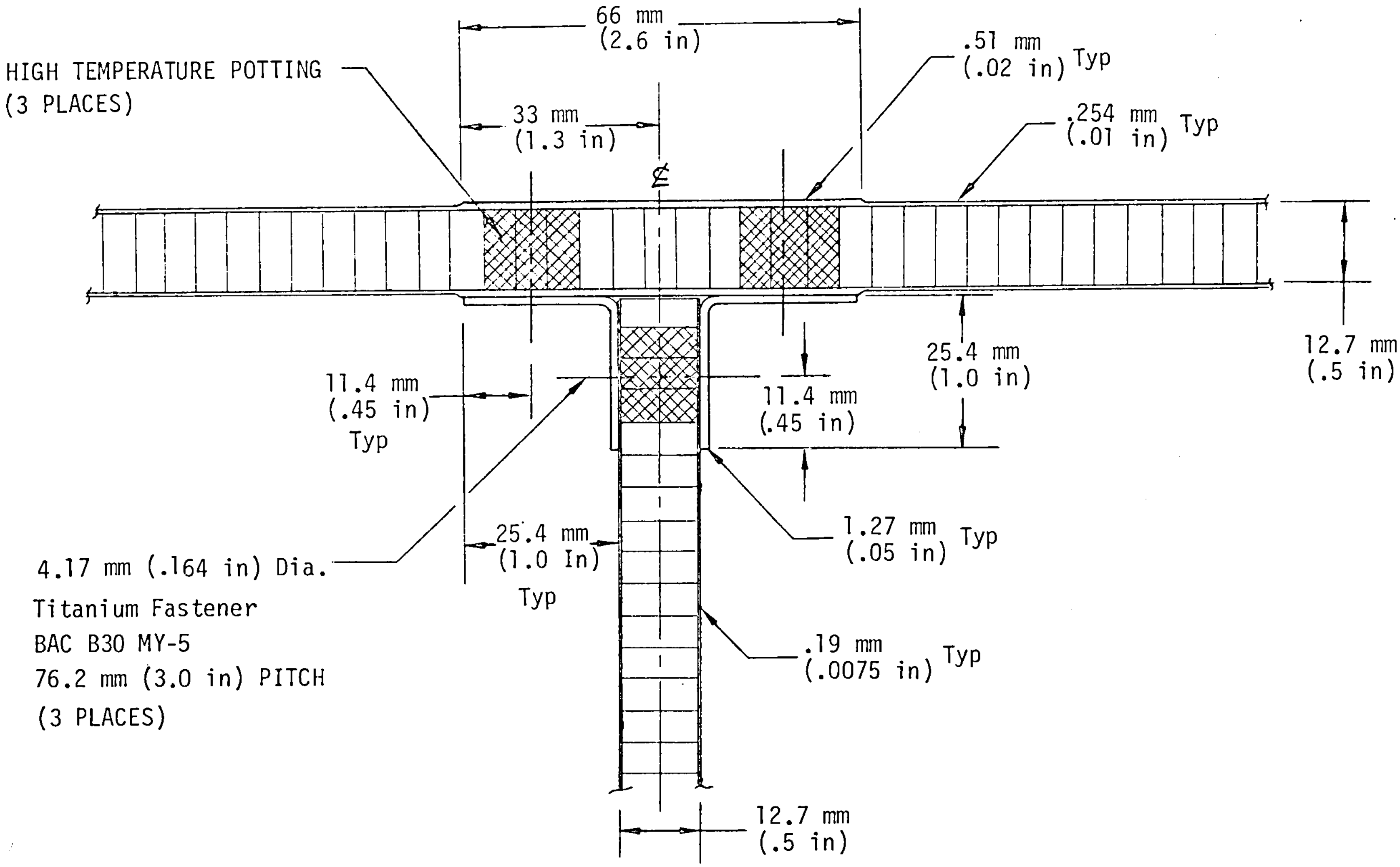


Figure 2-8: Type 4 Bolted Joint Concept

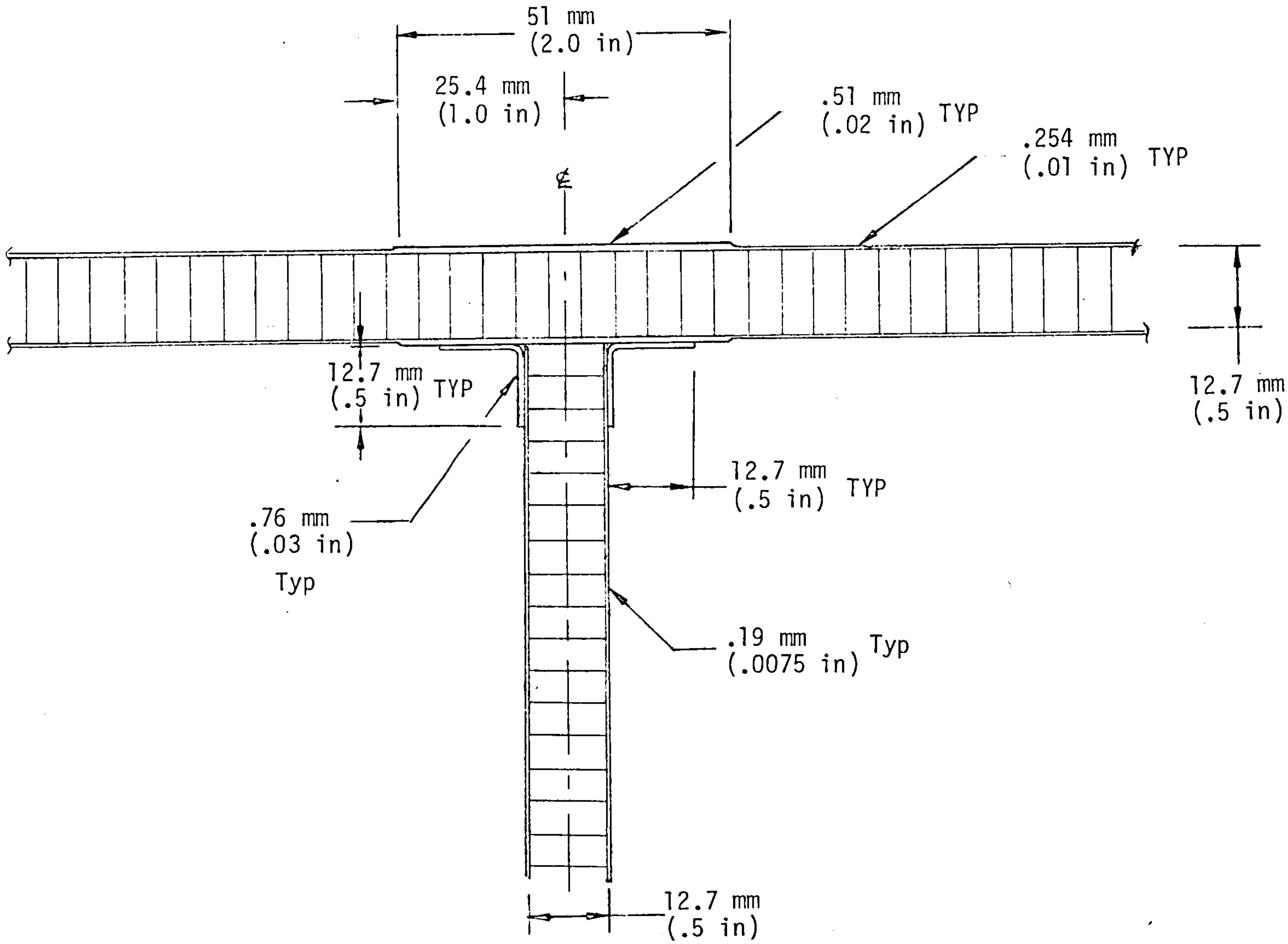


Figure 2-9: Type 4 Bonded Joint Concept

Room and elevated temperature tension tests, except for strain gaged and moisture conditioned specimens, have been completed for Celion 3000/PMR-15 laminates of $0°_{16}$, $90°_{30}$, $(0,\pm45,90)_{4S}$ and $\pm45°_{8S}$. Room temperature compression tests of $(90,\pm45,0)_{4S}$ have also been completed. Quality control panels for these specimens had an average fiber volume of 51.4% as reported in Reference 8. Tension and compression test results are summarized in Figures 2-10 through 2-14 and are for the "as tested" specimens. If the data in Figures 2-10 through 2-14 are ratioed up by 12.8%, to reflect a nominal fiber volume of 58%, the values are in agreement with the ultimate tensile strength of 551.6 MPa (80,000 psi) assumed for establishing joint design loads reported in Reference 1.

Test results are plotted as functions of temperature and specimen conditioning in Figures 2-15 through 2-19. The $0°_{16}$ laminates are fiber dominated and are not significantly affected by temperature (see Figs. 2-15). Data shown for the aged $0°_{16}$ laminate (Cond. 2) at 561K (550°F), see Figures 2-15, are lower than expected and are probably bad test data; however, examination of these specimens did not reveal any apparent test anomalies. A repeat test using a spare specimen is planned. As the laminate configurations become more resin matrix dominated, $(0,\pm45,90)_{4S}$, $\pm45°_{8S}$ and $90°_{30}$, the property degradation with temperature becomes more significant. This trend is shown by the data in Figures 2-16 through 2-18.

Ultimate tensile stresses, in general, show a decline due to aging (Cond. 2) and thermal cycling (Cond. 3), except for the $\pm45°_{8S}$ laminates. The $\pm45°_{8S}$ laminate strength at room temperature is not affected by aging (Cond. 2) while there is a significant drop in strength due to thermal cycling (Cond. 3), (see Fig. 2-17). At elevated temperature, there is no significant change in the $\pm45_{8S}$ laminate strength due to aging or thermal cycling (see Fig. 2-17). This is because the $\pm45_{8S}$ laminate is resin matrix dominated and the resin strength degradation due to temperature is large compared to any strength degradation caused by aging or thermal cycling. In addition, the elevated temperature acts as a stress reliever to any locked in stresses caused by thermal cycling.

Tension modulus data are also shown in Figures 2-15 through 2-19. As expected, fiber dominated laminates show no change due to increased temperature (see Fig. 2-15). As laminates become more matrix dominated, $(0,\pm45,90)_S$, ±45, and 90°, the reduction in tension modulus due to temperature becomes greater (see Figs. 2-16 through 2-19). Aging and thermal cycling did not seem to have any significant effect on tension modulus (see Figs. 2-15 through 2-18).

Room temperature compression results are plotted in Figures 2-19. As noted, most of the specimens failed at the ends; however, failure stresses and compression modulii are within the expected ranges.

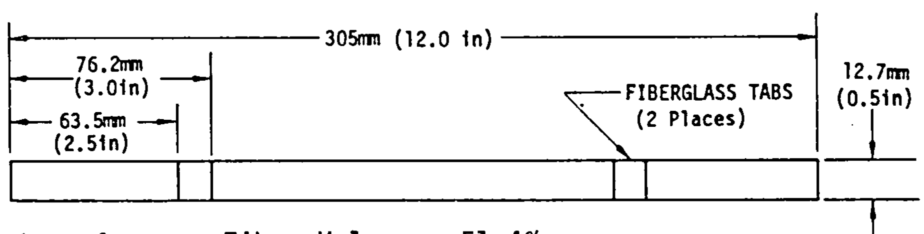
Metallographic Examination of Conditioned Panels

Figures 2-20 through 2-25 compare the extent of microcracking in quasi-isotropic Celion 3000/PMR-15 panels that were conditioned either by thermal aging (125 hours at 589K (600°F)) or by thermal cycling (125 cycles, 117K (-250°F) to 589K (600°F), with a one-hour hold at 589K (600°F) each cycle). Figures 2-20 and 2-21 compare typical sections of thermally aged vs. thermally cycled panels; the latter microcracked in the outer layers. Figures 2-22 and 2-23 show higher magnification views of the same panels. It is evident, from Figures 2-20 and 2-22, that:

1. the exposure to 589K (600°F) for 125 hours did not result in microcracking
2. the original cure/postcure cycle did not result in microcracking
3. the PMR-15 matrix successfully withstands the high residual stresses that result from cooling down from the 602K (625°F) peak cure/postcure temperature.

However, the thermal cycling does result in microcracking, as evident in Figures 2-21 and 2-23 and also in 2-24 and 2-25. The latter pair of photomicrographs are of a less-typical (but nevertheless frequently appearing) area where microcracking was not limited to the surface layers. Figures 2-26 and 2-27 are photomicrographs of a $[\pm45]_{8S}$ panel that was subjected to the 125 thermal cycles; a relatively minor amount of microcracking in the outer layers is evident.

