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NASA Contractor Report 159114

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

Quarterly Technical Progress Report No. 7

BOEING AEROSPACE COMPANY
Seattle, Washington 98124

NASA Contract NAS1-15644
April 1981

NASA
National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

FOREWORD

This report summarizes the work performed by the Boeing Aerospace Company (BAC) under NASA Contract NAS1-15644 during the period December 1, 1980, through March 31, 1981.

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. E. Harrison 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: J. B. Cushman, Design and Analysis; S. G. Hill, Materials and Processes.

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SUMMARY

This document reports on activities from December 1, 1980, through March 31, 1981, 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 allowables and "small specimen" testing and preliminary evaluation of attachment concpets. Test results are presented for rail shear and sandwich beam compression tests and tension tests of moisture conditioned specimens and bonded on "T" sections. Coefficient of thermal expansion data are presented for A7F (LARC 13 Amide-imide modified) adhesion. Static discriminator test results for Type 1 and Type 2 bonded and bolted preliminary attachment concepts are presented and discussed.

SECTION 1.0
INTRODUCTION

This is the 7th quarterly report covering results of activity during the period December 1, 1980, through March 31, 1981.

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 paramaters 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 scheduled is 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 1. 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.

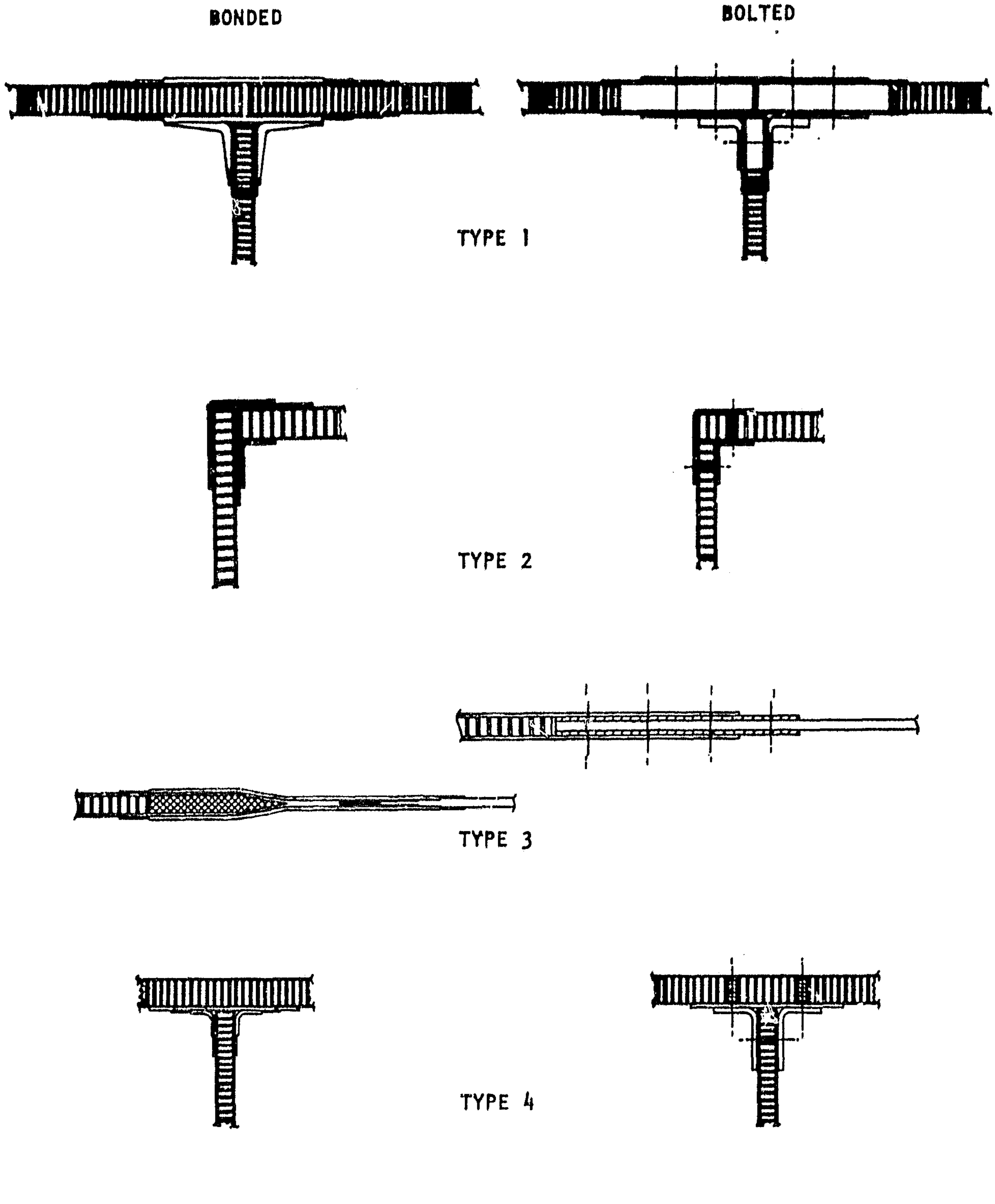

Figure 1-1: Generic Joint Concepts for 4 Attachment Types

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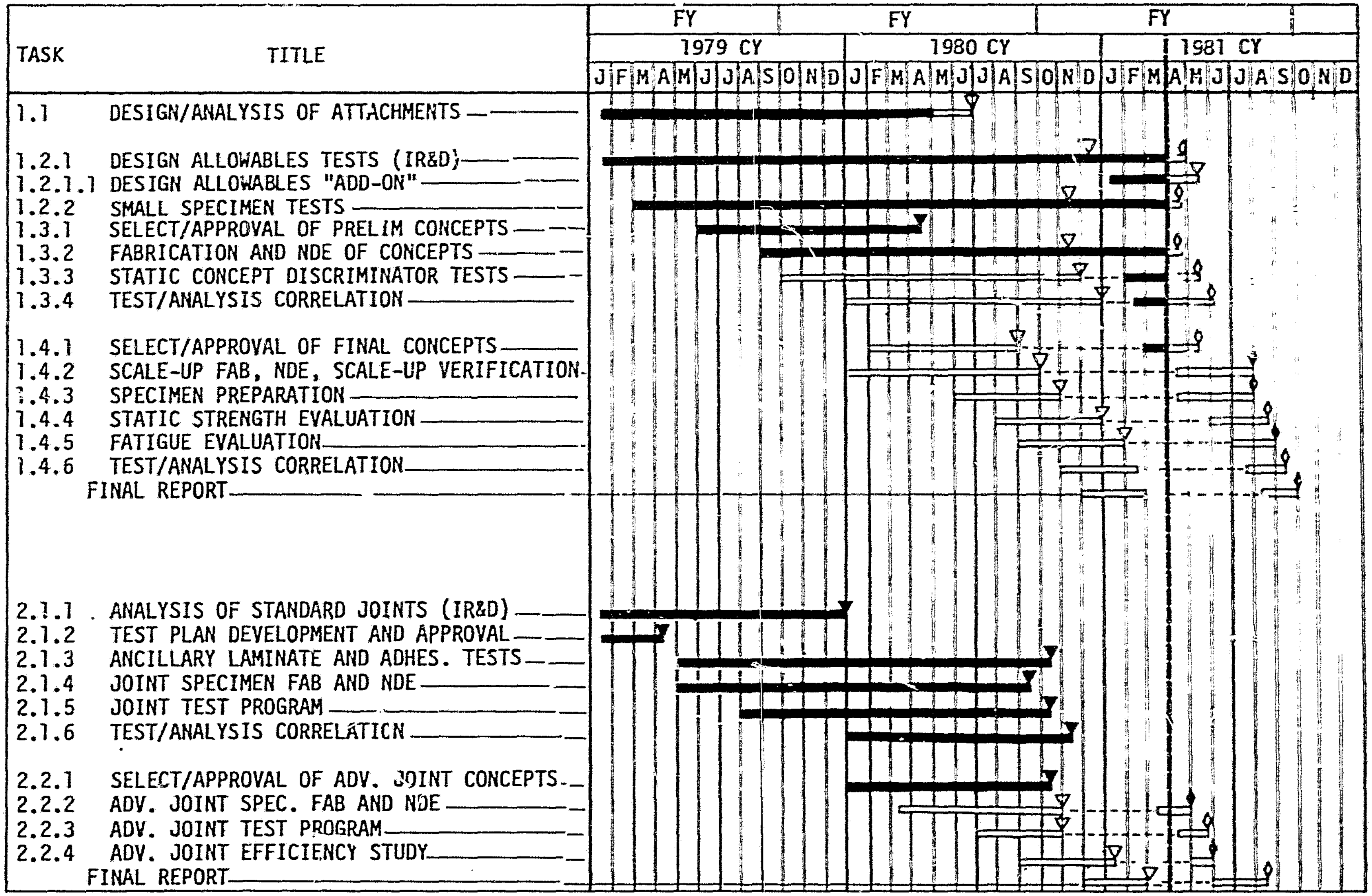

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Figure 1-2 : Master Program Schedule

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 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 tests 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 static discriminator test results and results of design allowables, small specimen testing and ancillary adhesive tests completed during this reporting period.

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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 the program 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. Results of the literature search have been reported in previous Quarterly Report numbers 1 through 6. Review of current literature is a continuous on-going process during performance of this contract. A summary of relevant literature reviewed during this reporting period is given below.

Reference 2 discusses residual thermal stresses in a symmetric double-lap joint resulting from cooling from an elevated cure temperature to room temperature. Analyses were performed using variational principles and compare results for a linear elastic response with a viscoelastic response. Results show the largest axial stresses occur within the adhesive layer. The viscoelastic analysis showed a reduction in stresses, due to viscoelastic creep, to 40 to 50% of the elastic results. This shows that prediction of joint thermal stresses based on elastic behavior, while conservative, may lead to improper conclusions concerning joint behavior. Time dependent viscoelastic analysis should be used for realistic design of adhesive joints.

Results of a time dependent viscoelastic analysis of residual thermal stresses in an unsymmetric graphite epoxy cross-ply laminate are presented in Reference 3.

Calculated plate curvatures due to residual thermal stresses are compared to measured values for various cool down paths. Results show good correlation. Analysis results are used to define an optimal cool down path that will minimize residual thermal stresses.

Reference 4 presents results of analyses evaluating residual internal stresses due to moisture conditioning of symmetric grapite/epoxy cross-ply laminates. Both elastic and viscoelastic analyses were performed. Results show lower residual stresses when moisture conditioned at 339K (150°F) as compared to 335K (180°F). Viscoelastic analyses show residual stresses three to six times less than the elastic analysis results.

2.1.2 Design and Analysis

The design analysis procedure used to develop the joint designs is shown in Figure 2-1 which illustrates the interaction between design, analysis and test. Shaded areas indicate percent completion.

Basic designs for all the bonded and bolted joints are presented in the 5th quarterly Report (CR 159112). Designs presented along with small specimen test results were used to arrive at the static discriminator specimen configurations presented in the 6th Quarterly Report (CR 159113). Final joint designs to be conducted under Task 1.4 will be defined when the "small specimen" and "static discriminator" tests are completed and results analyzed.

2.2 TASK 1.2 - Material and Small Component Characterization

This section discusses design allowables and small specimen testing.

