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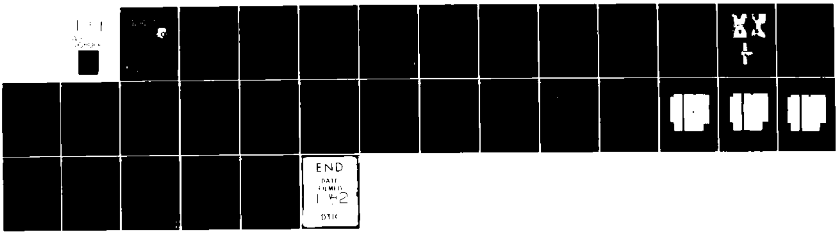

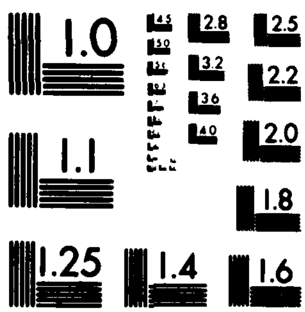
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AFWAL-TR-81-3114

EFFECTS OF BEARING/BYPASS LOAD INTERACTION ON LAMINATE STRENGTH

S.P. Garbo

McDonnell Aircraft Company
McDonnell Douglas Corporation
P.O. Box 516
St. Louis, Missouri 63166

September 1981

Final Report for Period 15 February 1981 - 15 September 1981

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The subject of this program was structural evaluation of mechanically fastened composite joints. Program objectives were threefold: (1) development and verification by test of improved static strength methodology, (2) experimental evaluation of the effects of manufacturing anomalies on joint static strength, and (3) experimental evaluation of joint fatigue life. The results of the original contract were reported in AFWAL-TR-81-3041. An add-on contract effort was performed to further evaluate the effects of bearing/bypass interaction on laminate strength. The results of the add-on contract

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are the subject of this report.

The work performed under the original contract indicated additional studies were needed to further verify bolted composite joint strength methodology. The objective of this add on effort was evaluation of bearing versus bypass load interactions on laminate strength. Three laminates from the family of 0°, ±45°, and 90° ply orientations were tested to failure under a range of tension bypass to bearing load ratios. Predictions of laminate strength were obtained using the Bolted Joint Stress Field Model (BJSFM) described in Volumes 1 and 3 of AFWAL-TR-81-3041. Failure behavior of laminates was documented using ultrasonic C-scan techniques, and failure zones about the fastener hole were correlated with predictions.

Laminate load-deflection and failure characteristics observed in tests were (1) prior to local bearing failure, bypass strength decreases as bearing stress increases, (2) nonlinear or discontinous load deflection behavior is exhibited prior to ultimate failures, (3) initiation of this nonlinear behavior coincides with predicted ply fiber or shear failures and (4) at high bearing stress, local ply damage relieves stress concentrations causing bypass strengths to level off or actually increase.

This report documents test procedures, test data, and theory/test correlations.

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FOREWORD

The work reported herein was performed by the McDonnell Aircraft Company (MCAIR) of the McDonnell Douglas Corporation (MDC), St. Louis, Missouri, under an extension to Air Force Contract F33615-77-C-3140, for the Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. This effort was conducted under Project No. 2401"Structures and Dynamics", Task 240101 "Structural Integrity for Military Aerospace Vehicles", Work Unit 24010110 "Effect of Variances and Manufacturing Tolerances on the Design Strength and Life of Mechanically Fastened Composite Joints". Capt. Robert L. Gallo (AFWAL/FIBEC) was the Air Force Project Engineer. The add-on work described in this report was conducted during the period 15 February 1981 through 15 September 1981.

Program Manager was Mr. Ramon A. Garrett, Branch Chief-Technology, MCAIR Structural Research Department. Principal Investigator was Mr. Samuel P. Garbo, MCAIR Structural Research Department.