CONDITION CODE	SPEC. NO.	CROSS SECTION AREA cm^2 (in^2)	TEST TEMP. $^oK(^oF)$	FAILURE LOAD KN (lb)	FAILURE STRESS MPa (ksi)	TENSION MODULUS GPa (10^6 psi)
1	4A-1	0.1568 (.0243)	294(70)	19.5(4390)	1245 (180.6)	118.2 (17.15)
	4A-2	0.1523 (.0236)	294(70)	19.3(4345)	1269 (184.1)	129.7 (18.82)
	4A-3	0.1581 (.0245)	294(70)	20.8(4685)	1318 (191.2)	120.6 (17.5)
	4A-4	0.1542 (.0239)	561(550)	21.2(4760)	1373 (199.1)	130.3 (18.9)
	4A-5	0.1600 (.0248)	561(550)	20.2(4540)	1262 (183.0)	117.3 (17.0)
	4A-6	0.1574 (.0244)	561(550)	20.0(4500)	1271 (184.4)	128.9 (18.69)
2	4B-1	0.1581 (.0245)	294(70)	19.1(4285)	1205 (174.8)	120.8 (17.53)
	4B-2	0.1413 (.0219)	294(70)	19.6(4410)	1388 (201.3)	139.8 (20.28)
	4B-3	0.1581 (.0245)	294(70)	20.0(4505)	1267 (183.8)	127.4 (18.55)
	4B-7	0.1445 (.0224)	561(550)	16.6(3740)	1151 (166.9)	131.1 (19.02)
	4B-8	0.1516 (.0235)	561(550)	16.8(3770)	1106 (160.4)	135.1 (19.59)
3	4C-1	0.1484 (.0230)	294(70)	18.4(4145)	1242 (180.2)	132.9 (19.27)
	4C-2	0.1516 (.0235)	294(70)	18.1(4080)	1197 (173.6)	130.7 (18.96)
	4C-3	0.1490 (.0231)	294(70)	17.7(3990)	1191 (172.7)	126.7 (18.37)
	4C-6	0.1542 (.0239)	561(550)	19.2(4320)	1246 (180.7)	125.9 (18.27)
	4C-7	0.1503 (.0233)	561(550)	17.9(4020)	1189 (172.5)	133.7 (19.39)
	4C-8	0.1471 (.0228)	561(550)	17.9(4030)	1218 (176.7)	125.6 (18.22)



NOTE: Specimen Average Fiber Volume - 51.4%

CONDITION CODE

1 - As cured/postcured

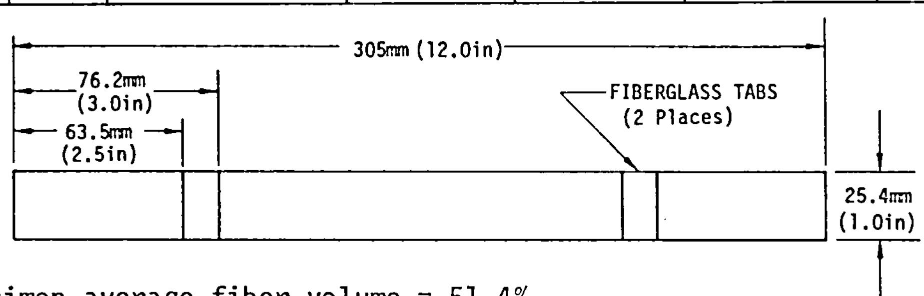
2 - Soaked for 450 ks (125 hrs) at 589K (600°F) in a one (1) atmosphere environment (air)

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).

Figure 2-10: Design Allowables Test No. 1, 0^o_{16} Tension

CONDITION CODE	SPEC. NO.	CROSS SECTION AREA cm^2 (in^2)	TEST TEMP °K (°F)	FAILURE LOAD KN (lb)	FAILURE STRESS MPa(ksi)	TENSION MODULUS GPa(10^6 psi)
1	8A-1	0.6071 (.0941)	294 (70)	3.33 (750)	54.9 (7.97)	7.72 (1.12)
	8A-2	0.5942 (.0921)	294 (70)	3.04 (684)	51.2 (7.42)	8.48 (1.23)
	8A-3	0.6077 (.0942)	294 (70)	2.14 (480)	35.1 (5.09)	8.34 (1.21)
	8A-4	0.5471 (.0848)	561 (550)	0.97 (218)	17.7 (2.57)	5.98 (.367)
	8A-5	0.5445 (.0844)	561 (550)	1.25 (280)	22.9 (3.32)	5.72 (.83)
	8A-6	0.5523 (.0856)	561 (550)	1.08 (242)	19.5 (2.83)	6.14 (.89)
2	8B-1	0.5877 (.0911)	294 (70)	2.53 (570)	43.1 (6.25)	8.14 (1.18)
	8B-2	0.6052 (.0938)	294 (70)	3.04 (684)	50.3 (7.29)	8.48 (1.23)
	8B-3	0.6026 (.0934)	294 (70)	2.58 (580)	42.7 (6.2)	8.48 (1.23)
	8B-4	0.6006 (.0931)	561 (550)	1.16 (261)	19.4 (2.81)	5.58 (.81)
	8B-5	0.6090 (.0944)	561 (550)	1.11 (250)	18.3 (2.65)	4.89 (.71)
	8B-6	0.6019 (.0933)	561 (550)	0.97 (218)	16.1 (2.34)	6.07 (.88)
3	9B-1	0.5813 (.0901)	294 (70)	2.61 (588)	44.9 (6.52)	7.64 (1.11)
	9B-2	0.5942 (.0921)	294 (70)	2.53 (569)	42.5 (6.17)	7.4 (1.08)
	9B-3	0.5974 (.0926)	294 (70)	2.45 (550)	40.9 (5.93)	7.8 (1.13)
	9B-6	0.5858 (.0908)	561 (550)	0.72 (161)	12.2 (1.77)	5.86 (.85)
	9B-7	0.5929 (.0919)	561 (550)	1.08 (242)	18.1 (2.63)	4.90 (.71)
	9B-8	0.5903 (.0915)	561 (550)	0.65 (146)	11.0 (1.6)	4.41 (.64)
	9B-11	0.5794 (.0898)	561 (550)	0.32 (73)	5.58 (0.81)	5.79 (.84)



NOTE: Specimen average fiber volume = 51.4%

CONDITION CODE

1 - As cured/postcured

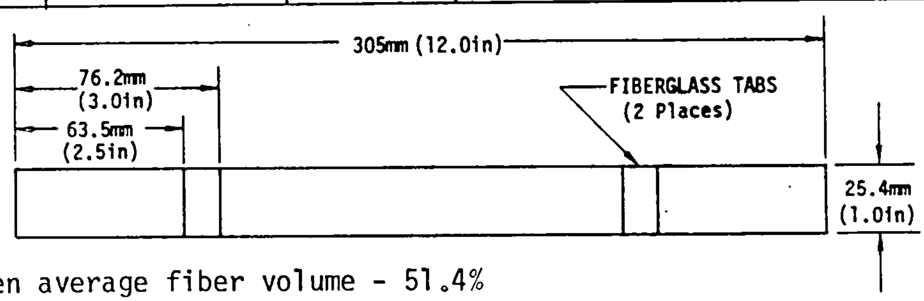
2 - Soaked for 450 ks (125 hrs) at 589K (600°F) in a one (1) atmosphere environment (air).

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).

Figure 2-11: Design Allowables Test No. 2, 90°_3, Tension

CONDITION CODE	SPEC. NO.	CROSS SECTION AREA cm^2 (in^2)	TEST TEMP °K (°F)	FAILURE LOAD KN (lb)	FAILURE STRESS MPa(ksi)	TENSION MODULUS GPA(10^6 psi)
1	14A-1	0.6045 (.0937)	294 (70)	30.9 (6940)	514 (74.6)	50.7 (7.36)
	14A-2	0.6290 (.0975)	294 (70)	31.0 (6980)	493 (71.5)	49.8 (7.22)
	14A-3	0.5948 (.0922)	294 (70)	31.1 (6990)	523 (75.8)	46.9 (6.80)
	14A-4	0.6200 (.0961)	561 (550)	31.6 (7100)	509 (73.9)	44.2 (6.41)
	14A-4	0.6335 (.0982)	561 (550)	31.1 (7000)	492 (71.3)	44.2 (6.41)
	14A-7	0.6271 (.0972)	561 (550)	27.9 (6280)	445 (64.6)	44.9 (6.52)
2	14B-1	0.6206 (.0962)	294 (70)	29.1 (6540)	468 (67.9)	49.1 (7.12)
	14B-2	0.5929 (.0919	294 (70)	29.0 (6520)	489 (70.9)	51.2 (7.43)
	14B-3	0.6142 (.0952)	294 (70)	29.1 (6560)	475 (68.9)	50.1 (7.27)
	14B-4	0.6297 (.0976)	561 (550)	29.2 (6560)	463 (67.2)	47.1 (6.83)
	14B-5	0.6194 (.0960)	561 (550)	27.1 (6100)	438 (63.5)	41.0 (5.94)
	14B-6	0.6058 (.0939)	561 (550)	27.6 (6200)	455 (66.0)	49.4 (7.16)
3	15B-1	0.6432 (.0997)	294 (70)	24.1 (5410)	374 (54.2)	47.0 (6.32)
	15B-2	0.6426 (.0996)	294 (70)	25.8 (5810)	402 (58.3)	46.7 (6.78)
	15B-3	0.6394 (.0991)	294 (70)	26.7 (6000)	417 (60.5)	45.8 (6.64)
	15B-6	0.6400 (.0992)	561 (550)	25.4 (5700)	396 (57.4)	53.3 (7.73)
	15B-7	0.6348 (.0984)	561 (550)	20.4 (4590)	Tab Failure	45.5 (6.60)
	15B-8	0.6374 (.0988)	561 (550)	25.0 (5630)	392 (56.9)	40.9 (5.93)



NOTE: Specimen average fiber volume - 51.4%

CONDITION CODE

1 - As cured/postcured.

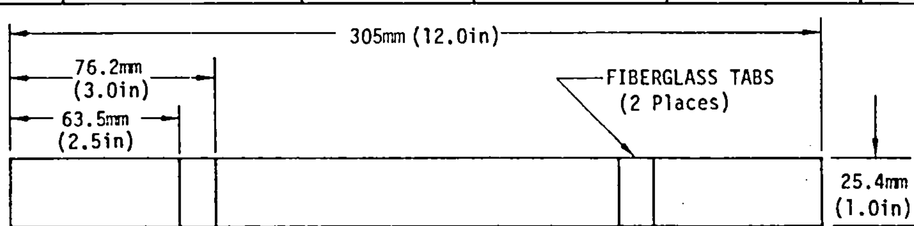
2 - Soaked for 450 ks (125 hrs) at 589K (600°F) in a one (1) atmosphere environment (air).

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).

Figure 2-12: Design Allowables Test No. 3, $(0,\pm 45,90)_{4s}$, Tension

CONDITION CODE	SPEC. NO.	CROSS SECTION AREA cm^2 (in^2)	TEST TEMP °K (°F)	FAILURE LOAD KN (lb)	FAILURE STRESS MPa(ksi)	TENSION MODULUS GPa (10^6 psi)
1	10A-1	0.6555 (.1016)	294 (70)	13.0 (2925)	198 (28.7)	14.3 (2.08)
	10A-2	0.6561 (.1017)	294 (70)	13.6 (3065)	208 (30.1)	15.0 (2.18)
	10A-3	0.6613 (.1025)	294 (70)	13.4 (3005)	202 (29.2)	14.2 (2.06)
	10A-4	0.6561 (.1017)	561 (550)	6.67 (1500)	101 (14.7)	6.82 (.99)
	10A-5	0.6606 (.1024)	561 (550)	7.35 (1652)	111 (16.1)	9.1 (1.32)
2	10B-1	0.6297 (.0976)	294 (70)	12.3 (2760)	194 (28.2)	14.4 (2.09)
	10B-2	0.6445 (.0999)	294 (70)	13.3 (2985)	205 (29.8)	14.1 (2.05)
	10B-3	0.6316 (.0979)	294 (70)	13.7 (3070)	216 (31.3)	14.9 (2.16)
	10B-5	0.6419 (.0995)	561 (550)	6.24 (1402)	97.2 (14.1)	10.5 (1.53)
	10B-6	0.6484 (.1005)	561 (550)	6.04 (1358)	93 (13.5)	9.38 (1.36)
	10B-7	0.6342 (.0983)	561 (550)	7.38 (1660)	116 (16.9)	7.99 (1.16)
3	11B-1	0.6368 (.0987)	294 (70)	8.1 (1820)	127 (18.4)	12.5 (1.81)
	11B-2	0.6355 (.0985)	294 (70)	9.5 (2140)	150 (21.7)	13.7 (1.99)
	11B-3	0.6329 (.0981)	294 (70)	9.9 (2235)	157 (22.7)	13.4 (1.95)
	11B-6	0.6400 (.0992)	561 (550)	6.56 (1474)	102 (14.8)	11.1 (1.27)
	11B-7	0.6187 (.0959)	561 (550)	6.98 (1570)	113 (16.4)	9.5 (1.38)
	11B-8	0.6316 (.0979)	561 (550)	7.51 (1688)	119 (17.2)	10.5 (1.53)
	11B-9	0.6394 (.0991)	561 (550)	7.22 (1622)	113 (16.4)	10.1 (1.46)
	11B-10	0.6181 (.0958)	561 (550)	6.65 (1494)	108 (15.6)	7.72 (1.12)



NOTE: Specimen Average Fiber Volume 51.4%

CONDITION CODE

1 - As cured/postcured

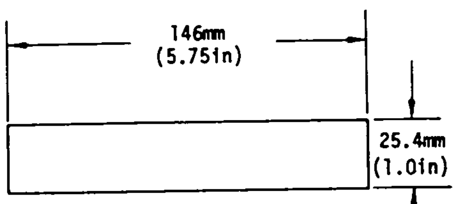
2 - Soaked for 450 ks (125 hrs) at 589K (600°F) in a one (1) atmosphere environment (air).

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).

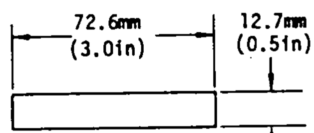
The cryogenic temperature of 116K (-250°F) shall be held for 1800 sec (1/2 hr) and the maximum temperature of 589K (600°F) shall be held for 3600 sec (1 hr) per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min).