2.2.1 TASK 1.2.1 - Design Allowables

Flatwise tension tests of Celion 3000/PMR-15 laminates bonded to Hexcel HRH 327-3/16-8 core have been completed (Matrix 1 Test 8). Specimens were 50.8 mm (2.0 inches) square $(0/\pm45/90)_{2S}$ laminates bonded to the core with A7F (LARC 13 amide-imide modified) adhesive. Specimers tested at room temperature and at 116K (-250°F) had aluminum load blocks bonded to the laminates. Elevated

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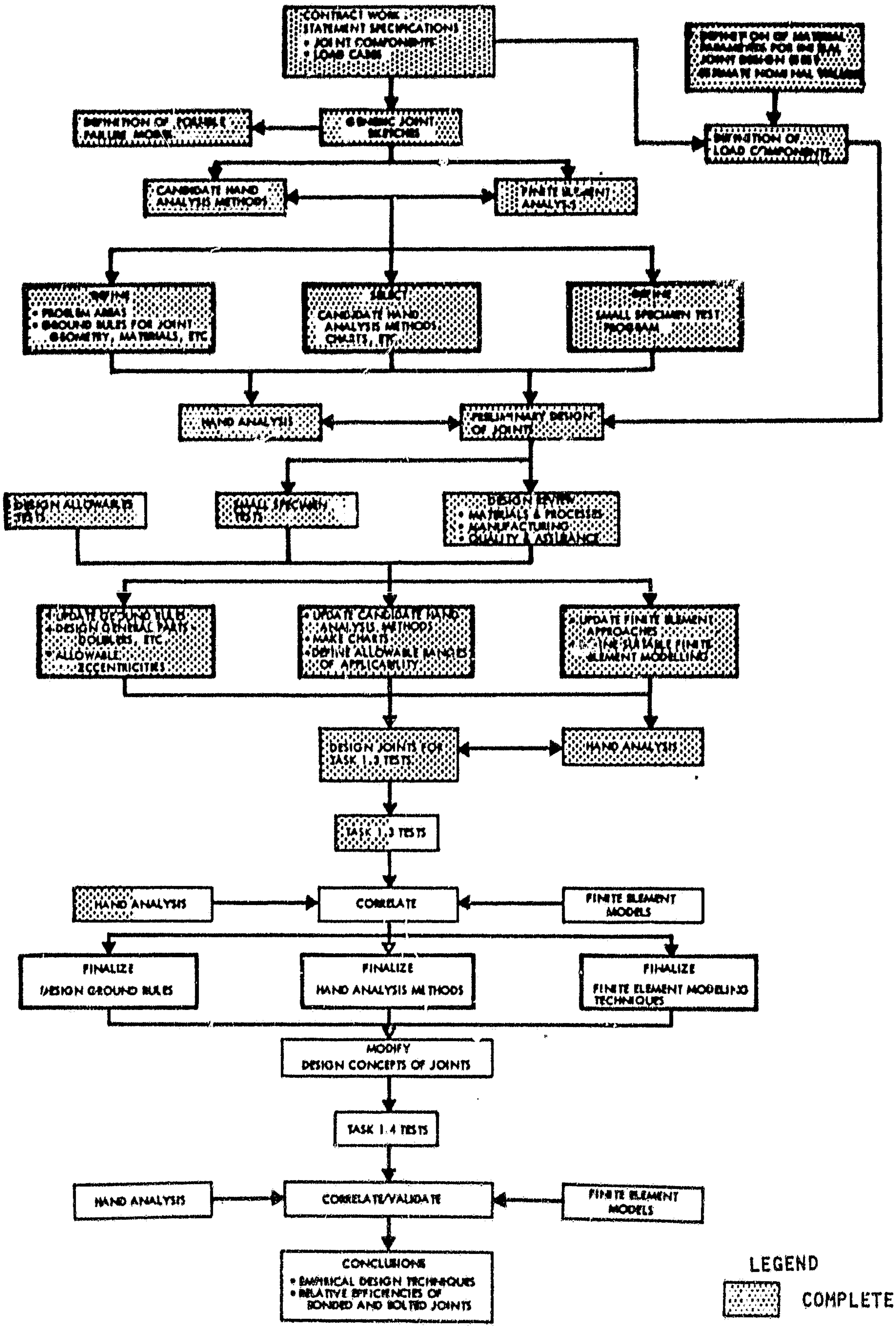

Figure 2-1: Task 1 Design/Analysis/Test Flow Diagram

temperature, 561K (550°F), specimens had steel load blocks. Test results are given in Table 2-1. Large differences in the coefficients of thermal expansion between the aluminum load blocks and the laminates results in large thermal stresses at 116K (-250°F). This explains the premature failures for the 116K (-250°F) tests. All the room temperature specimens had interlaminar tension failures of the laminate. Three of these also exhibited a 25% core to laminate bond area failure. All except one of the elevated temperature tests had adhesive failures at the laminate to load block interfaces. The other specimen (Spec. No. 1-8-2-7) had 100% failure of the core to laminate bond.

Previous tests were conducted to evaluate the transverse tension strength of Celion 3000/PMR-15 laminates (Matrix 1, Test 7) and are reported in Reference 5. The laminate was also $(0/\pm45/90)_{2S}$ but the specimens were 31.8 mm (1.25 inch) in diameter instead of 50.8 mm (2.0 inch) square. Both specimen configurations, when tested at room temperature, had interlaminar tension failure of the laminate. A comparison of average failure stresses are given in Table 2-2.

TABLE 2-2 COMPARISON OF INTERLAMINAR TENSION STRENGTH

Celion 3000/PMR-15 - $(0/\pm45/90)_{2S}$ - Room Temperature

	31.8 mm (1.25 inch) Dia. Spec. MPa (psi)	50.8 mm (2.0 inch) Square Spec. MPa (psi)
Cured/Post Cured	26.4 (3832)	6.23 (903)
Aged 125 Hours at 589 K (600°F)	13.3 (1931)	5.05 (732)

As can be seen, even though the failure modes were the same (interlaminar tension), the failure stress is significantly different for the two specimen configurations. This demonstrates the strong dependence of test results on the specimen configuration and points out the need for standardization of test procedures. In addition, application of test results to design practice must account for any differences in loading conditions.

TABLE 2-1 Design Allowables - Celion 3000/PMR-15, MATRIX 1, Flatwise Laminate To Core
ENGLISH UNITS

Spec. No.	Condition Code	Temp. ^{o}F	Failure Load lbs	Failure Stress psi	Failure Mode
1-8-1-1	1	70	3825	956	Inter.
1-8-1-2	1	70	3945	986	Inter.+25% Core
1-8-1-3	1	70	3075	769	Inter.
1-8-1-4	1	-250	▷1	▷1	Inter.
1-8-1-5	1	-250	1440	360	Adhesive
1-8-1-6	1	-250	630	158	Adhesive
1-8-1-7	1	550	1775	455	Adhesive
1-8-1-8	1	550	1435	368	Adhesive
1-8-1-9	1	550	1005	251	Adhesive
1-8-1-10	1	550	1475	369	Adhesive
1-8-2-1	2	70	2950	741	Inter.
1-8-2-2	2	70	2975	744	Inter.+25% Core
1-8-2-3	2	70	2850	713	Inter.+25% Core
1-8-2-4	2	-250	▷1	▷1	Inter.
1-8-2-5	2	-250	▷1	▷1	Inter.
1-8-2-6	2	-250	▷1	▷1	Inter.
1-8-2-7	2	550	2440	613	100% Core
1-8-2-8	2	550	2235	559	Adhesive
1-8-2-9	2	550	2265	569	Adhesive
1-8-2-10	2	550	2165	552	Adhesive

Condition Code
1 Cured/Post Cured
2 Aged 125 Hrs at $600^{o}F$

▷1 Specimen Broke Prematurely Due to Thermal Stresses Caused by Aluminum Load Blocks.

All Specimens 2 in. x 2 in.

Adhesive = Adhesive to Laminate at Load Block
Inter. = Interlaminar Tension
Core = Core to Laminate Bond Failure

TABLE 2-1 Design Allowables - Celion 3000/PMR-15 MATRIX 1 Flatwise Laminate To Core
METRIC UNITS

Spec. No.	Condition Code	Temp. K	Failure Load kN	Failure Stress MPa	Failure Mode
1-8-1-1	1	294	17.0	6.59	Inter.
1-8-1-2		294	17.5	6.[illegible]	Inter.+25% Core
1-8-1-3		294	13.7	5.30	Inter.
1-8-1-4	1	116	▷1	▷1	Inter.
1-8-1-5		116	6.41	2.48	Adhesive
1-8-1-6		116	2.80	1.09	Adhesive
1-8-1-7	1	561	7.90	3.14	Adhesive
1-8-1-8		561	6.38	2.54	Adhesive
1-8-1-9		561	4.47	1.73	Adhesive
1-8-1-10		561	6.56	2.54	Adhesive
1-8-2-1	2	294	13.1	5.11	Inter.
1-8-2-2		294	13.2	5.13	Inter.+25% Core
1-8-2-3		294	12.7	4.92	Inter.+25% Core
1-8-2-4	2	116	▷1	▷1	Inter.
1-8-2-5		116	▷1	▷1	Inter.
1-8-2-6		116	▷1	▷1	Inter.
1-8-2-7	2	561	10.9	4.23	100% Core
1-8-2-8		561	9.9	3.85	Adhesive
1-8-2-9		561	10.1	3.92	Adhesive
1-8-2-10		561	9.6	3.80	Adhesive

Condition Code
1 Cured/Post Cured
2 Aged 125 hrs at 589 K

▷1 Specimen Broke Prematurely Due to Thermal Stresses Caused by Aluminum Load Blocks.

Adhesive = Adhesive to Laminate at Load Block
Inter. = Interlaminar Tension
Core = Core to Laminate Bond Failure

All Specimens 50.8 mm x 50.8 mm

In-plane rail shear tests (Matrix 1, Test 13) for a $\pm45_{3S}$ laminate of Celion 3000/PMR-15 have been completed. Tests were conducted using procedures in Reference 6. Bonded and tapered titanium rails, provided by NASA LaRC, were used for load introduction. Each specimen was instrumented with a uniaxial strain gage bonded at 45° to the load path. Test results are summarized in Table 2-3. Ultimate shear stress and initial shear modulus data shown are higher than equivalent data reported in Reference 6 for an HTS-1/PMR-15 laminate of $\pm45_{2S}$ layup tested with the same rail fixtures. Failure stresses shown in Table 2-3 are probably lower than actual ultimates for those specimens that failed in the grip area; however, modulus data should be valid since they are based on initial slopes of the stress-strain curves. Shear modulus data compare very well with values predicted using uniaxial material properties from earlier design allowable tests reported in Reference 7. Predicted G_{XY} values were 36.7 GPa (5.33×10^6 psi) and 36.4 GPa (5.28×10^6 psi) at room temperature and 561K (550°F) respectively as compared to average measured values of 40.5 GPa (5.88×10^6 psi) and 33.3 GPa (4.83×10^6 psi) respectively for aged specimens.

Sandwich beam compression tests (4 point bending) of Celion 6000/PMR-15 laminates with a $(0/\pm45/90)_S$ layup have been completed. Test results are summarized in Table 2-4. The average compressive failure stresses were 452 MPa (65.6Ksi) and 407 MPa (59.1 Ksi) at room temperature and 561K (550°F) respectively. The average compression moduli were 61.9 Gpa (8.98×10^6 psi) and 59.9 GPa (8.69×10^6 psi) respectively.