Figure 2-13: Design Allowables Test No. 6, $\pm 45°_{8s}$, Tension

CONDITION CODE	SPEC. NO.	CROSS SECTION AREA cm^2 (in^2)	TEST TEMP °K(°F)	FAILURE LOAD KN (lb)	FAILURE STRESS MPa(ksi)	COMPRESSION MODULUS GPa(10^6 psi)
1	12A-1	0.6239 (.0967)	294 (70)	33.18 (7460)	531.6 (77.1)	41.45 (6.012)
	12A-2	0.6323 (.0980)	294 (70)	33.09 (7440)	523.3 (75.9)	41.19 (5.974)
	12A-3	0.6284 (.0974)	294 (70)	31.14 (7000)	495.7 (71.9)	41.35 (5.997)
2	12B-1	0.6245 (.0968)	294 (70)	29.36 (6600)	470.2 (68.2)	35.76 (5.186)
	12B-2	0.6194 (.0960)	294 (70)	30.07 (6760)	485.4 (70.4)	39.15 (5.678)
	12B-3	0.6187 (.0959)	294 (70)	34.52 (7760)	557.8 (80.9)	39.25 (5.693)
	12B-5	0.6226 (.0965)	294 (70)	33.27 (7480)	534.3 (77.5)	40.71 (5.904)
3	13B-1	0.6387 (.0990)	294 (70)	30.25 (6800)	473.7 (68.7)	47.18 (6.843)
	13B-2	0.6052 (.0938)	294 (70)	31.32 (7040)	517.8 (75.1)	38.36 (5.564)
	13B-3	0.6277 (.0973)	294 (70)	36.12 (8120)	575.7 (83.5)	38.43 (5.574)



ROOM TEMPERATURE



ELEVATED TEMPERATURE

NOTE: Specimen Average Fiber Volume 51.4%

CONDITION CODE

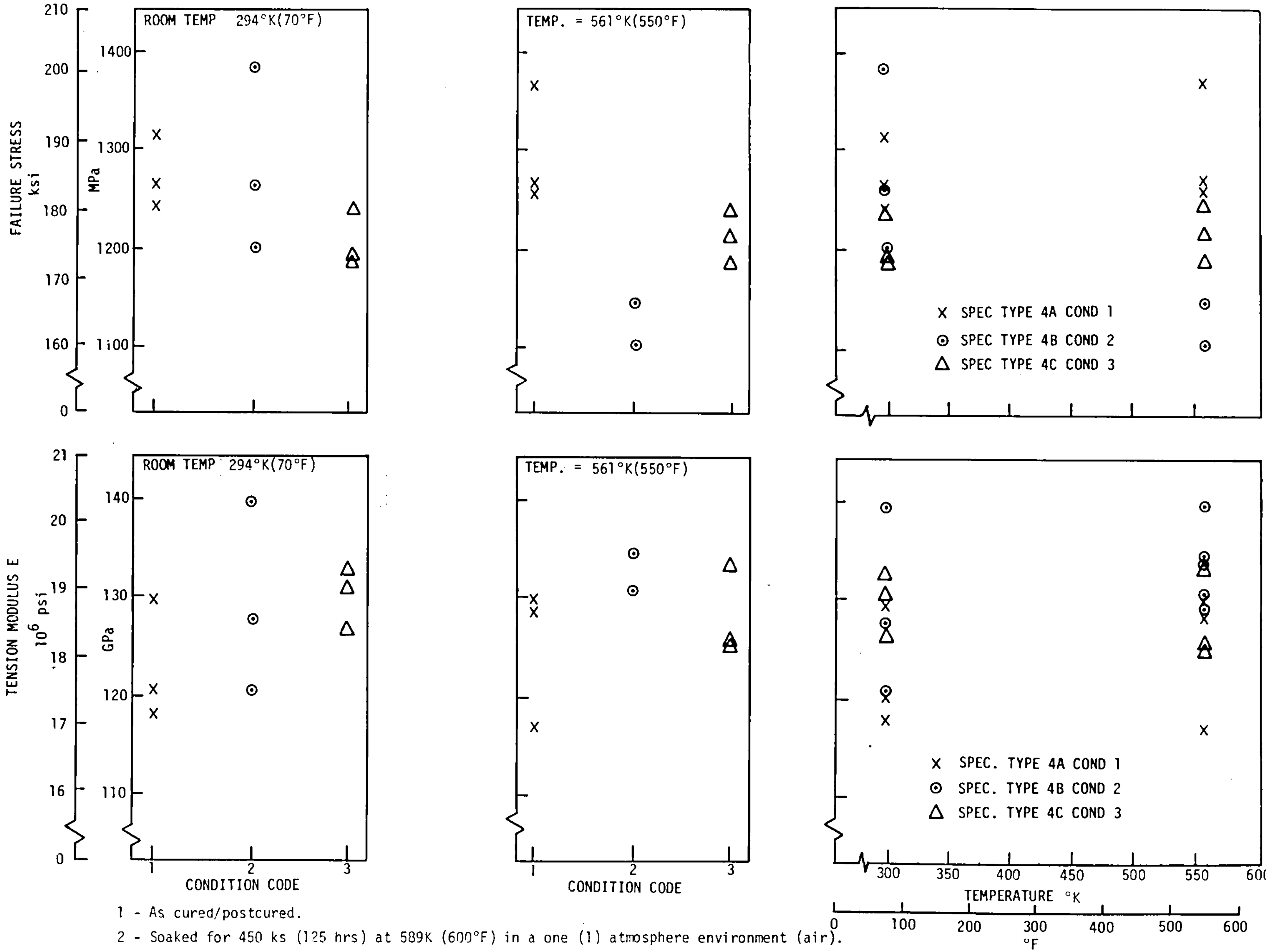
1 - As cured/postcured

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).

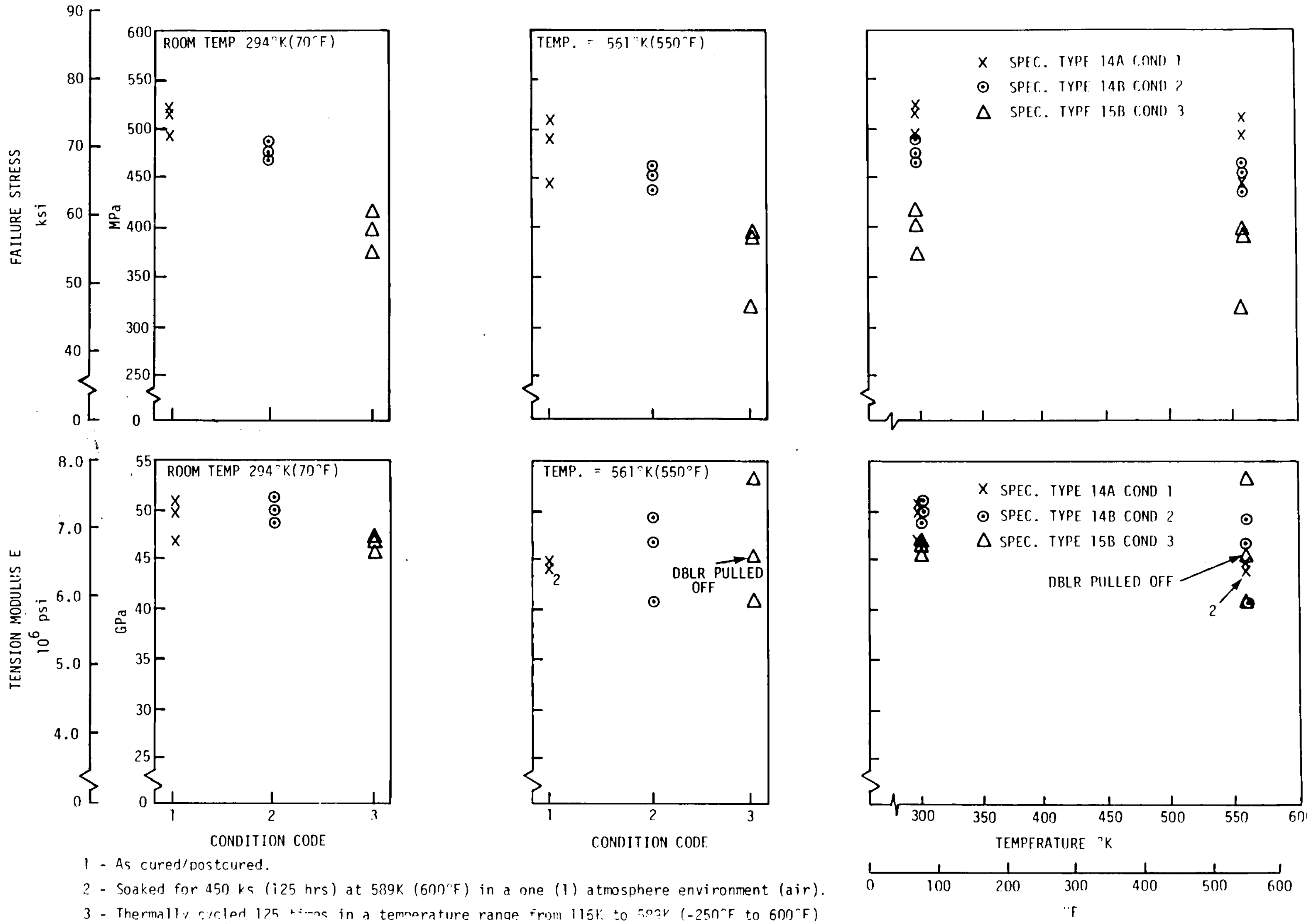
The cryogenic temperature of 116K (-250°F) shall be held for 1800 sec (1/2 hr) and the maximum temperature of 589K (600°F) shall be held for 3600 sec (1 hr) per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min).

Figure 2-14: Design Allowables Test No. 4, $(90,\underline{+}45,0)_{4s}$, Compression



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)

Figure 2-15: Design Allowables Test No. 1, 0°_{16} GR/PI, Tension

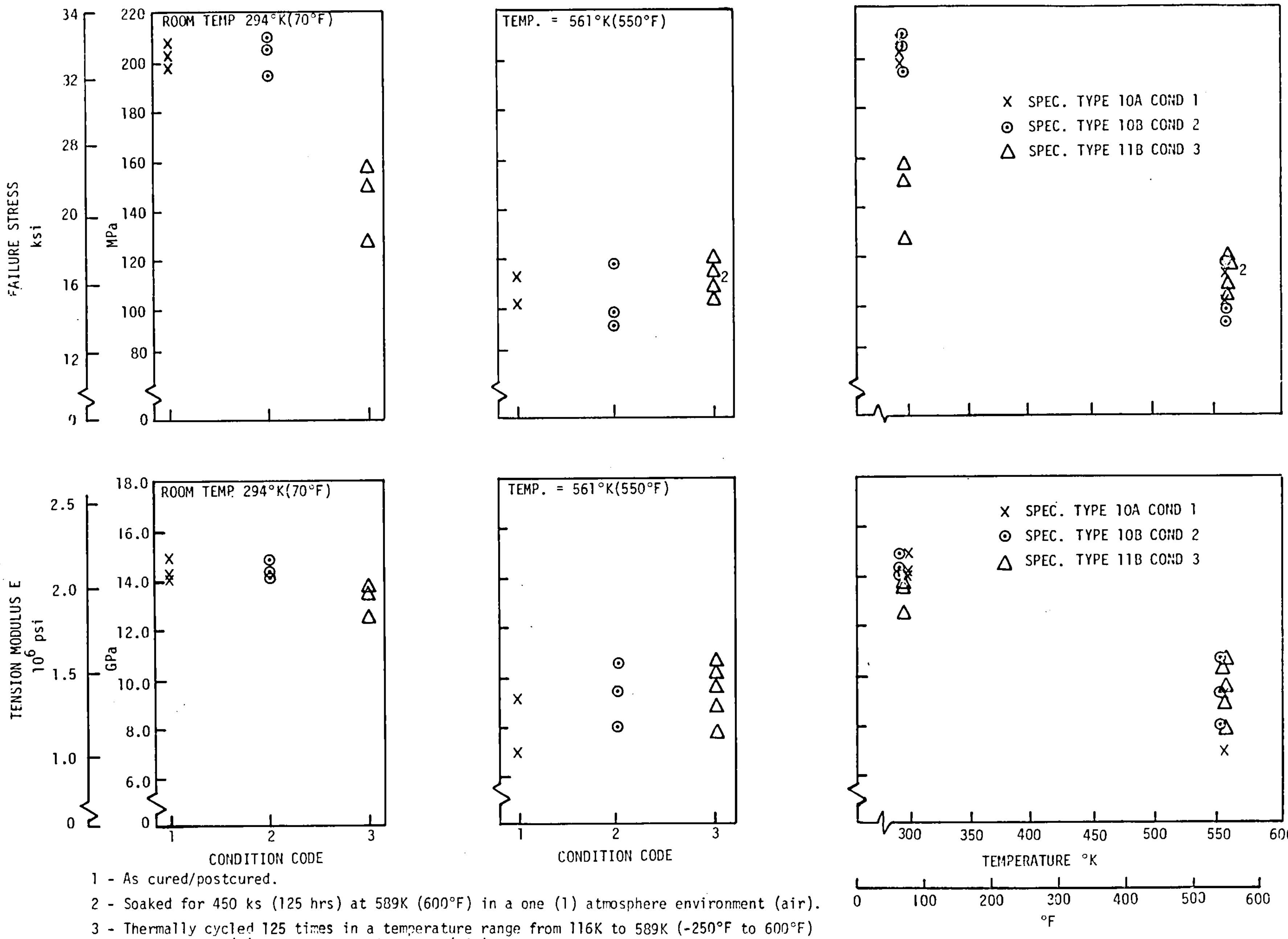


1 - As cured/postcured.

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)

Figure 2-16: Design Allowables Test No. 3, $(0,+45,90)_{4s}$, Tension



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)

Figure 2-17: Design Allowables Test No. 6, $(\pm 45^\circ)_{8s}$ GR/PI, Tension

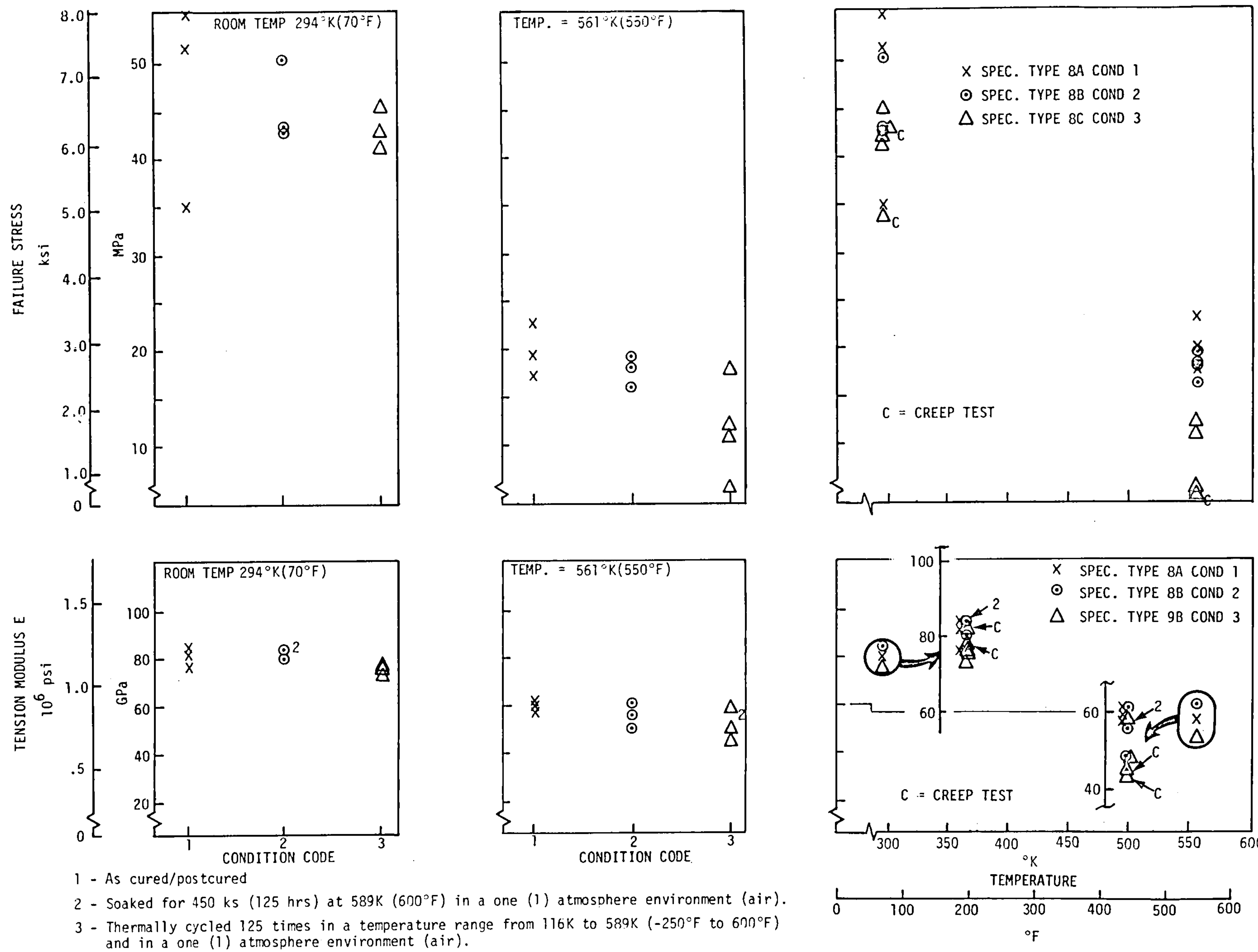


Figure 2-18: Design Allowables Test No. 2, (90°_{30}) GR/PI, Tension

▲ 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).

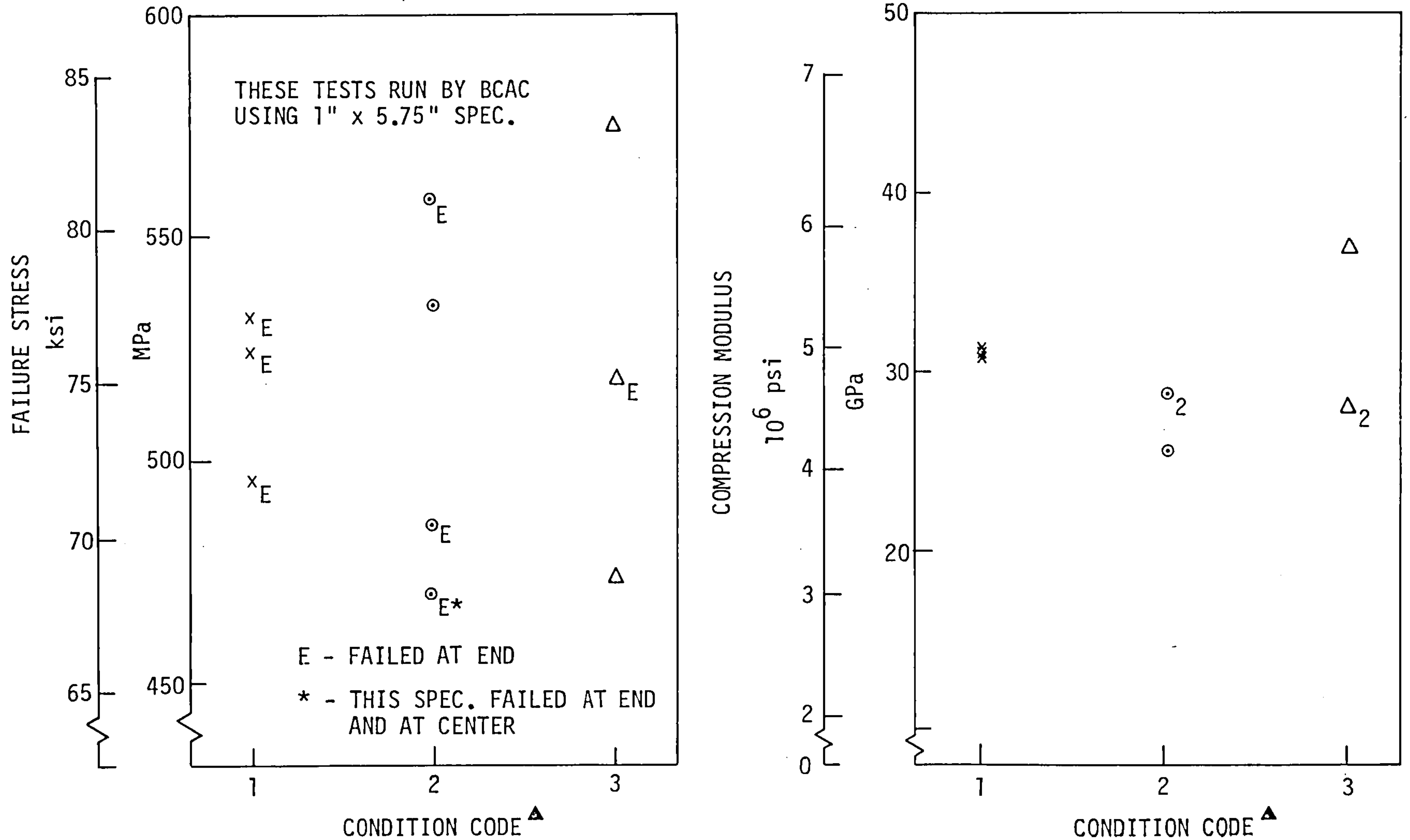
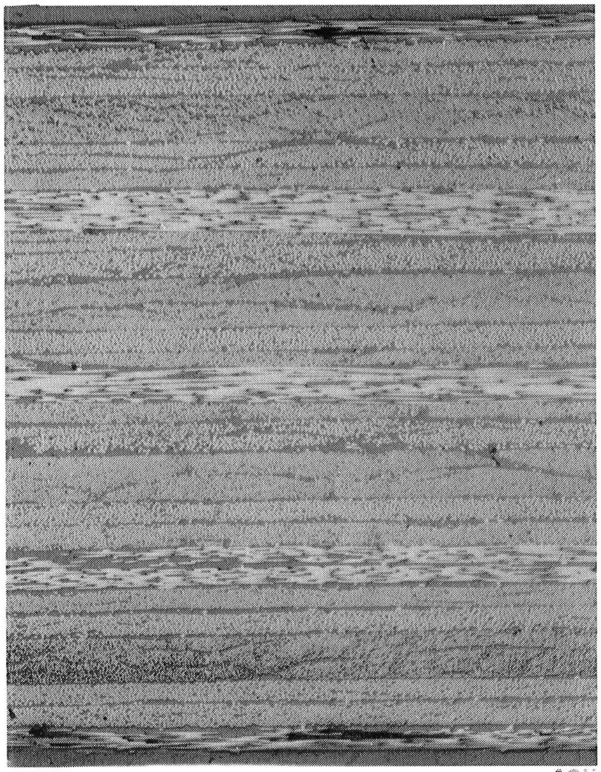
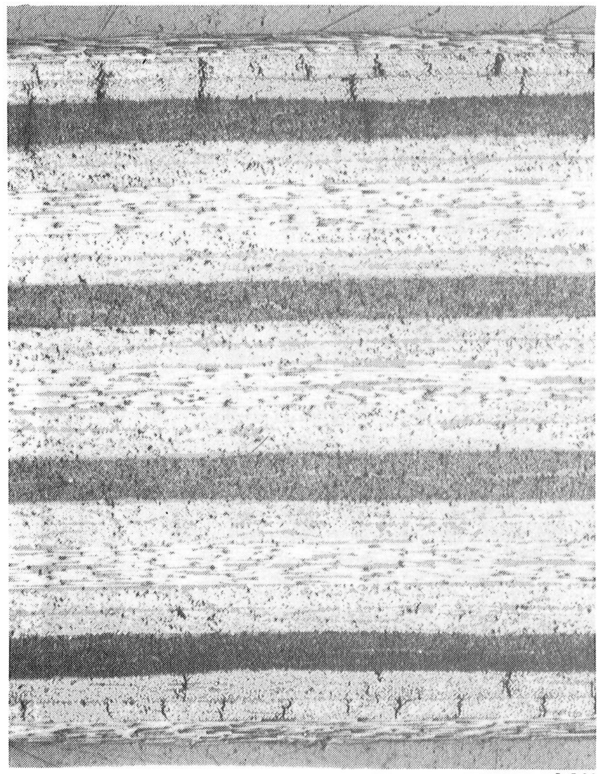


Figure 2-19: Design Allowables Test No. 2, $(90,\pm45,0)_{4s}$ GR/PI, Compression, Room Temperature = 284K (70°F)