Previous compression tests (see Reference 7) were conducted on Celion 3000/PMR-15 laminates with a $(90/\pm45/0)_{4S}$ layup. Specimens were end loaded coupons with a supporting face plate. Average compression failure stresses for these specimens were 578 MPa (83.8 Ksi) and 466 MPa (67.6 Ksi) at room temperature and 561K (550°F) respectively which are higher than the sandwich beam test results. Average compression moduli for the coupon tests were 43.8 GPa (6.35×10^6 psi) and 46.8 GPa (6.79×10^6 psi) at room temperature and 561K (550°F) respectively which are lower than the sandwich beam test results. These differences can be partially attributed to differences in material and layup. The major reason, however, is probably because of a nonuniform compression stress through the thickness of the sandwich beam laminates due to laminate bending

TABLE 2-3 Design Allowables Tests - Celion 3000/PMR-15
MATRIX 1 Test 13
In-Plane Rail Shear

ENGLISH UNITS

Spec. No.	Condition Code	Temp. °F	Failure Load lbs	Failure Stress ksi	Shear Modulus 10^6 Gxy-psi	Failure Mode
1-13-1-1	1	70	1750	20.1	No Data	Bond Failure
1-13-1-2		70	5310	64.8	5.96	Shear and
1-13-1-3		70	4720	56.2	5.51	Interlaminar In Grip Area
1-13-1-4	1	550	4565	54.3	6.84	Shear
1-13-1-5		550	3895	46.9	4.43	Shear
1-13-1-6		550	3545	42.2	6.38	Shear
1-13-2-7	2	70	4810	51.7	5.94	Interlaminar
1-13-2-8	2	70	4540	52.2	5.81	In Grip Area
1-13-2-9	2	550	2770	32.2	4.71	Bond Failure
1-13-2-10	2	550	3100	37.3	4.96	In Grip Area

Condition Code
1 Cured/Post Cured
2 Aged 125 Hrs at 600°F

Laminate Lay-Up $\underline{+}45_{3s}$

TABLE 2-3 Design Allowables Tests - Celion 3000/PMR-15
MATRIX 1 Test 13
In-Plane Rail Shear

METRIC UNITS

Spec. No.	Condition Code	Temp. K	Failure Load kN	Failure Stress MPa	Shear Modulus Gxy-GPa	Failure Mode
1-13-1-1	1	294	7.78	138.6	No Data	Bond Failure
1-13-1-2		294	23.6	446.8	41.1	Shear and Interlaminar In Grip Area
1-13-1-3		294	21.0	387.5	38.0	
1-13-1-4	1	561	20.3	374.4	47.2	Shear
1-13-1-5		561	17.3	323.4	30.5	Shear
1-13-1-6		561	15.8	291.0	44.0	Shear
1-13-2-7	2	294	21.4	356.5	41.0	Interlaminar in Grip Area
1-13-2-8	2	294	20.2	359.9	40.1	
1-13-2-9	2	561	12.3	220.0	32.5	Bond Failure In Grip Area
1-13-2-10	2	561	13.8	257.2	34.2	

Condition Code

1 Cured/Post Cured
2 Aged 125 Hrs at 589 K

Laminate Lay-Up $\pm 45_{3s}$

TABLE 2-4: Sandwich Beam Compression Tests,
4 Point Bending - Celion 6000/PMR-15,
Aged 125 hrs at 589K (600°F)

Spec No.	Laminate Lay-up	Laminate Thickness mm	(inch)	Temp K	(°F)	Compression Failure Stress MPa	(ksi)	Compressive Modulus GPa	(10^6 psi)
1-5-2-1	$(0/\pm45/90)_S$	1.02	(.04)	294	(70)	464	(67.3)	63.1	(9.15)
3				294	(70)	523	(75.8)	--	--
4				294	(70)	455	(66.0)	--	--
1-5-2-2				561	(550)	461	(66.8)	59.8	(8.67)
5				561	(550)	385	(55.8)	--	--
6				561	(550)	459	(66.6)	--	--
1-12-2-1				294	(70)	416	(60.3)	60.7	(8.8)
3				294	(70)	404	(58.6)	--	--
4				294	(70)	450	(65.3)	--	--
1-12-2-2				561	(550)	387	(56.2)	60.0	(8.7)
5				561	(550)	346	(50.2)	--	--
6[1]	$(0/\pm45/90)_S$	1.02	(.04)	561	(550)	318	(46.1)	--	--

[1] Failed outside of test section.

caused by large beam deflections. When the failure load is averaged over the thickness, it gives an apparent lower failure stress. Examination of the specimens also indicates a combined peel and buckling failure which would yield lower failure stresses. The compression moduli for the sandwich beam specimens are based on strain gages bonded to the outer or 0^o ply. Results compare favorably with tension moduli reported for the same laminate layup in Reference 7.

Coefficient of Thermal Expansion (CTE) tests have been completed for A7F (LARC 13 amide-imide modified) adhesive. Test results for cured/post cured specimens and specimens aged 125 hours at 589K (600°F) are presented in Table 2-5. Data show a significant decrease in CTE due to aging.

TABLE 2-5 COEFFICIENT OF THERMAL EXPANSION
A7F Adhesive (LARC 13 Amide-Imide Modified)

Conditioning	Average Temperature	CTE
	K (°F)	mm/mm-K x 10^{-6} (in/in-Fx16^{-6})
Cured/Post Cured	279 (43)	26.6 (14.8)
	385 (234)	30.3 (16.8)
	483 (410)	35.4 (19.7)
Aged	363 (194)	17.5 (9.7)
	471 (388)	20.8 (11.6)

Tension testing of moisture conditioned Celion 3000/PMR-15 laminates (Matrix 1, Tests 2, 3 and 6) has been completed. Layups tested were $(90)_{30}$, $(0, \pm 45, 90)_{4S}$ and $(\pm 45)_{8S}$. Specimens were conditioned by exposure to 95% RH at 333K $\pm$6K (140°F $\pm$10°F) and atmospheric pressure until saturated, i.e., achieved constant weight. Strain gages were installed on the $(\pm 45)_{8S}$ specimens to enable calculation of the in-plane shear modulus, G_{12}. Specimen configurations are given in Reference 1. Comparison of test results for the four conditioning environments evaluated (cured/post cured, aged, thermally cycled and moisture conditioned) are presented in Figures 2-2 through 2-4. Data shown are based on only 3 to 5 data points each and, though indicative of trends, are certainly not conclusive due to the lack of a statistical base.

The data indicate that moisture conditioning does not have any significant effect on tension strength and modulus when tested at room temperature; however, all the elevated temperature specimens had significant blistering of the laminate visible after test. This was caused by vaporization of the entrapped moisture and resulting internal pressure which resulted in separation of the lamina. The specimens were brought up to temperature in approximately 20 minutes and then held at temperature for 5 minutes prior to test. The blistering was most pronounced on the $(90)_{30}$ laminate and explains the low tension strength and modulus at 561°K (550°F). Blistering of the $(0/\pm45/90)_{4S}$ laminate was less severe and, because the major portion of the load is carried by the 0° and 45° lamina, any strength degradation would be less pronounced. The $(\pm45)_{8S}$ laminate also had blistering, however, the elevated temperature strength data was lost because of premature load pad failure. The modulus data are valid since they are based on strain gages.

2.2.2 TASK 1.2.1.1 - Design Allowables Modification

Formal approval and "go-ahead" of a contract modification to conduct additional design allowables testing of Celion 6000/PMR-15 laminates was received on 12 January 1981. The detail test plan, D180-26011-2, was released on 9 February 1981 and approved by NASA, LaRC, on 10 March 1981. Tests to be conducted are tension, compression, in-plane shear (bolted rails) and short beam shear at temperatures of 116K (-250°F), room temperature and 589K (600°F). Laminates to be evaluated are (0), $(0/+45/90/-45)_S$ and $(\pm45)_S$. A total of 225 specimens will be tested.

Celion 6000/PMR-15 prepreg for the design allowables testing has been received (Lot 2W4878). Quality control test results are given in Table 2-6. Specimen fabrication is complete and installation of required strain gages is in progress. Compression testing of uninstrumented specimens has been started. The

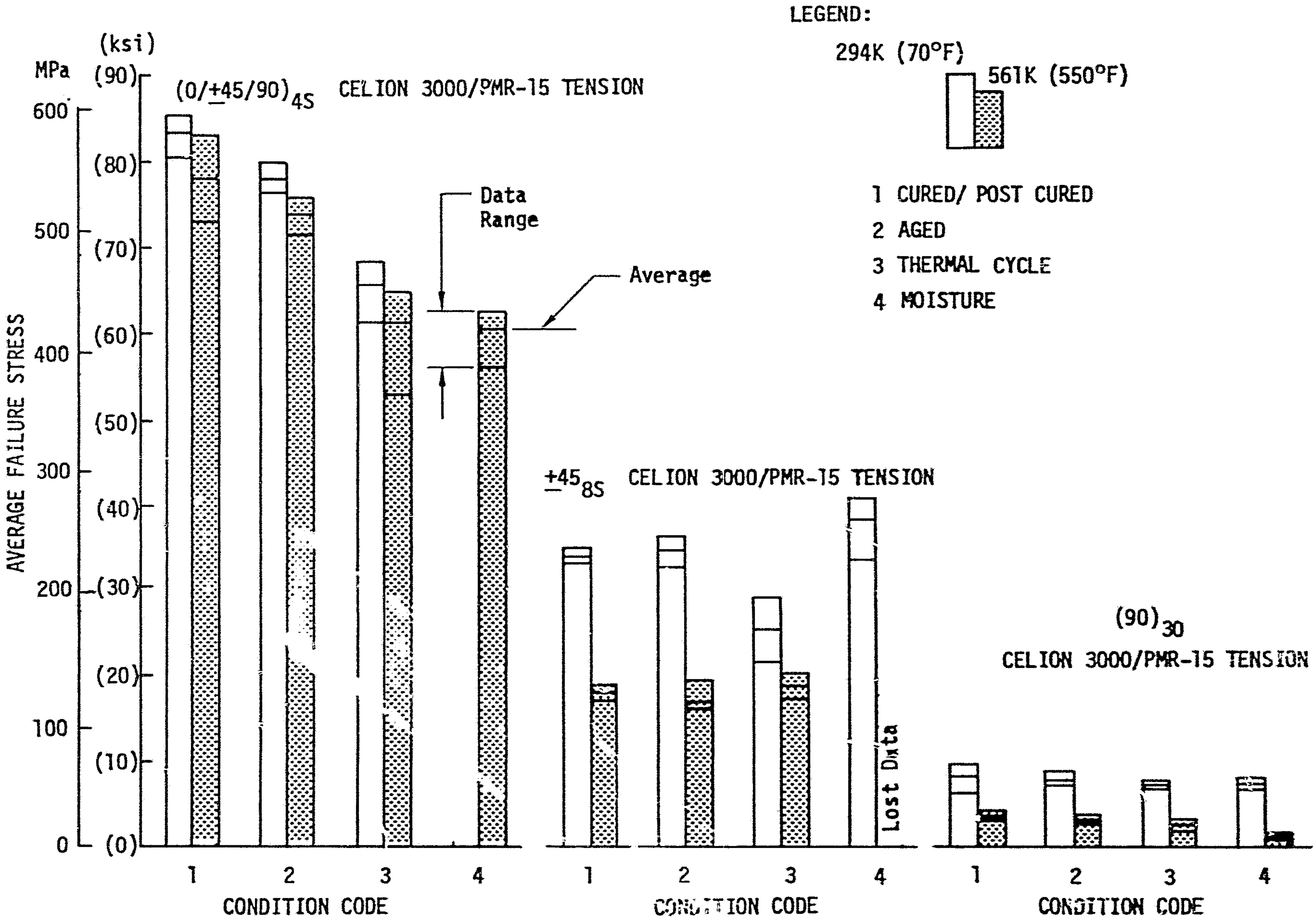

Figure 2-2. Effect of Environmental Conditioning on Tension Failure Stress
Celion 3000/PMR-15