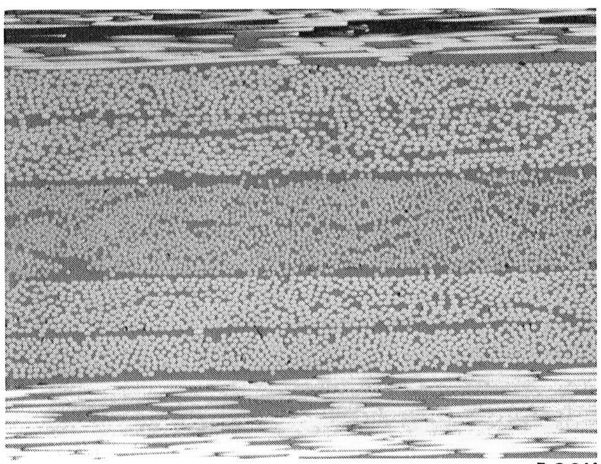
48X

Figure 2-20: 2W4582-14B $(0,\underline{+}45,90)_{4s}$, Condition 2, Aged



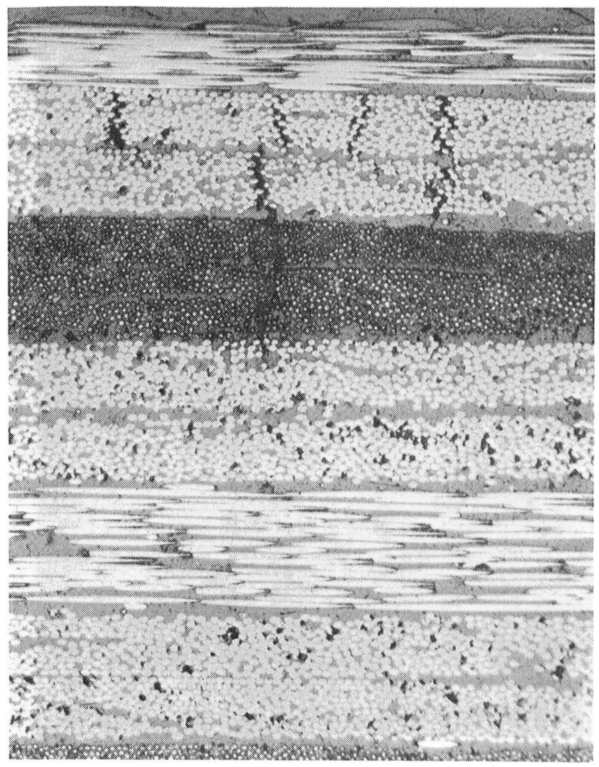
42X

Figure 2-21: 2W4582-13B $(90,\underline{+}45,0)_{4s}$, Condition 3, Cycled



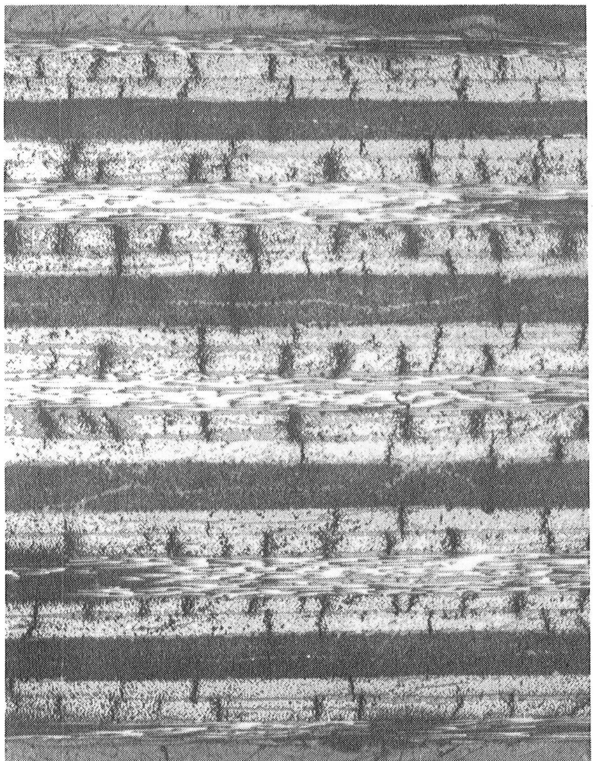
120X

Figure 2-22: 2W4582-14B $(0,\underline{+}45,90)_{4s}$, Condition 2, Aged



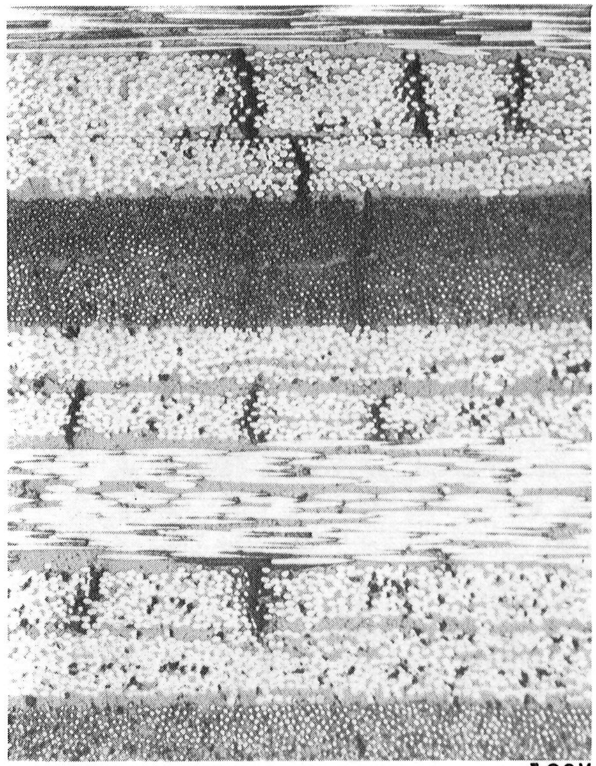
120X

Figure 2-23: 2W4582-13B $(90,\underline{+}45,0)_{4s}$, Condition 3, Cycled



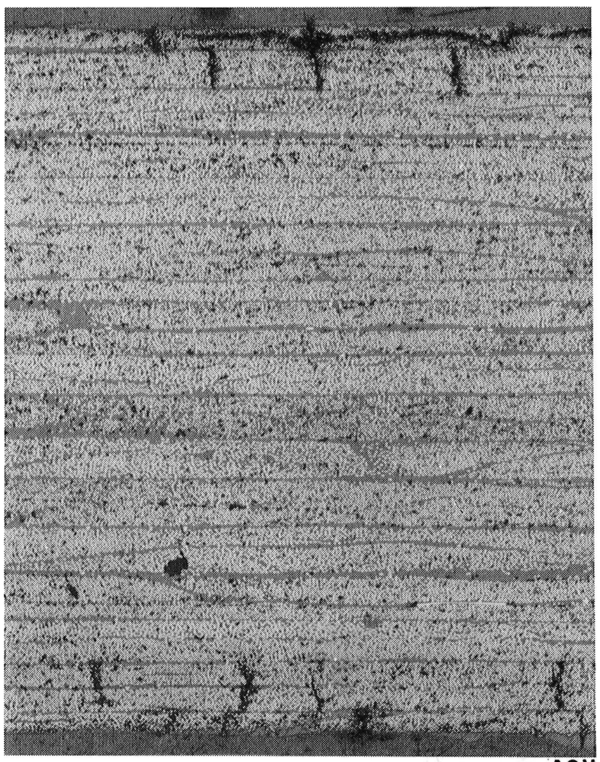
42X

Figure 2-24: 2W4582-13B $(90,\underline{+}45,0)_{4s}$, Condition 3, Cycled



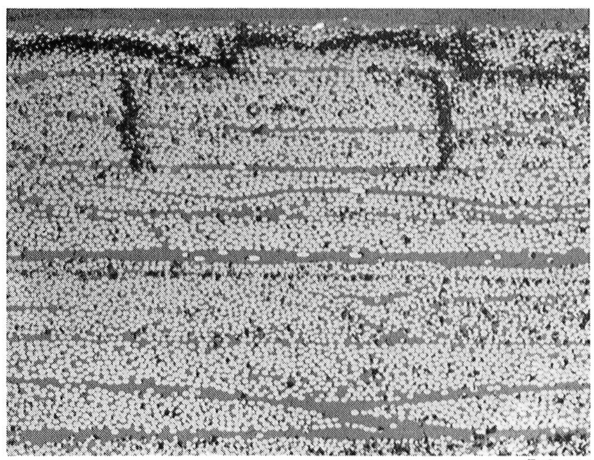
120X

Figure 2-25: 2W4582-13B $(90,\underline{+}45,0)_{4s}$, Condition 3, Cycled



48X

Figure 2-26: 2W4582-11B $(\underline{+}45)_{8s}$, Condition 3, Cycled



120X

Figure 2-27: 2W4582-11B $(\underline{+}45)_{8s}$, Condition 3, Cycled

Figure 2-28 presents data on the change in glass transition temperature (Tg) as a result of the thermal aging and thermal cycling conditioning. As expected, the increase in Tg is higher for thermally cycled panels, as their time/temperature exposure includes 125 hours at 589K (600°F) plus the additional elevated temperature exposure during heatup and cooldown.

Figure 2-28: Effect of Conditioning on Tg

Panel No.	As Cured/Postcured	After Aging	After Cycling
2W4582-7	619K (655°F)	---	626K (667°F)
2W4582-10	614K (646°F)	624K (664°F)	---
2W4582-13	621K (658°F)	---	639K (191°F)
2W4582-14	611K (640°F)	620K (657°F)	---

Microcracking is attributed to the stresses which result from the difference in CTE (Coefficient of Thermal Expansion) of the fibers and resin. These stresses are higher in cross-plied laminates due to the resulting biaxial restraint. Other conditions affecting the formation and degree of microcracking include:

1. cooling to lower temperatures (e.g., 116K (-250°F))
2. increase in resin brittleness (correlates with an increase in Tg)
3. thermal shock
4. fiber volume
5. microcrack growth due to cycling.

The microcracks do not break any fibers, but they do act as miniature stress concentrators, resulting in some small loss in properties.

Coefficient of Thermal Expansion (CTE)

The CTE for the Celion 3000/PMR-15 laminates was determined using TMA (thermomechanical analysis) and dilatometer techniques. Actually, the TMA method is also a quartz tube dilatometer, of lower sensitivity. The data presented in Figure 2-29 have been corrected for the CTE of fused quartz. The low-expansion (in-plane) specimens were 9.5 mm (.375 in) wide by 63.5 mm (2.5 in) long, with the length direction defined as the x-axis. Due to laminate symmetry, expansion in the y-direction is equal to that in the x-direction.

Figure 2-29: CTE DATA

Specimen No.	Laminate	Condition*	Test Axis	CTE, μm/m/K		
				116K to RT	RT to 589K	116K to 589K
2W4582-15D1	$(0/\pm45/90)_{4S}$	2	X	2.13	2.65	2.45
2W4582-15D3	$(0/\pm45/90)_{4S}$	2	X	2.17	2.79	2.55
2W4582-15C2	$(0/\pm45/90)_{4S}$	1	X	2.14	2.55	2.39
2W4582-10B	$(\pm45)_{8S}$	2	Z		52.9	
2W4582-7C	$(0/\pm45/90)_{2S}$	3	Z		48.1	
2W4582-13B	$(\pm45/90/0)_{4S}$	3	Z		37.7	
2W4582-14B	$(0/\pm45/90)_{4S}$	2	Z		48.5	
2W4582-14	$(0/\pm45/90)_{4S}$	1	Z		54.7	
2W4582-10	$(\pm45)_{8S}$	1	Z		54.1	

* 1 = as cured/postcure, 2 = aged 125 hrs @589K, 3 = 125 thermal cycles

2.2.2 TASK 1.2.2 - Small Specimen Tests

A total of 25 panels have been fabricated this quarter, with panel dimensions as large as 889 mm (35 in) by 160 mm (24 in) and including panels 96 plies thick (6.6 mm, (.26 in) cured thickness). Due to similarity of layups required, many of the panels will be used for both TASK 1.2.2 and TASK 2.1.4. Slightly modified cure cycles have been used on some panels fabricated from the two most recent prepreg lots. The intention of the modifications was to increase resin flow/panel consolidation to compensate for changes in the PMR-15 resin. Quality control test data for the prepreg, lots 2W4604, 2W4632 and 2W4643, are shown in Figures 2-30 & 2-31.

The small specimen test matrix and specimen definition has been completed. Tests to assess pull-off strength of bonded angles and tension capability of honeycomb close-out designs are shown in Matrix 4C (Fig. 2-32).

2.3 TASK 1.3 - Preliminary Evaluation of Attachment Concepts

Results from the small specimen tests along with designs developed during the second cut screening will be used to select joint concepts for testing under this task. Ambient and elevated static tests to failure will be performed on at least 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.

QUALITY CONTROL TEST DATA

Figure 2-30: Prepreg Physical Properties (Boeing data)

Lot No.	Roll No.	(Wet) Resin Solids, %	(Dry) Resin Solids, %	Volatile Content, %	Gel Time, Seconds
2W4604	2	43.4	36.6	10.6	33
	7	43.9	37.1	10.7	31
	9	42.9	36.1	10.6	29
2W4632	1	43.3	35.6	11.8	30-35
	2	42.7	35.2	11.7	30
2W4643	1	37.4	31.3	7.8	45
	2	40.3	35.0	8.2	45
	3	40.9	35.4	8.4	50
	4	39.8	34.5	8.2	38

Figure 2-31: QUALITY CONTROL TEST PANEL PROPERTIES (Averaged)

PROPERTY		30-Ply Panel, Lot 2W4604, Roll 2	28-Ply Panel, Lot 2W4604, Roll 7	Lot 2W4632, Roll 1	Lot 2W4632 Roll 2
Fiber Volume, %		58.4	58.2	57.7	56.6
Resin Content, w/o		34.3	34.4	34.7	36.0
Specific Gravity		1.567	1.562	1.557	1.557
Void Content, v/o		0.2	0.4	0.7	0.3
Panel Thickness		2.08 mm (.082")	1.91 mm (.075")	1.88 mm (.074")	1.95 mm (.073")
Per Ply Thickness		0.069 mm (.0027")	0.068 mm (.0027")	0.067 mm (.0026")	0.066 mm (.0026")
Tg (TMA Method)		614-625K (642-666°F)	622K (660°F)	--	--
Flexural	At Ambient	1241 (180)	1317 (191)	1510 (219)	1572 (228)
Strength	At 589K (600°F)	819 (119)	914 (133)	889 (129)	889 (129)
MPa (ksi)	Aged, at 589K (600°F)	929 (135)	981 (142)	965 (140)	938 (136)
Flexural	At Ambient	115 (16.7)	111 (16.1)	121 (17.6)	110 (15.9)
Modulus	At 589K (600°F)	113 (16.4)	110 (15.9)	144 (20.9)	117 (17.0)
GPa (Msi)	Aged, at 589K (600°F)	130 (18.9)	123 (17.9)	148 (21.4)	131 (19.0)
Short Beam	At Ambient	101 (14.7)	98 (14.3)	98 (14.2	111 (16.1)
Shear Strength	At 589K (600°F)	64 (9.2)	57 (8.3)	49 (7.1)	50 (7.2)
MPa (ksi)	Aged, at 589K (600°F)	61 (8.8)	61 (8.9)	54 (7.8)	54 (7.9)

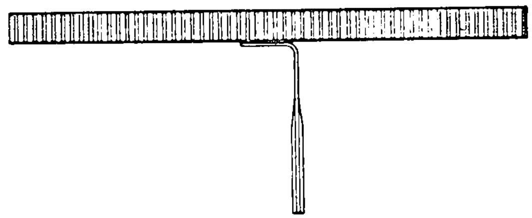
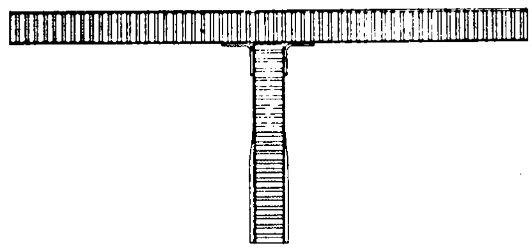
TEST NO.	TEST SCHEMATIC	SPEC. CONFIG.	CONDITION	NO. OF TESTS @		NO. OF SPEC.
				ROOM TEMP.	561K (550°F)	
1a 1b 1c		Figure 2-32a	1 2 3	3 3 3	3 3 3	6 6 6
2a 2b 2c		Figure 2-32b	1 2 3	3 3 3	3 3 3	6 6 6
3a 3b 3c		Figure 2-32c	1 2 3	3 3 3	3 3 3	6 6 6
4a 4b 4c		Figure 2-32d	1 2 3	3 3 3	3 3 3	6 6 6

Figure 2-32: Test Matrix 4C - Small Specimen Tests

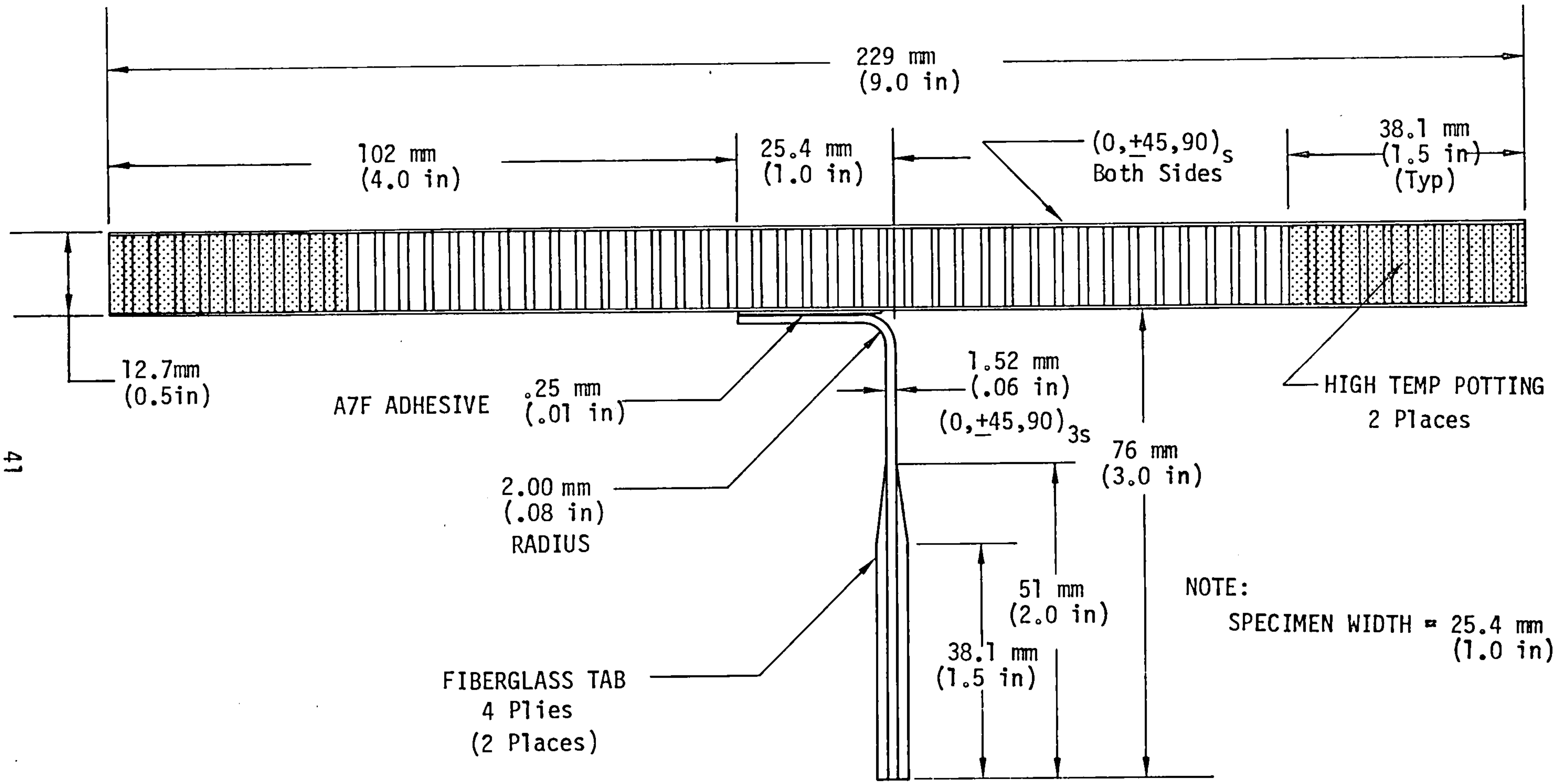


Figure 2-32a: Test Matrix 4C Specimen Configuration

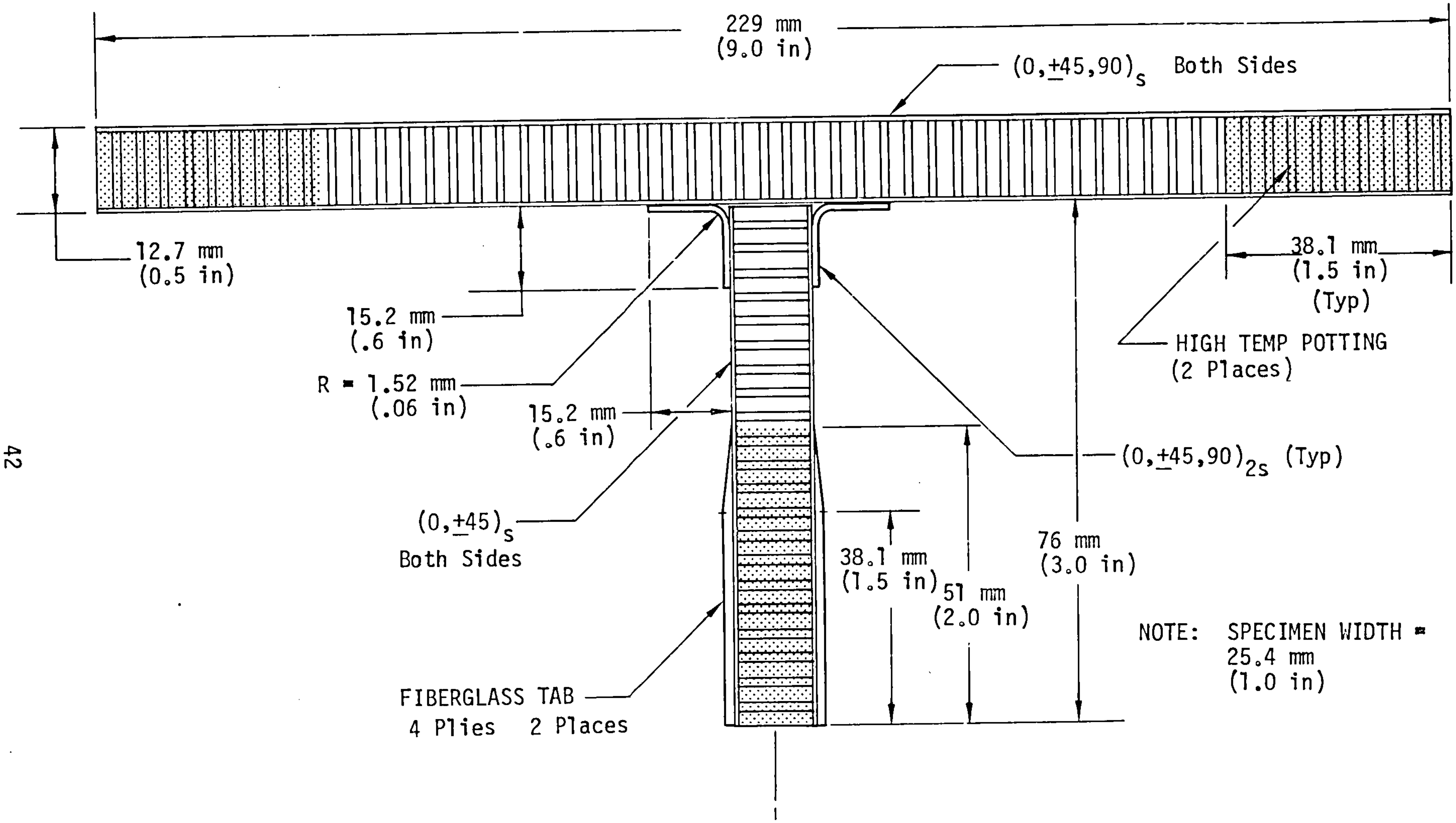


Figure 2-32b: Test Matrix 4C Specimen Configuration

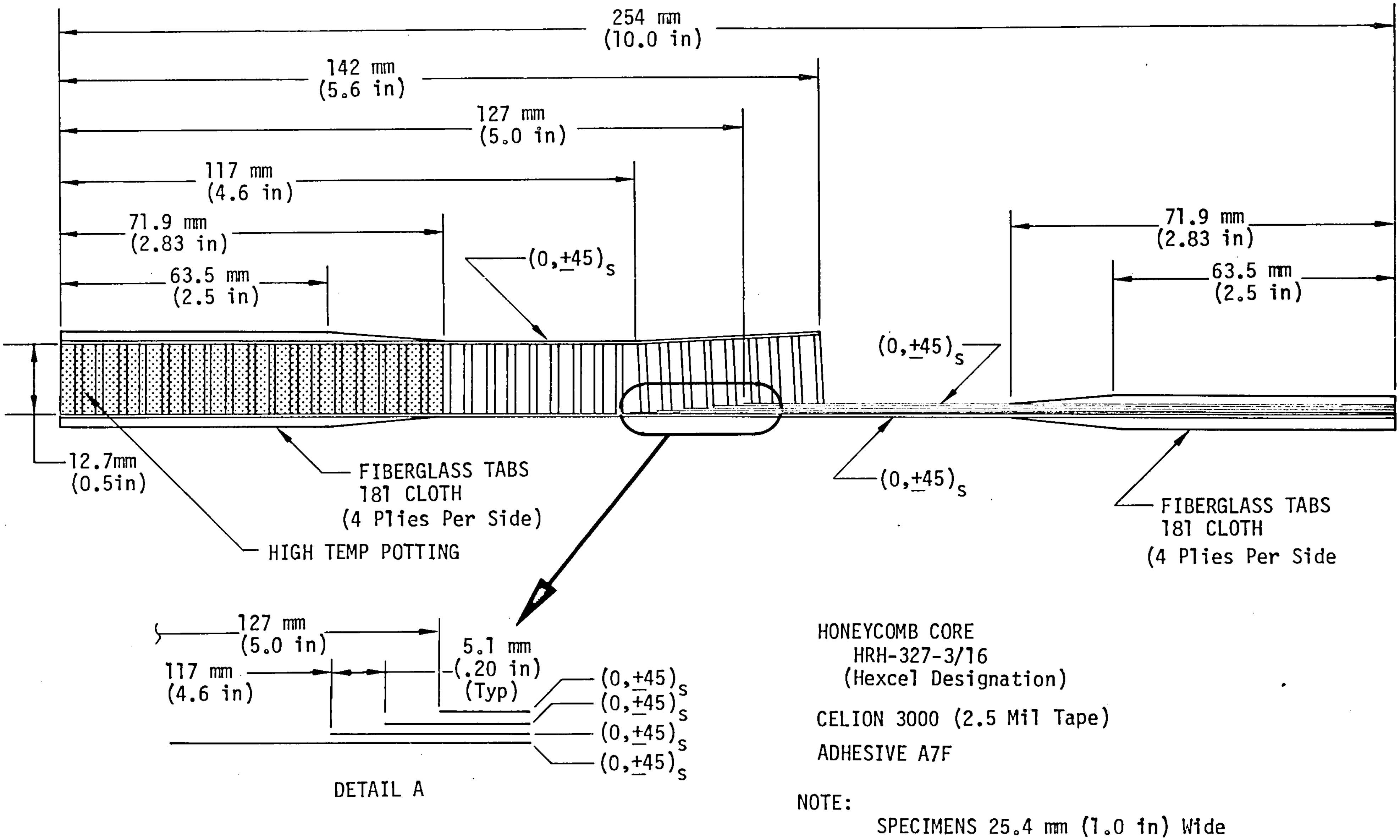


Figure 2-32c: Test Matrix 4C Specimen Configuration

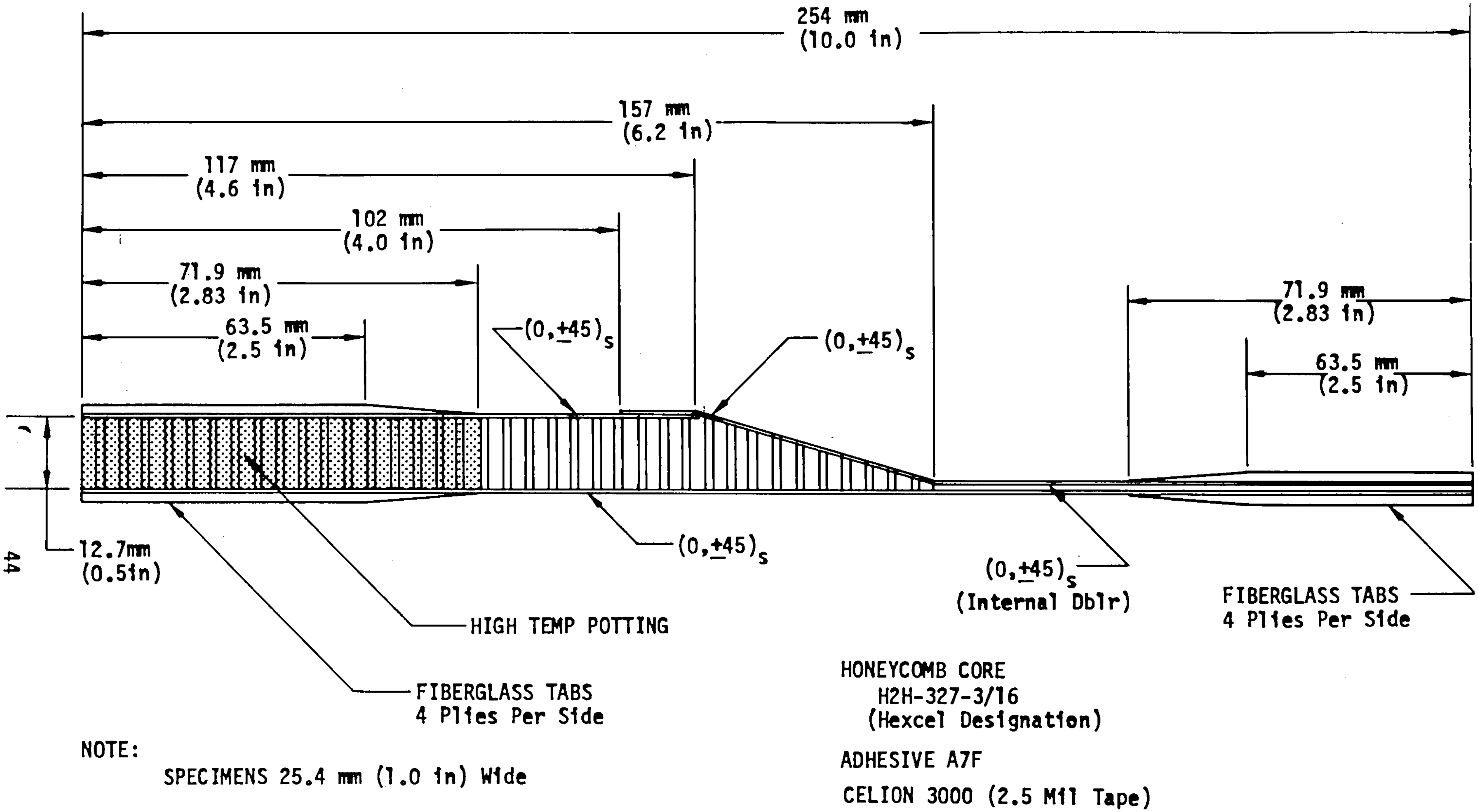


Figure 2-32d: Test Matrix 4C Specimen Configuration

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

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 incorporating simplifying assumptions regarding cross-ply and other three-dimensional effects and imposed beam-type behavior of laminates or lamina.

Two studies were completed during this reporting period. The first assessed the effects of adding an adhesive fillet at the end of the splice plate on a double-lap joint. The second assessed the effect of increasing the number of elements used through the thickness of the adhesive. Model configuration, boundary conditions and material properties used for both studies are shown in Figure 3-2.

The model used to assess an adhesive fillet had only one adhesive element in the Y grid direction. Analyses were conducted for two different minimum element sizes in the X-grid direction: 0.254 mm (0.01 in) minimum (Model 1C, Fig. 3-3) and 0.127 mm (0.005 in) minimum (Model 1D, Fig. 3-3). The fillet was assumed to be a 0.75 rad (45°) triangular shape. Analysis results are

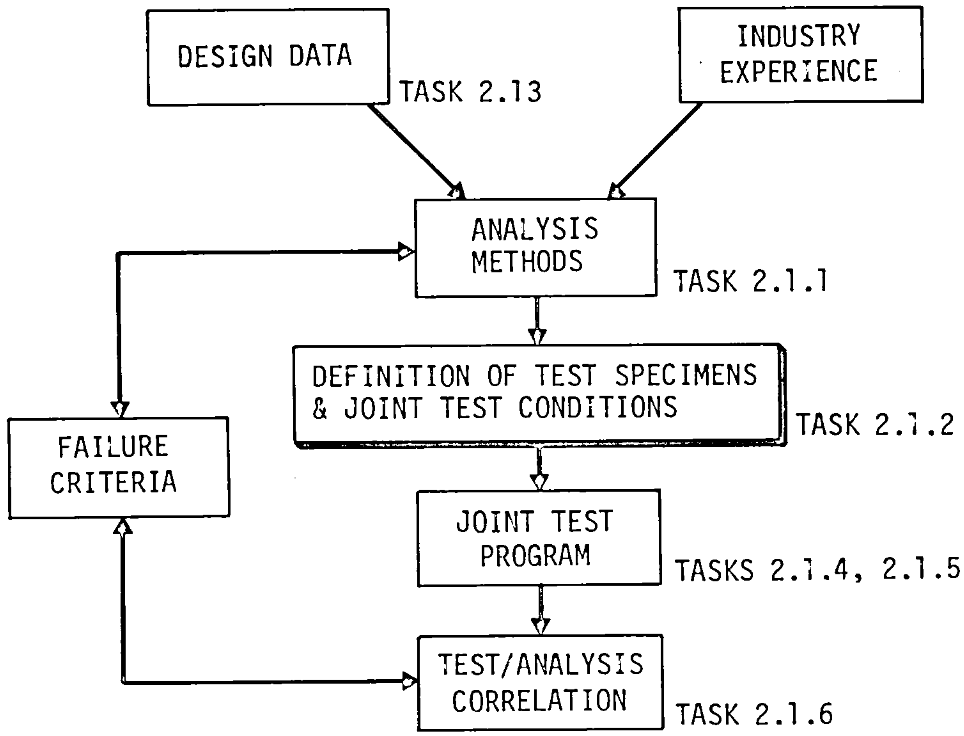
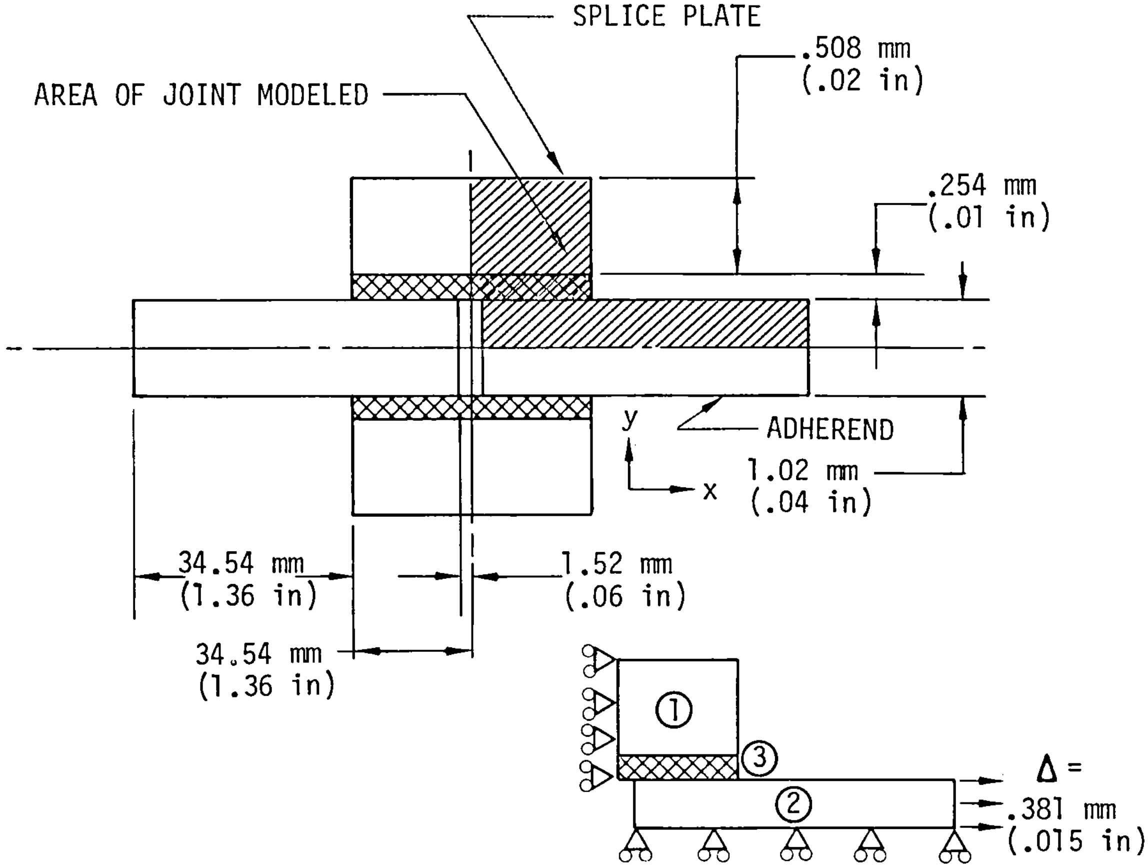


Figure 3-1: Task 2 Bonded Joint Subtasks



BOUNDARY CONDITIONS

MATERIAL PROPERTIES

1 $(0/\pm45/90)_s$ } E_1 = 137 GPa (20×10^6 psi) For 0° Laminate

2 $(0/\pm45/90)_s$ } E_2 = 11 GPa (1.6×10^6 psi) For 90° Laminate

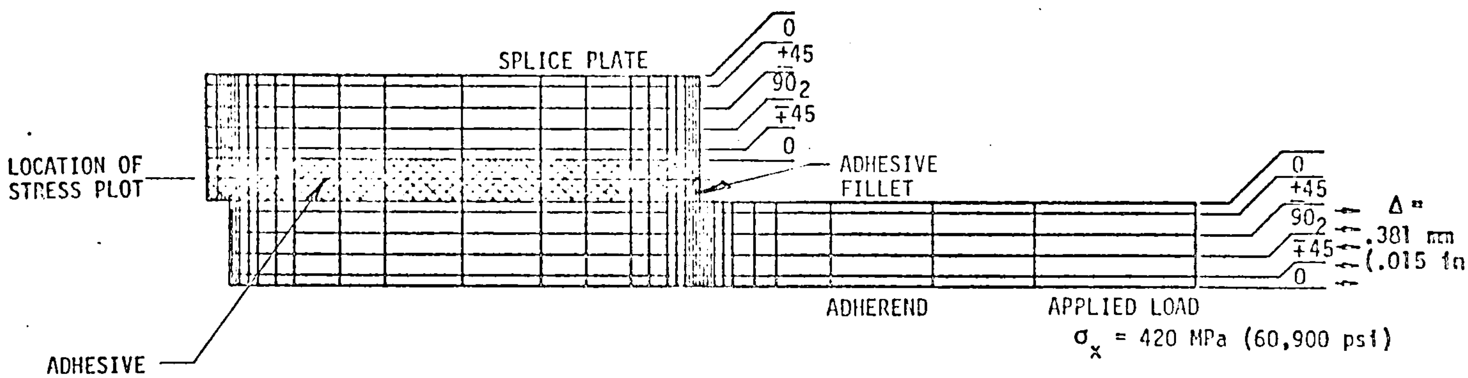
μ = .25

G = 5.8 GPa ($.85 \times 10^6$ psi) For $\pm45°$ Laminate

ADHESIVE: 3 G = 2.1 GPa ($.309 \times 10^6$ psi)

ASSUMED HOMOGENOUS AND ISOTROPIC

Figure 3-2: Study Model Configuration



MODEL 1C 'X' DIMENSION OF ELEMENTS IN HIGH STRESS AREA = .254 mm (.01 in)

MODEL 1D 'X' DIMENSION OF ELEMENTS IN HIGH STRESS AREA = .127 mm (.005 in)

Figure 3-3: Element Arrangements