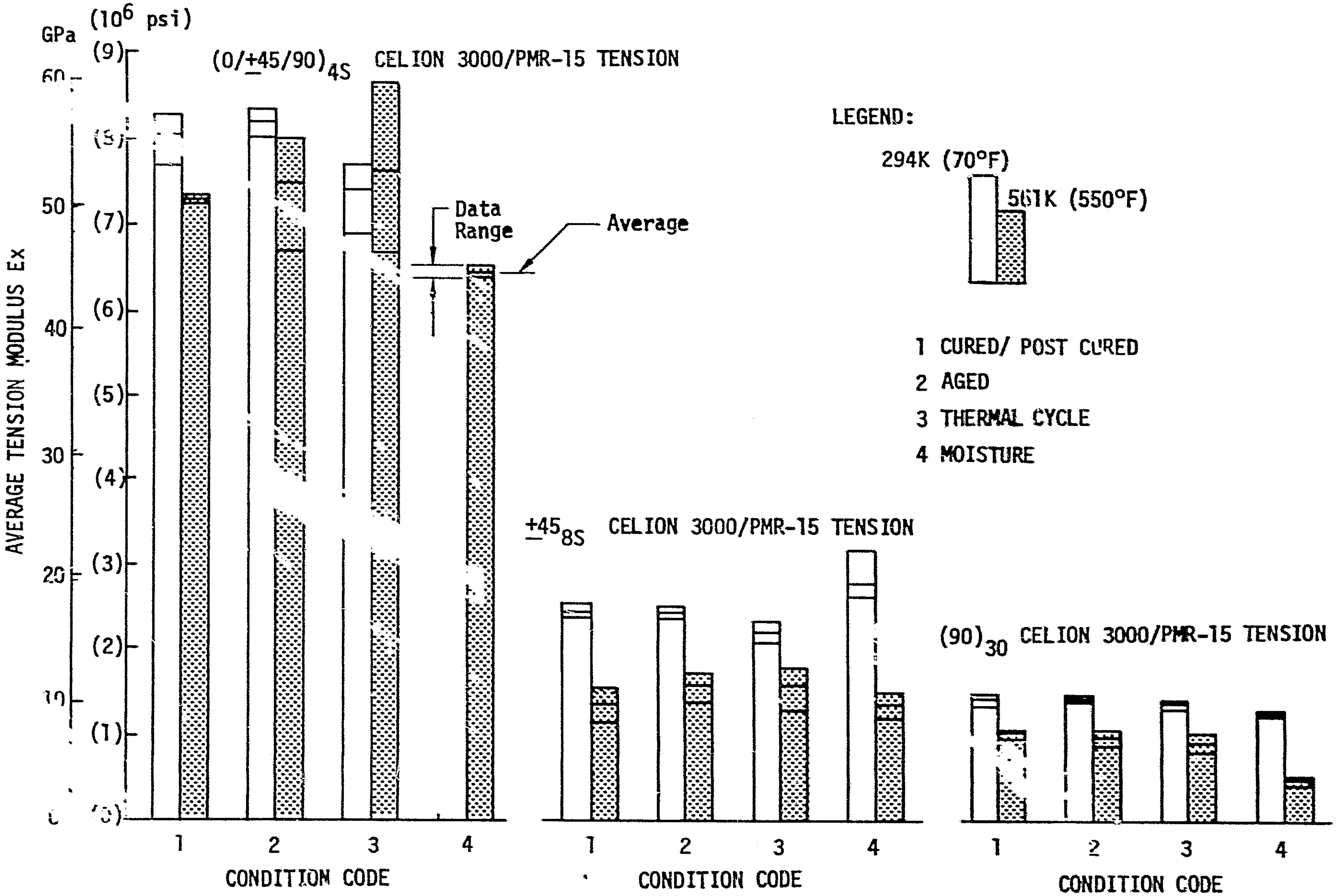

Figure 2-3. Effect of Environmental Conditioning on Tension Modulus Celion 3000/PMR-15

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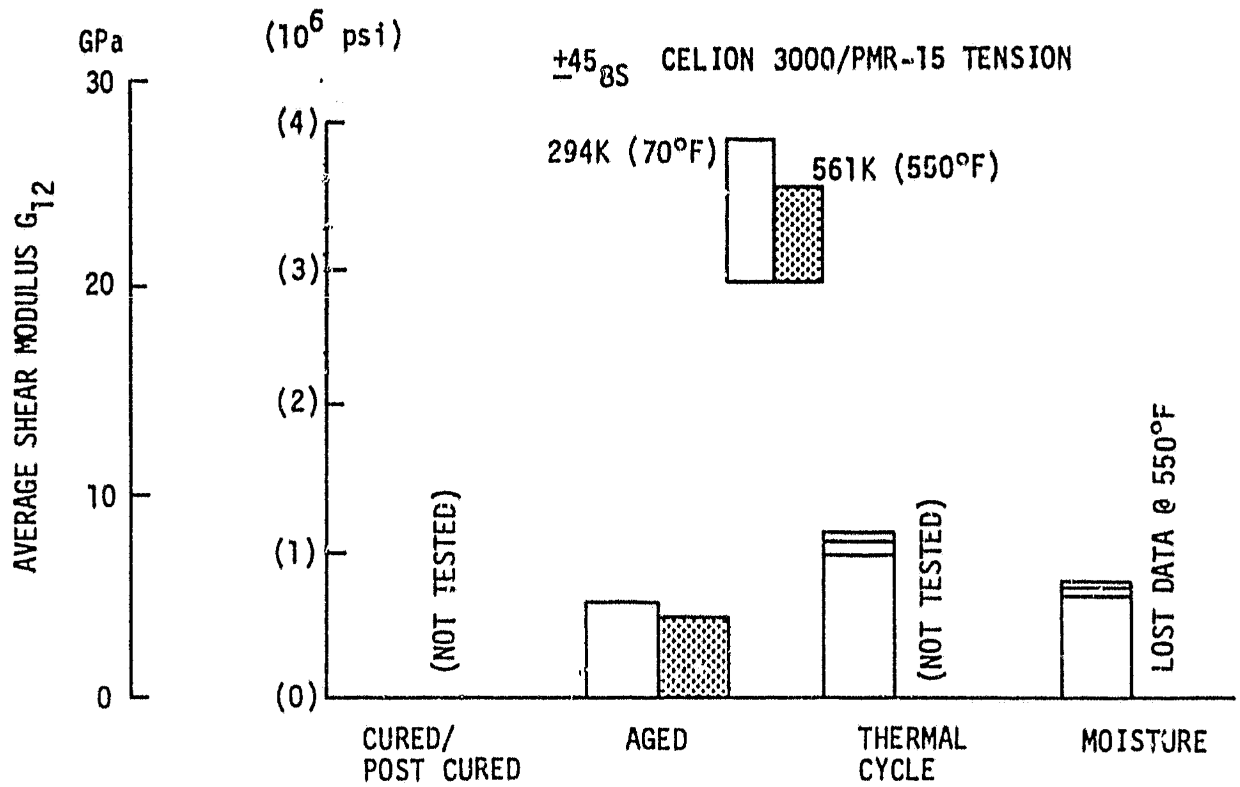


Figure 2-4. Effect of Environmental Conditioning on Shear Modulus G_{12} -Celion 3000/PMR-15

TABLE 2-6: Quality Control Test Panel Properties (Averaged)
Design Allowables Celion 6000/PMR-15

Property		Requirement	LOT 2W4878
Fiber Volume, %		58 $\pm$2	[1]
Resin Content, %		30 $\mp$3	36
Specific Gravity g/cc		1.54	[1]
Void Content, %		1	[1]
Flexural Strength MPa (ksi)	At Ambient	1515 (220)	1538 (223)
	At 589K (600°F)	757 (110)	827 (120)
	Aged, at 589K (600°F)	757 (110)	958 (139)
Flexural Modulus GPa (msi)	At Ambient	117 (17)	123 (19.9)
	At 589K (600°F)	103 (15)	108 (15.7)
	Aged, at 589K (600°F)	103 (15)	134 (19.4)
Short Beam Shear Strength MPa (ksi)	At Ambient	96 (14)	92 (13.3)
	At 589K (600°F)	41 (6)	59 (8.5)
	Aged, at 589K (600°F)	41 (6)	59 (8.6)

[1] Test data not available

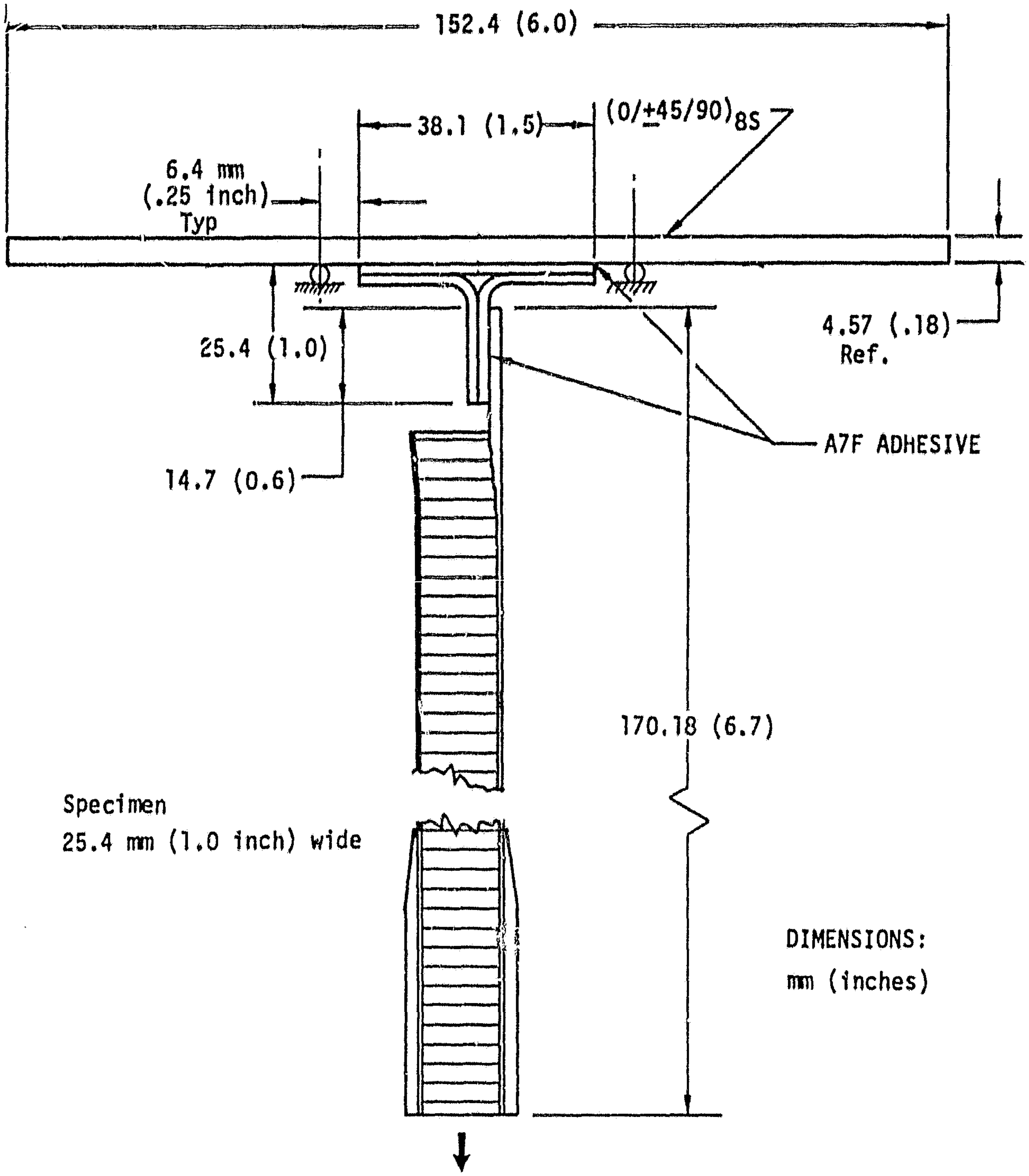


Figure 2-5 Matrix 4C Test 3b, Revised, "T" Pull-off Tests A7F Adhesive, Aged 125 Hours at 589K (600°F)

Table 2-7 Matrix 4C Test 3b Revised, "T" Pull-off Tests
A7F Adhesive, Aged 125 Hours at 589K (600°F)

SPECIMEN NUMBER	TEMPERATURE K (°F)	FAILURE LOAD N (lb)	AVERAGE STRESS MPa (psi)
4C-3B-2-1	294 (70)	1597 (359) [1]	1.61 (233)
4C-3B-2-2	294 (70)	1401 (315) [2]	1.43 (208)
4C-3B-2-3	294 (70)	1219 (274) [2]	1.25 (181)
4C-3B-2-4	561 (550)	1192 (268) [1]	1.21 (175)
4C-3B-2-5	561 (550)	1339 (301) [1]	1.34 (194)
4C-3B-2-6	561 (550)	1406 (316) [1]	1.41 (205)

[1] Adhesive to laminate failure on beam

[2] Interlaminar tension failure on "T"

compression tests are being conducted using a NASA supplied IITRI compression test fixture.