summarized in Figure 3-4. Comparing adhesive stresses at a common reference point, 0.254 mm (0.01 in) inward (toward ℄) from the edge of the splice plate, shows a reduction in τ_{xy} and σ_y with the addition of a fillet; however, the σ_x stress increases. At the same reference point, the σ_y stress in the adherend lamina adjacent to the adhesive is reduced with the addition of a fillet.

In a double lap joint the peak σ_y stress in the adherend lamina adjacent to the adhesive occurs near the end of the splice plate. Reducing the minimum element size, Model 1C to Model 1D, caused an increase in peak σ_y and also moved its location nearer the end of the splice plate. The peak occurs in the center of the last adhesive element. Adding a fillet to the coarse grid, Model 1C, also increased the peak σ_y and, in addition, moved it so that it peaks directly under the fillet. Adding a fillet to the fine grid, Model 1D, did not increase the peak σ_y stress; however, the location did move so that it occurred directly under the fillet.

Analyses to assess the effect of increasing the number of finite elements used through the thickness (y-grid direction) of the adhesive layer also used the double lap joint shown in Figure 3-2. Models with 1, 2 and 3 elements were studied in Reference 8 and showed the σ_y stress increased as the number of elements increased; however, the τ_{xy} stress approached an asymptote. Models analyzed during this reporting period considered 4 and 5 adhesive elements. The shear stress, τ_{xy}, and normal stress, σ_y, for the adhesive and lamina adjacent to the adhesive for all the models are summarized in Figures 3-5.

An increase from 2 to 5 adhesive elements had no appreciable effect on the maximum shear stresses, τ_{xy}; however, the peak normal stress, σ_y, in the adhesive asymptotically approaches the value of σ_y in the splice plate lamina adjacent to the adhesive. Note, however, that the peak values of σ_y in the lamina adjacent to the adhesive do not appreciably change while going from 2 to 5 adhesive elements. Further finite element analyses to correlate test results and assess effects of various changes in joint parameters will be made using 2 elements through the adhesive thickness.