2.2.3 TASK 1.2.2 - Small Specimen Tests

Testing of a bonded "T" section (Matrix 4C, Test 3b revised) to evaluate web attachment designs has been completed. Specimen configuration and test set-up are shown in Figure 2-5. Test results are summarized in Table 2-7. Failure loads exceeded the minimum design requirement of 730 N (164 lbs).

Results of double angle (two 90° angles) web attachment tests were reported in Reference 5. The double angle attachment had average failure loads of 1019 N (229 lbs) and 1192 N (268 lbs) at 294K (70°F) and 561K 550°F) respectively. The "T" attachment averages were 1406 N (316 lbs) and 1312 N (295 lbs) respectively. Since the 90° angles are easier to fabricate than a "T" section and they exceed the design load requirements, they will be used for the bonded web attachments for Type 1 and Type 4 joints in TASK 1.4.

2.3 TASK 1.3 - Preliminary Evaluation of Attachment Concepts

Static strength tests of Type 1 bonded and bolted joints (Reference SK2-078001 and SK2-078002, Figures 2-6 and 2-7) and Type 2 bonded and bolted joints (Reference SK2-078003 and SK2-078006, Figures 2-8 and 2-9) for Matrix 5 have been completed. Type 1 joints were loaded in axial tension as shown in Figure 2-10. Type 2 joints were loaded to give a moment and vertical shear at the corner as shown in Figure 2-11. Test results are given in Tables 2-8 and 2-9 for Type 1 and Type 2 respectively and are discussed below.

The Type 1 bonded joints had 33 mm (1.3 inches) lap lengths with co-cured doublers on the sandwich face sheets. Specimens were 76.1 mm (3.0 inches) wide. In all cases the specimens failed in interlaminar shear at the doubler to face sheet interface (See Figure 2-12) at loads below the design ultimate of 66.2KN (9600 lb). Average failure loads were 52.6KN (7627 lbs) at room temperature and 44.7KN (6477 lbs) at 561K (550°F). Loads are transferred from the sandwich 0.51 mm (.02 inch) face sheets, into the co-cured doubler, through the adhesive bond line and into the splice plates. Failure probably initiated due