LOCATION	ITEM	MODEL 1C .245 mm (.01 in) Minimum Element		MODEL 1D .127 mm (.005 in) Minimum Element	
		WITHOUT FILLER MPa (psi)	WITH FILLER (MPa (psi)	WITHOUT FILLER MPa (psi)	WITH FILLER MPa (psi)
ADHESIVE .254 MM (.01 in) FROM END OF SPLICE PLATE	τ_{xy}	46.9 (6800)	46.8 (6790)	50.7 (7360)	47.4 (6880)
	σ_y	23.4 (3400)	13.1 (1900)	23.8 (3450)	13.1 (1900)
	σ_x	23.6 (3420)	34.1 (4950)	27.9 (4050)	34.1 (4950)
ADHEREND LAMINA ADJACENT TO ADHESIVE	σ_y Lamina ▷1	22.0 (3190)	12.5 (1820)	22.2 (3220)	11.7 (1700)
	Peak σ_y Lamina	31.2 (4520)	52.3 (7580)	53.3 (7730)	53.4 (7750)

▷1 .254 mm (.01 in) From End of Splice Plate

Figure 3-4: Finite Element Analysis - Double Lap Joint Effect of Adhesive Fillet

STRESS	NUMBER OF ADHESIVE ELEMENTS				
	1	2	3	4	5
PEAK τ_{xy} ADHESIVE* MPa (psi)	45.3 (6570)	47.2 (6850)	47.1 (6830)	47.1 (6830)	47.1 (6830)
τ_{xy} ADHEREND* MPa (psi)	30.1 (4370)	31.6 (4585)	31.9 (4625)	32.0 (4640)	32.1 (4650)
τ_{xy} SPLICE PLATE* MPa (psi)	35.3 (5120)	33.3 (4830)	33.2 (4810)	33.0 (4790)	33.0 (4790)
PEAK σ_y ADHESIVE* MPa (psi)	11.7 (1700)	18.4 (2665)	19.5 (2835)	20.0 (2905)	20.3 (2945)
σ_y ADHEREND* MPa (psi)	8.3 (1205)	9.3 (1345)	9.4 (1370)	9.5 (1380)	9.5 (1385)
σ_y SPLICE PLATE* MPa (psi)	22.6 (3285)	21.4 (3105)	21.2 (3070)	21.1 (3060)	21.0 (3050)

* Stresses shown are .381 mm (.015 in) from end of splice plate.

Figure 3-5: Finite Element Analysis - Double Lap Joint Varying Number of Adhesive Elements

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

A work statement and specimen configuration for thick adherend tests to evaluate A7F (amide-imide modified LARC 13) have been sent to Dr. J. R. Vinson, University of Delaware, for final negotiations. The proposed specimen configuration is shown in Figure 3-6. Boeing will build 18 specimens for testing at the University of Delaware; 6 specimens at 116K (-250°F), 6 at room temperature and 6 at 561K (550°F). Data to be provided are shear stress-strain curves for each specimen and ultimate shear stresses.

The "A7F" film adhesive prepared last December from Amoco AI-1130L and NASA-supplied LARC 13 resins exhibited good strength properties. This batch of "A7F" adhesive was used to bond a lap shear test panel for TASK 2.1.4. A C-scan of the 51 mm (2.0 in) overlap bondline showed that the bond was defect-free; however, the adhesive flow was considered to be unacceptable (no filleting). The lower than expected flow was caused by an excess of aluminum powder. A fresh batch of LARC 13 was supplied by NASA and a corrected formulation, based on the actual (by test) solids contents of the two resins, was used to make a new batch of "A7F" film adhesive. Testing is in progress.

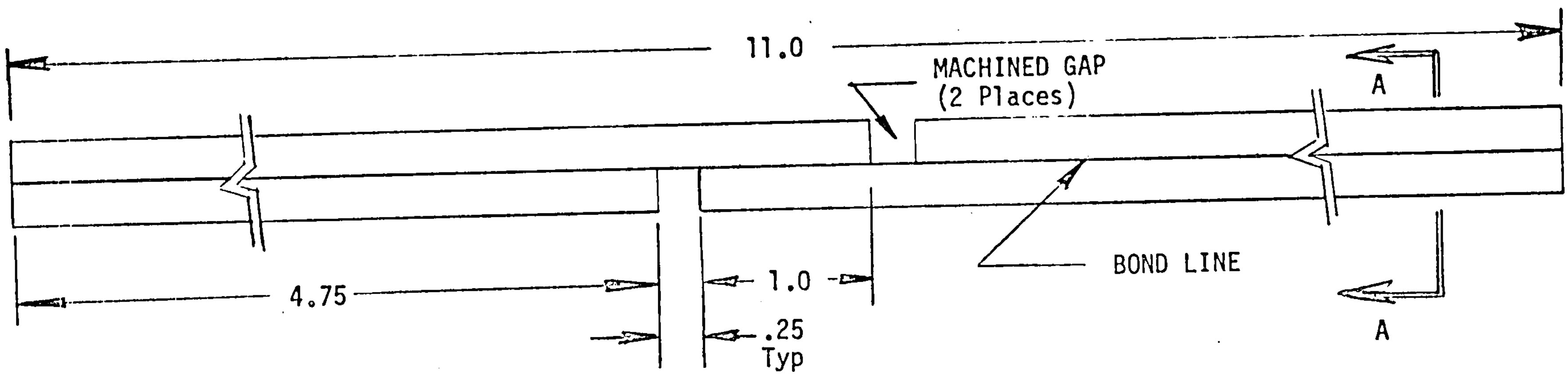
3.1.4 TASK 2.1.4 - Joint Specimen Fabrication and Non-Destructive Evaluation

A series of panels were fabricated for this task. Refer to the TASK 1.2.3 section for details.

The four panels discussed in Reference 2 for fabricating "out of sequence" test specimens were cured, postcured, and prepared for bonding. Due to an error in formulating the first "A7F" batch (refer to the preceding section for details), only one panel was bonded. This panel will be rebonded (at the opposite ends) with the reformulated "A7F", thereby eliminating having two different adhesive formulations in the test series.

3.1.5 TASK 2.1.5 - Joint Test Program

The specimen configuration for the symmetric step-lap joints test in Matrix 3G (Ref. 8) is shown in Figure 3-7.



BOND TWO .25 x 1.00 INCH PIECES TOGETHER WITH A7F (LARC-13 Amide-Imide Modified) ADHESIVE.

MACHINE GAPS AS SHOWN AFTER BONDING

MATERIAL: TITANIUM 6Al-4V

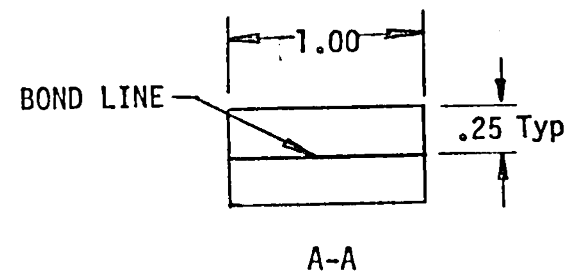
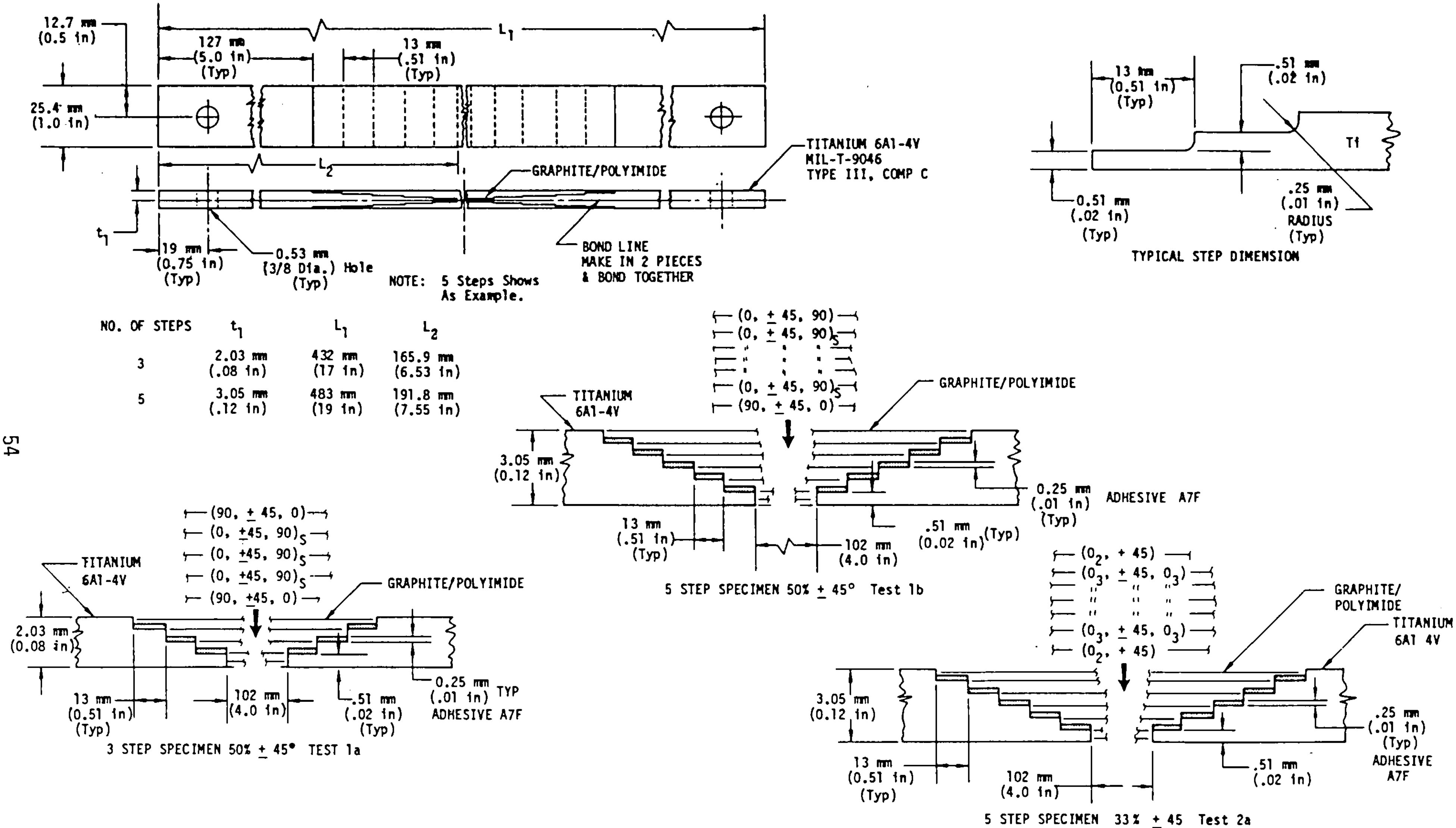


Figure 3-6: Thick Adherend Test Specimen



NO. OF STEPS	t_1	L_1	L_2
3	2.03 mm (.08 in)	432 mm (17 in)	165.9 mm (6.53 in)
5	3.05 mm (.12 in)	483 mm (19 in)	191.8 mm (7.55 in)

Figure 3-7: Test Matrix 3G, Specimen Configuration

SECTION 4.0

CONCLUDING REMARKS

During this reporting period the principal program activities dealt with preliminary design of joint concepts assessment of GR/Pi material, verification of LARC 13 and A7F adhesive, cutting and testing of design allowables specimens, fabrication of small specimens and standard joint panels and finite element modeling studies of double lap bonded GR/PI joints. Preliminary designs have been completed for some of the joint concepts selected during the 2nd cut screening. Design allowables specimens have been cut and testing initiated. Small specimens and standard joint panels have been fabricated. A7F adhesive has been prepared. Definition of the small specimens test matrix was completed and the specimen configuration for the symmetric stepped-lap standard joint test matrix (Matrix 3G) has been defined. Finite element modeling studies to assess adhesive fillets and the number of elements through the adhesive thickness were completed.

Results from activities discussed in this report have led to the following conclusions:

- *Thermal cycling produces significant microcracking in (0,$\pm$45,90) panels.*
- *Better quality prepreg is obtained if resin batches are held to a maximum of 11 kg (24 lb).*

REFERENCES

1. Arnquist, J. L. and Skoumal, D. E., "Design, Fabrication and Test of Graphite/Polyimide Composite Joints and Attachments in Advanced Aerospace Vehicles", Quarterly Technical Progress Report #1, Contract NAS1-15644, April 15, 1979. NASA CR-159080.

2. Arnquist, J. L. and Skoumal, D. E., "Design, Fabrication and Test of Graphite/Polyimide Composite Joints and Attachments for Advanced Aerospace Vehicles", Quarterly Technical Progress Report #2, Contract NAS1-15644, July 15, 1979. NASA CR-159109.

3. NASA TP 1507, "A Critical Examination of Stresses in an Elastic Single Lap Joint", Paul A. Cooper, James Wayne Sawyer, September 1979.

4. Technical Paper "Design Allowables for PMR-15 Graphite/Polyimide Bolted Joints", Dale W. Wilson, R. Byron Pipes, D. Reigner and J. Webster, University of Delaware; presented at ASTM Symposium 2 and 3 October 1979, Dearborn, Michigan.

5. "The Strength of Bolted Joints for Multi-Directional CFRP Laminates", T. A. Collings, Composites Journal, January 1977.

6. NASA Technical Paper 1496, "Elevated Temperature Application of the IITRI Compression Test Fixture for Graphite/Polyimide Filamentary Composites", B. Basaya Raju, Charles J. Camarda, and Paul A. Cooper, September 1979.

7. "Thermal Microcracking in Celion 6000/PMR-15 Graphite Polyimide" C. T. Herakovich, J. G. Davis, Jr., J. S. Mills; to be presented at Internation Conference on Thermal Stresses in Materials and Structures in Severe Thermal Environments", March 1980, Blacksburg, Virginia.

8. Arnquist, J. L. and Skoumal, D. E., "Design, Fabrication and Test of Graphite/Polyimide Joints and Attachments for Advanced Aerospace Vehicles", Quarterly Progress Report #3, Contract NAS1-15644, NASA CR-159110, October 15, 1979.

9. Sheppard, C. H., Hoggatt, J. R., and Symonds, W. A., "Quality Control Developments for Graphite/PMR-15 Polyimide Composite Materials", NASA CR-159182.