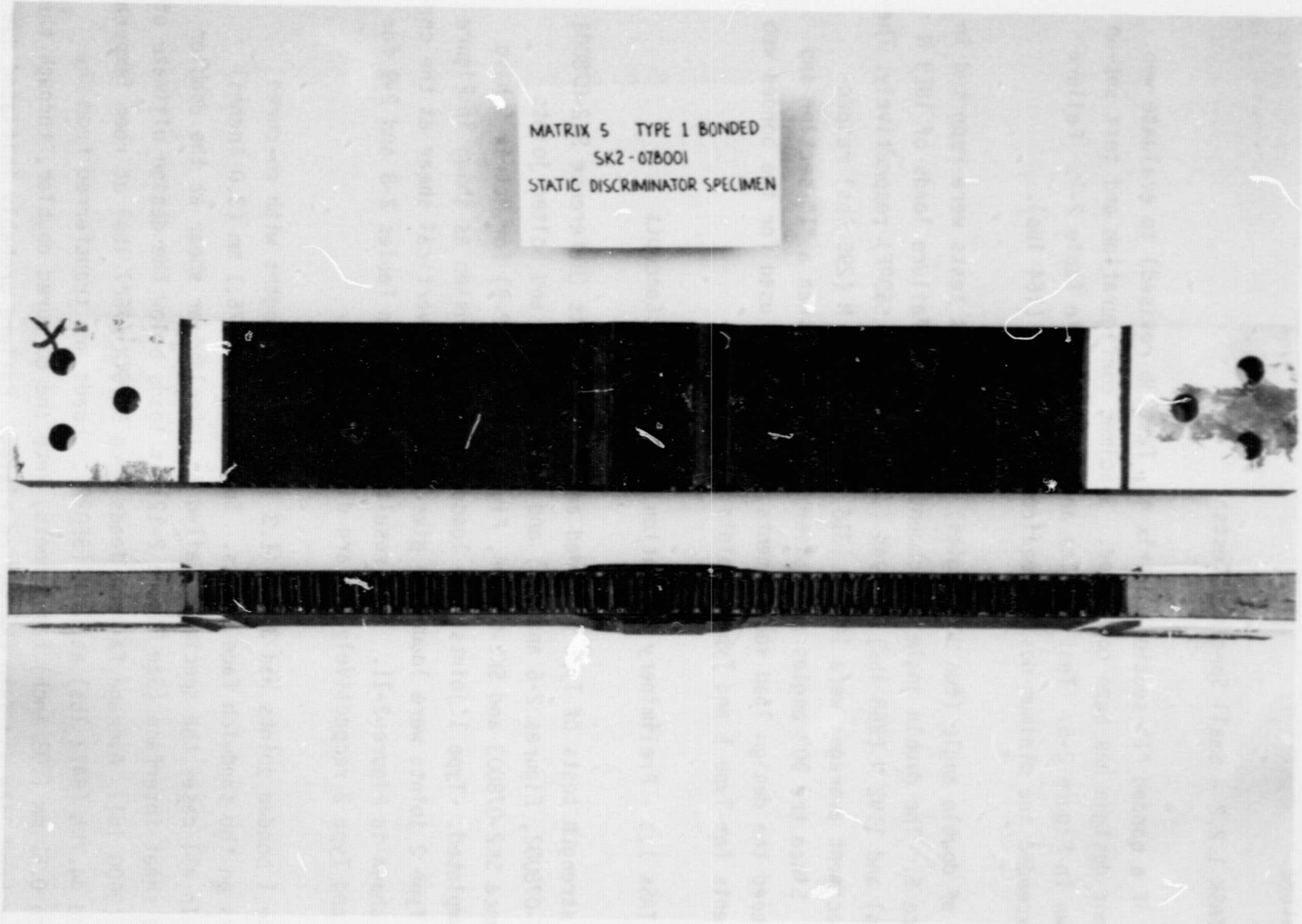


Figure 2-6: Type 1 Bonded Joint

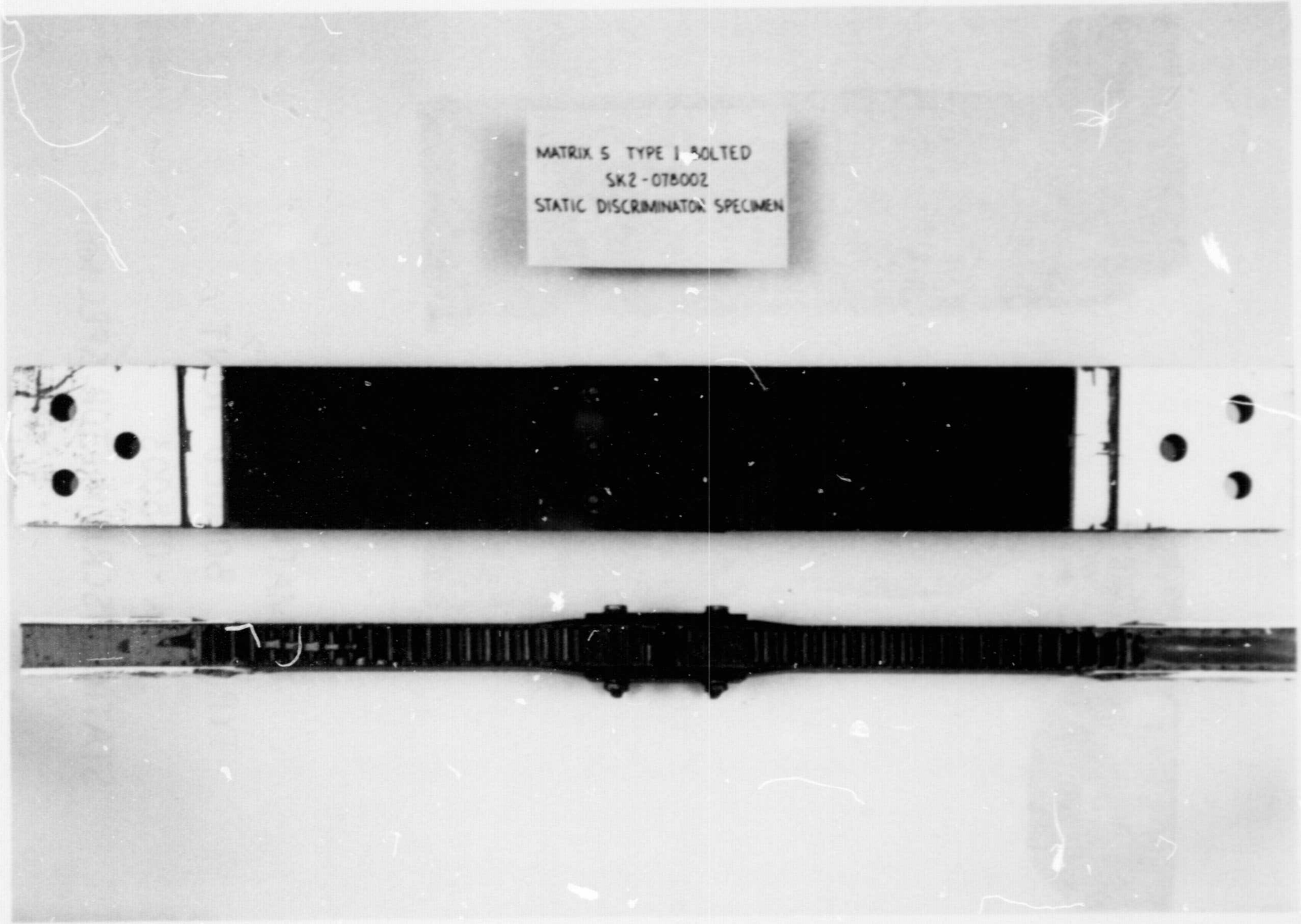


Figure 2-7: Type 1 Bolted Joint

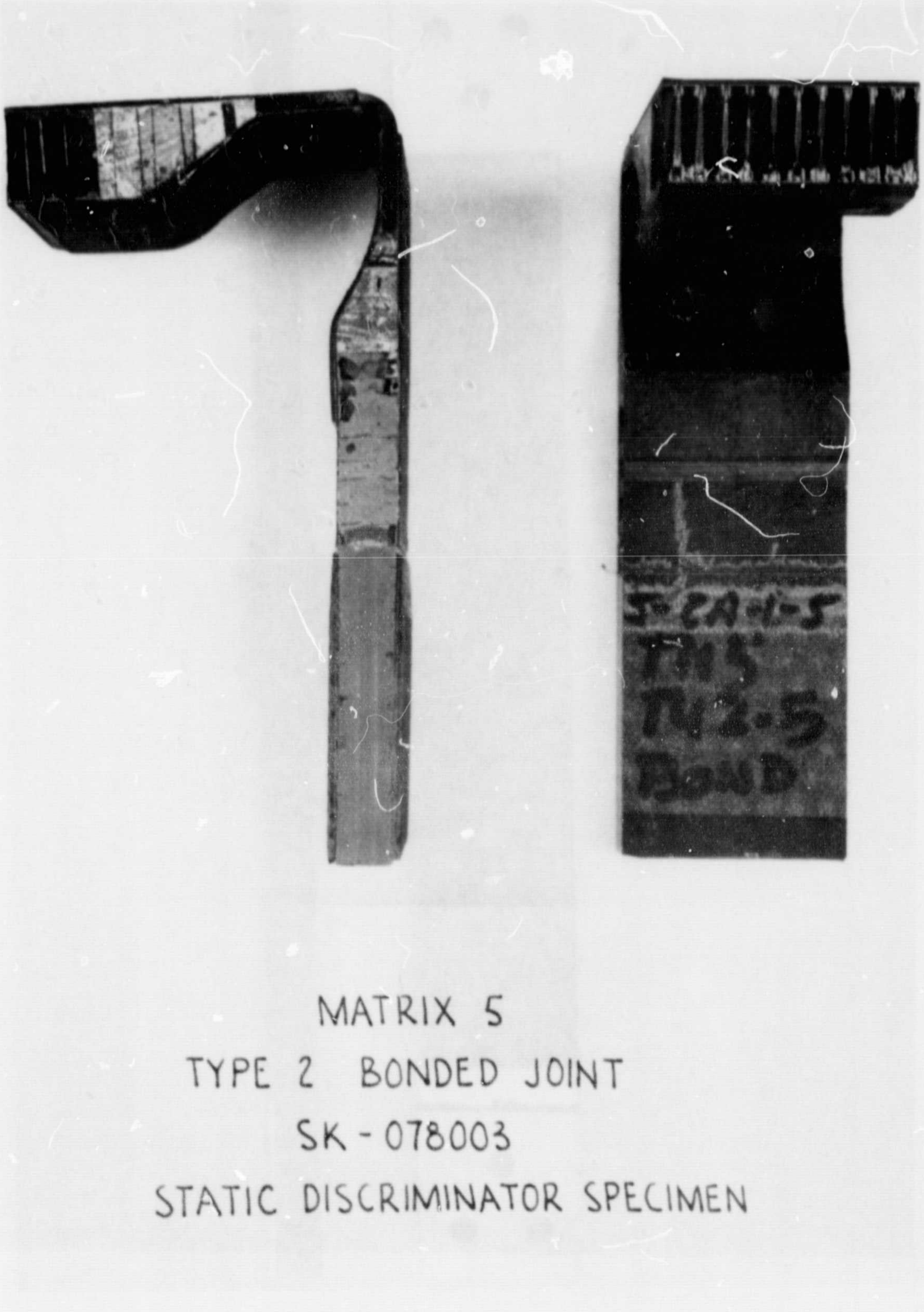


Figure 2-8: Type 2 Bonded Joint

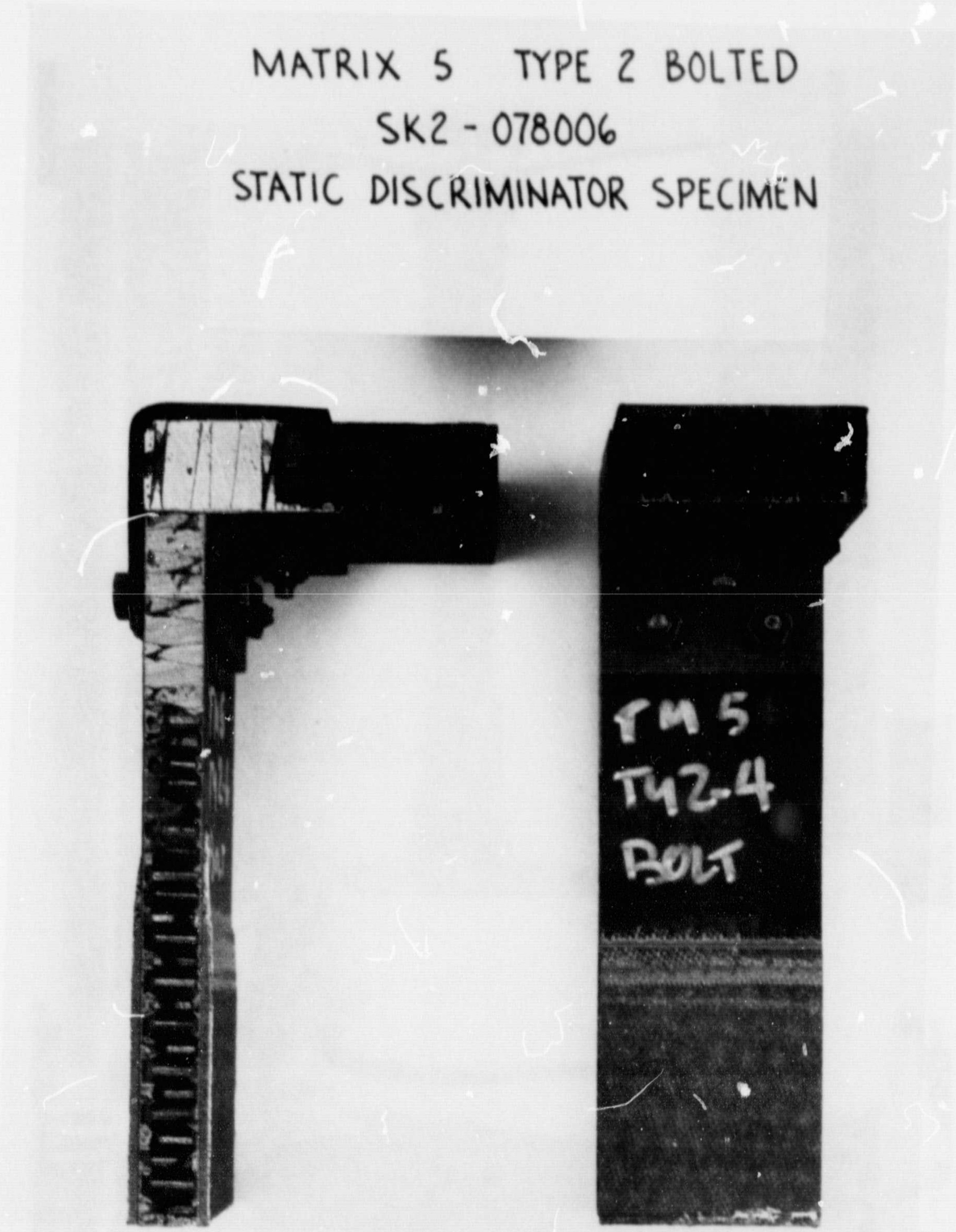


Figure 2-9: Type 2 Bolted Joint

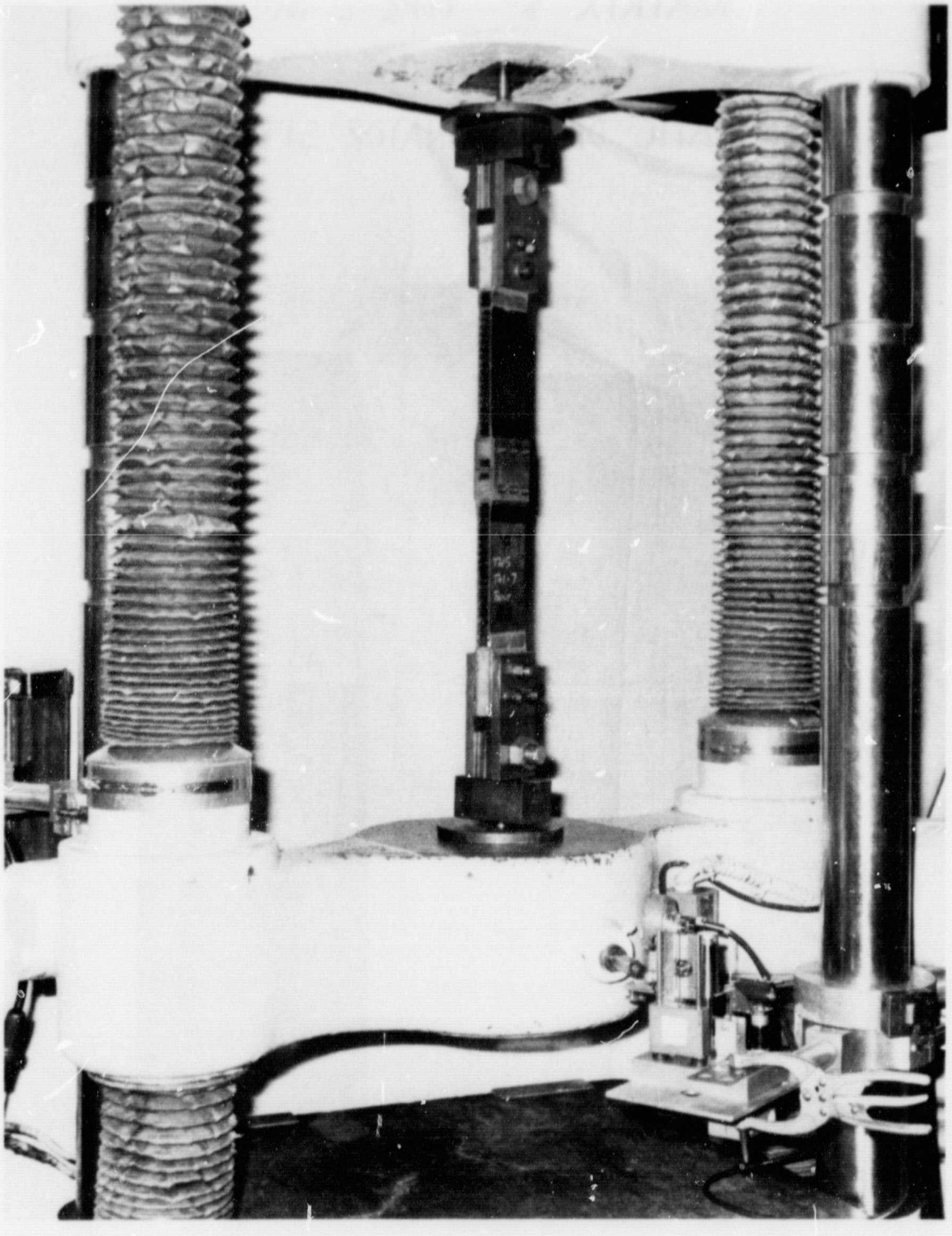
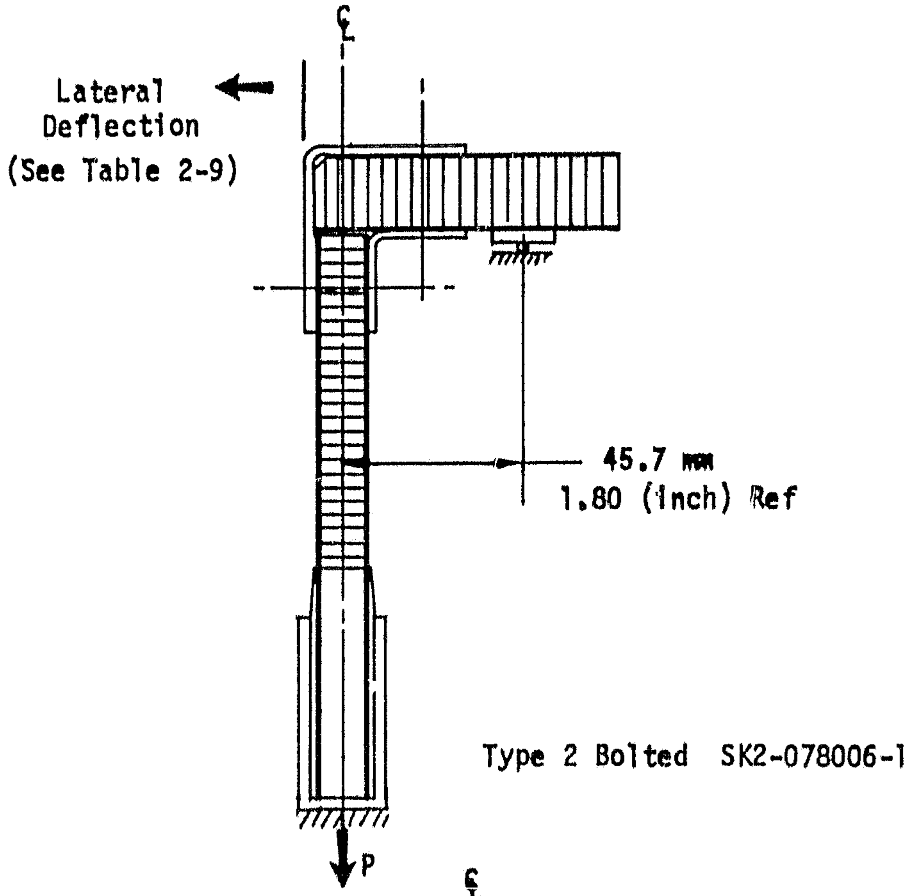


Figure 2-10: Test Setup Type 1 Joints



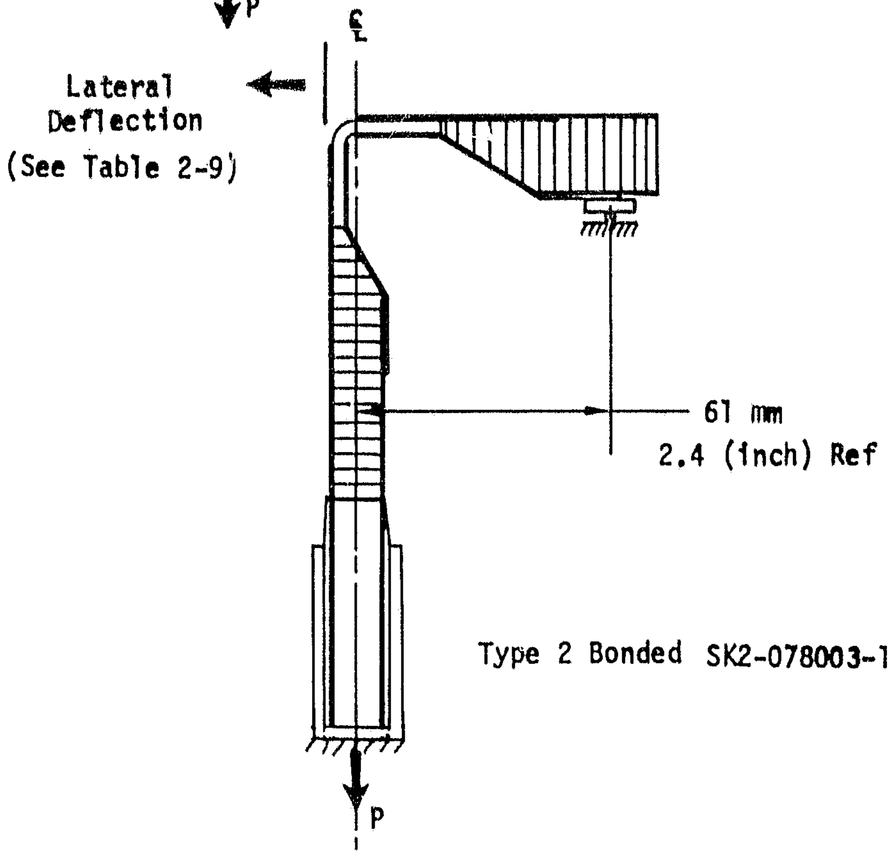


Figure 2-11: Matrix 5 - Test Load Schematic Type 2 Bonded & Bolted Joints

Table 2-8 Matrix 5-- Static Discriminator Tests, Type 1 Bonded and Bolted Joints, Cured/Post Cured

SPECIMEN NUMBER	JOINT TYPE	TEMPERATURE K (°F)	ULTIMATE LOAD ▷1 kN (lb)	FAILURE MODE
5-1A-1-4	(Type 1 Bonded) SK2-078001	294 (70)	34.3 (7700)	Doubler Shear
5-1A-1-6		294 (70)	34.9 (7840)	Doubler Shear
5-1A-1-7		294 (70)	32.6 (7340)	Doubler Shear
5-1A-1-1	(Type 1 Bonded) SK2-078001	561 (550)	30.8 (6920)	Doubler Shear
5-1A-1-2		561 (550)	27.5 (6180)	Doubler Shear
5-1A-1-3		561 (550)	28.2 (6330)	Doubler Shear
5-1B-1-1	(Type 1 Bolted) SK2-078002	294 (70)	40.0 (9000)	Cover Tension
5-1B-1-2		294 (70)	43.1 (9700)	Cover Tension
5-1B-1-3		294 (70)	33.4 (7500)	Doubler Shear
5-1B-1-5	(Type 1 Bolted) SK2-078002	561 (550)	34.8 (7820)	Doubler Shear
5-1B-1-6		561 (550)	29.8 (6700)	Doubler Shear
5-1B-1-7		561 (550)	34.5 (7760)	Doubler Shear

▷1 Specimen width = 76.2 mm (3.0 inches)

TABLE 2-9: Static Discriminator Tests,
Type 2 Bonded and Bolted

Spec No.	Type	Temp K (°F)	Design Mom. mm-N/mm (in-lb/in)	Failure Mom. mm-N/mm (in-lb/in)	Lateral Defl. mm (inch)
5-2A-1-4	Bonded	294 (70)	285 (64)	467 (105)	2.54 (0.1)
5-2A-1-5	Bonded	294 (70)	285 (64)	427 (96)	2.24 (.088)
5-2A-1-6	Bonded	294 (70)	285 (64)	360 (81)	2.03 (.08)
5-2A-1-1	Bonded	561 (550)	285 (64)	1214 (273)	N.A.
5-2A-1-2	Bonded	561 (550)	285 (64)	343 (77)	N.A.
5-2A-1-3	Bonded	561 (550)	285 (64)	338 (76)	N.A.
5-2B-1-1	Bolted	294 (70)	285 (64)	1286 (289)	N.A.
5-2B-1-2	Bolted	294 (70)	285 (64)	1286 (289)	11.2 (.44)
5-2B-1-3	Bolted	294 (70)	285 (64)	1308 (294)	12.2 (.48)
5-2B-1-4	Bolted	561 (550)	285 (64)	1339 (301)	N.A.
5-2B-1-5	Bolted	561 (550)	285 (64)	1686 (379)	N.A.
5-2B-1-6	Bolted	561 (550)	285 (64)	1334 (300)	N.A.

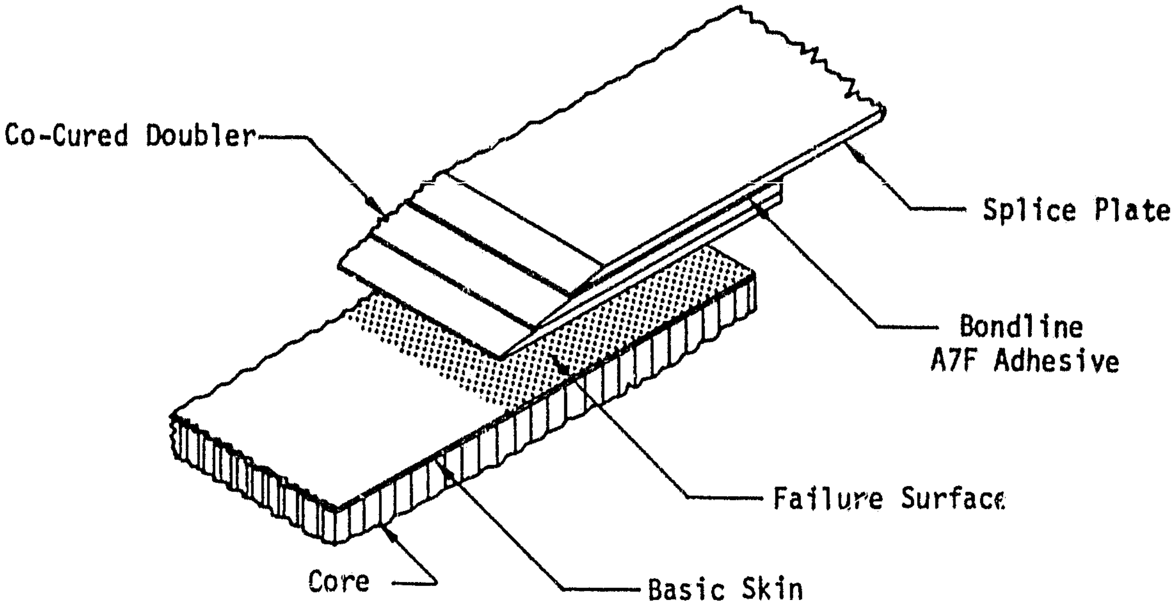


Figure 2-12 Static Discriminator Tests, Type 1 Bonded, Failure Mode

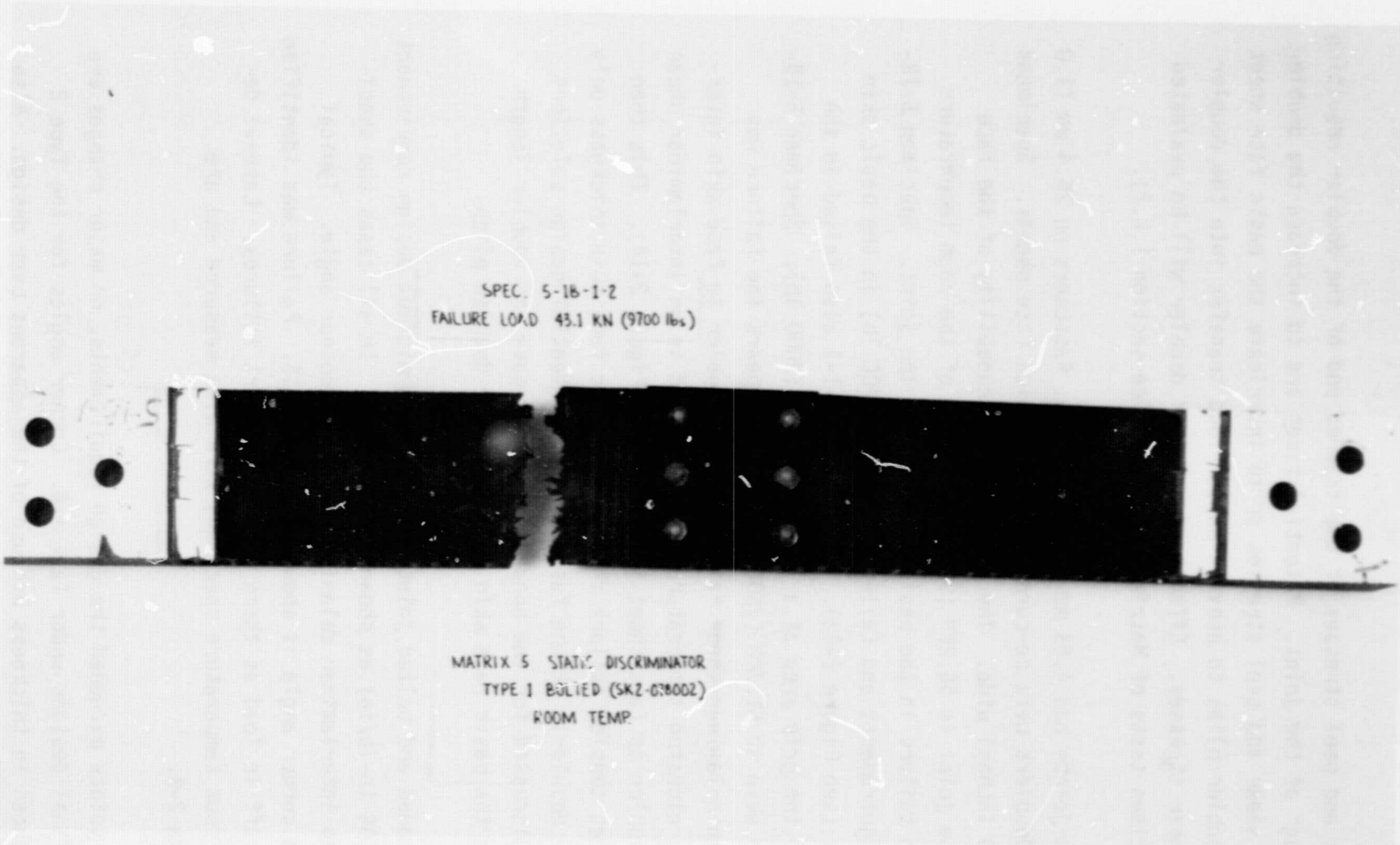


Figure 2-13: Failed Type 1 Bolted Joint

to combined shear and peel stresses at the tapered end of the doubler resulting in an "unzippering" of the joint. Potential fixes are to increase the doubler length to reduce shear and peel stresses or to interleave the basic face sheet plies with the doubler plies to provide better load transfer into the doubler and reduce the shear stresses. Effects of a longer doubler will be evaluated by the small specimen tests of Matrix 4B test 4a (See section 1.2.2).

The Type 1 bolted joints had 4.83 mm (.19 inch) dia. fasteners on 25.4 mm (1.0 inch) spacing. Doublers were co-cured on the sandwich face sheets. Specimens were 76.2 mm (3.0 inches) wide. The ultimate load capability of the face sheets outside the joint is 66.2KN (9600 lbs). Two of the room temperature tests resulted in failure in the basic skin outside the joint. Specimen 5-1B-1-2 met design requirements and failed at 66.9KN (9700 lb) in the basic skin outside the joint (see Figure 2-13). Specimen 5-1B-1-1 also failed in the basic skin but in the grip area at a load of 62.1KN (9000 lb). Specimen 5-1B-1-3 failed in the skin at 51.7KN (7500 lb) but it appears the failure was initiated by an interlaminar shear failure at the doubler to face skin interface. All of the elevated temperature tests resulted in an interlaminar shear failure at the doubler to face sheet interface (See Figure 2-14). This then propagated to a net tension failure through the basic face skin thickness only (not the complete doubler), at the fastener row. Potential design solutions are the same as discussed for the bonded joint; increase the doubler length and/or interleave the basic face skin plies with the doubler plies.

All the Type 2 bonded and bolted joints exceeded the minimum design requirement of 285 mm-N/min (64 in-lb/in) as shown in Table 2-9. In all cases the specimens failed due to interlaminar delamination of the corner angle. Typical delamination of a corner angle is shown in Figure 2-15. Failure was identified by a sudden drop-off in load as there were no two part failures. Lateral deflections of the room temperature specimens were also measured and are presented in Table 2-9.

Since the Type 2 joints exceeded the design requirements, no major changes are planned for the final designs under Task 1.4. Corner angles for the Type 2 bolted may be reduced in thickness because of the apparent over design. Also, examination of the Type 2 bonded joints indicates that the skin doublers in the bonded area may not be required.

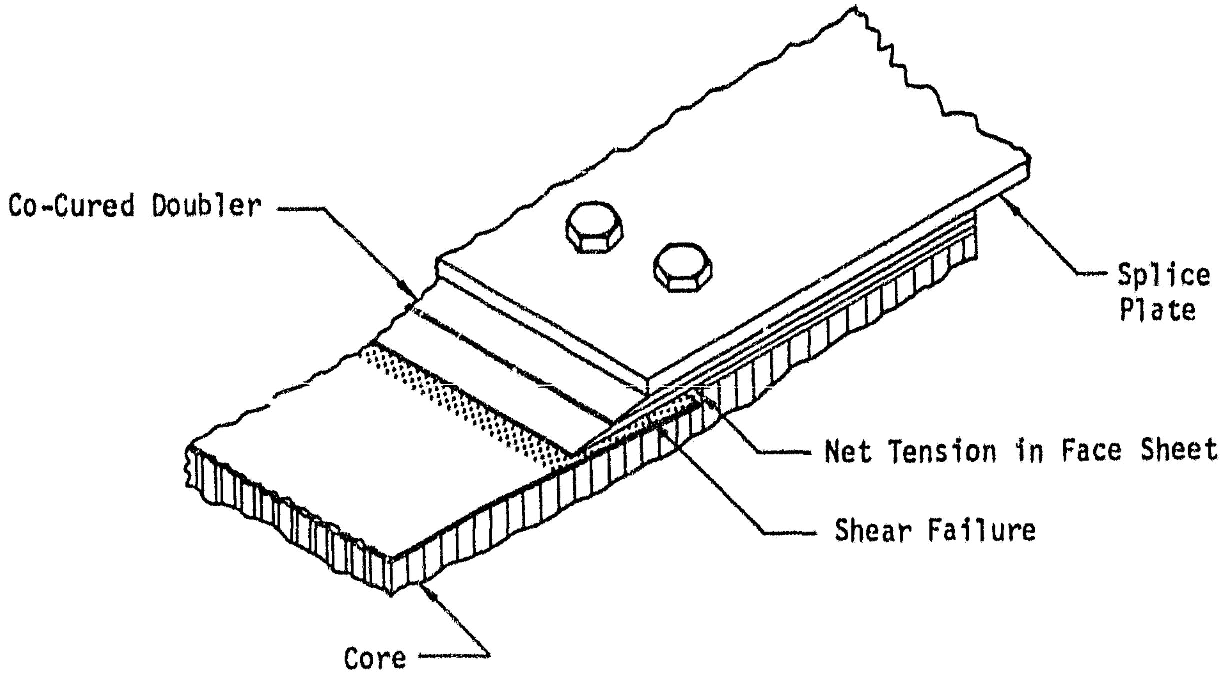


Figure 2-14 Static Discriminator Tests, Type 1 Bolted, Failure Mode

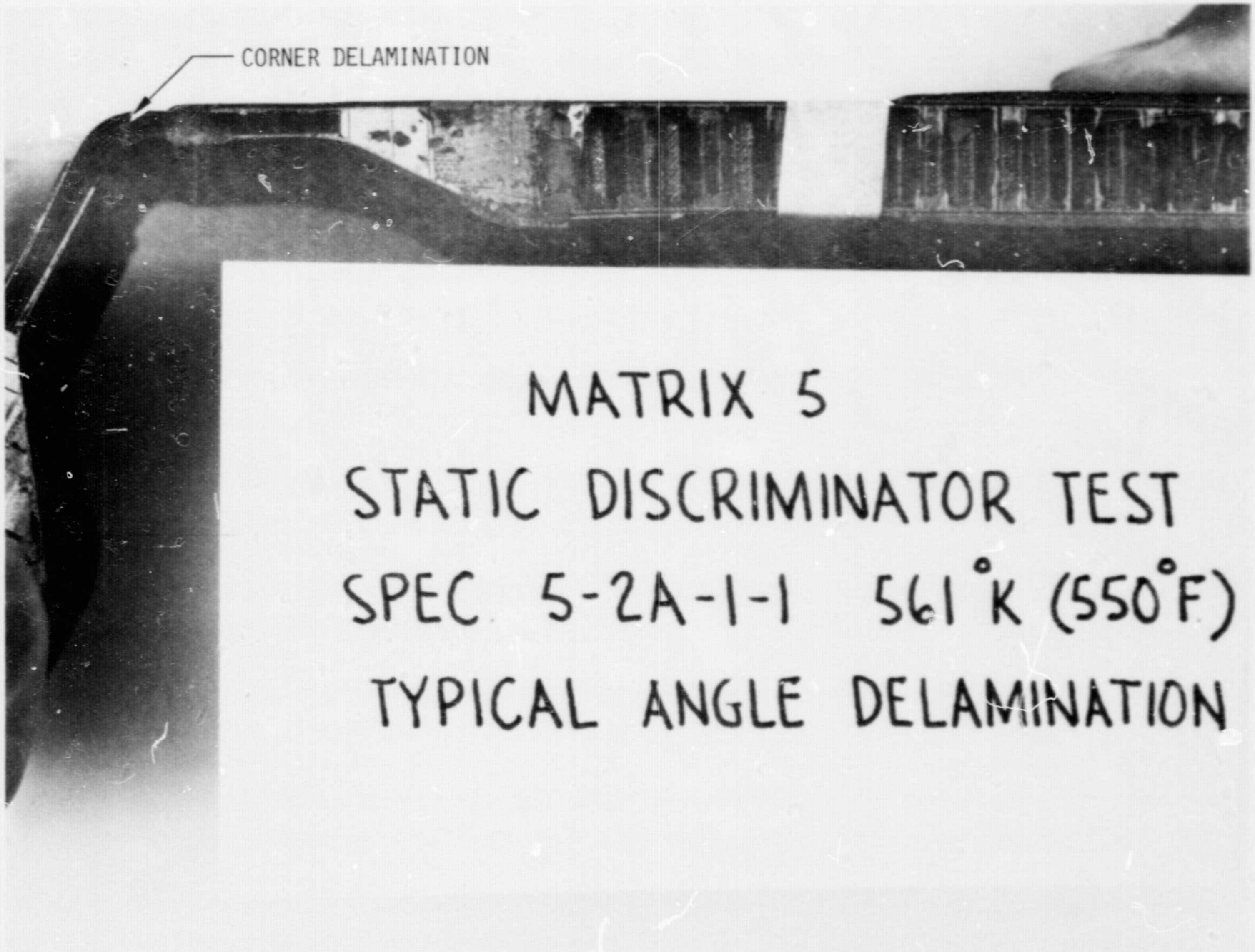


Figure 2-15: Corner Angle Delamination, Type 2 Bonded Joint

SECTION 3.0
CONCLUDING REMARKS

During this reporting period the principal program activities dealt with design allowables and small specimen testing and starting of Matrix 5 static discriminator tests.

Overall results to date have shown that failure of the bonded joints is governed by the interlaminar shear and transverse tension strengths of the Celion 3000/PMR-15 laminates. In virtually every case there has been an interlaminar failure, with only a few exceptions of combination cohesive and laminate failures at elevated temperature.

The bonded joint efficiencies increase at elevated temperatures. This is partially attributed to a decrease in the thermal stresses. In addition, at elevated temperature, there is a decrease in the shear modulus of the resin and adhesive (see References 7 and 8). This results in a reduction in the severity of stress concentrations and a corresponding increase in joint strength.

Bolted joints behaved as predicted based on the small specimen test results. No failure occurred in the bolted joint designs in the bolt load transfer area (except when preceded by a shear failure of the doubler).

The Type 2 corner joints have been demonstrated to carry the required design load; however, there is a large difference in joint flexibility between the bonded and bolted concepts. If low joint flexibility is a design constraint, other design selections must be found for the Type 2 bonded configuration. Delamination in the corner of the Type 2 attachment angles was not expected. Failure was caused by transverse tension and must be accounted for when considering fatigue loading.

Test results have also shown that a bonded web attachment that puts the bonded joint in pure tension will carry the required design load under static condition. It is generally considered poor design practice, however, to have a bonded joint in pure tension. In actual practice a fastener would be required, particularly when considering fatigue.

Results of testing discussed in this report have led to the following conclusions:

- The CTE of A7F adhesive decreases due to aging at 589K (600°F).

- Rapid heating of moisture saturated Celion 3000/PMR-15 laminates to 561K (550°F) can result in blistering and delamination with a corresponding reduction in tension strength and modulus. Moisture has no effect on room temperature properties.

- The co-cured doublers on the Type 1 bonded and bolted joints must be redesigned to meet the design loads.

- Type 2 bonded and bolted joints are adequate for the design loads.

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