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LIST OF ILLUSTRATIONS

1. INTRODUCTION

This report documents the work done on an extension to Air Force Contract F33615-77-C-3140. The results of the original contract effort are reported in Reference 1. The work in this extension was performed to further verify bolted composite joint strength methodology and study failure behavior. The primary objective of this add-on effort was evaluation of the effects of bearing versus bypass stress interactions on laminate strength. Three laminates from the family of 0°, ±45°, and 90° ply orientations (0°/±45°/90°) were tested to failure under a range of tension bypass to bearing stress load ratios. Predictions of laminate strength were obtained using the Bolted Joint Stress Field Model (BJSFM) described in Reference 1.

This report documents test procedures, test data, and theory/test correlations.

II. TEST PROGRAM

The objective of this test program was to provide data on the effects of variations in bearing-to-bypass load ratios on laminate strength. Three laminate variations evaluated under the original contract (Reference 1) were utilized. The test matrix is detailed in Figure 1. All tests were performed at room temperature with as-manufactured test specimens. Specimens were fabricated from AS/3501-6 graphite-epoxy. A total of 53 specimens were tested.

Layups — % Plies of $0^{\circ}/\pm45^{\circ}/90^{\circ}$ Orientation	Bearing Stress Test Conditions - ksi (No. of Specimens Tested at Each Condition)						
	0	30 - 40	60	70	80	90	100
50/40/10	2	4	4	–	4	4	–
30/60/10	1	–	4	–	4	4	4
19/76/5	2	–	4	4	4	4	–
	Total Number of Tests = 53						

GP13-0580-1

Figure 1. Test Matrix

Specimen geometry and laminate stacking sequences are detailed in Figures 2 and 3 respectively. For the load interaction study, a specially designed, hydraulically actuated, scissor mechanism was used to apply bearing loads to fastener holes independently of bypass loads. Details of the scissor mechanism were previously reported in Volume 2 of Reference 1. Test setups are illustrated in Figure 4. The test specimen is shown on the right of this figure inserted into hydraulic end grips. On the left of Figure 4, the scissor mechanism is shown attached to the test specimen. Figure 5 provides a closeup of the specimen attached to the scissor mechanism and furnishes details of the local compliance gages used to document bolt-load versus local specimen deflection between fastener holes.

Specimen loading was accomplished either by (1) applying and maintaining specific bolt-bearing loads and then increasing bypass loads until specimen failure occurred, or (2) by applying a specific bypass load and then increasing bearing loads until failure occurred. In all cases, specimen load-versus-displacement and load-versus-strain response was monitored in the fastener region and in the specimen gross section areas.

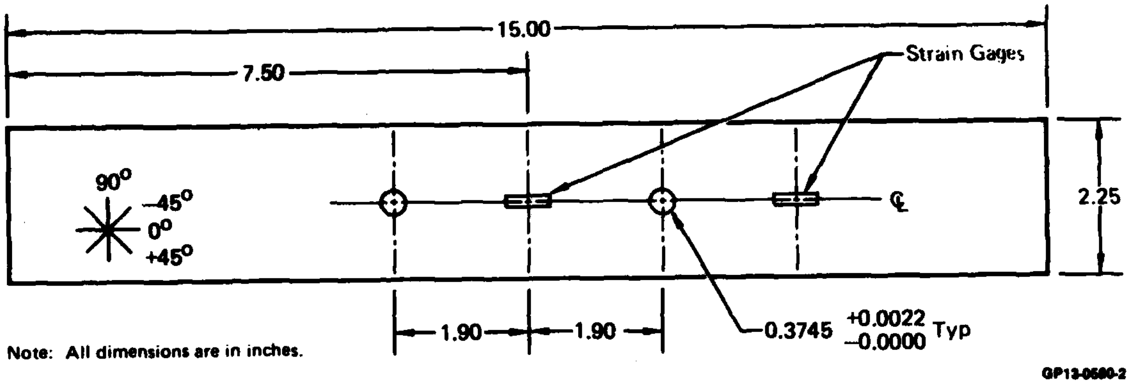

Figure 2. Specimen Geometry

Ply No. (To ℄)	Laminate Stackings		
	50/40/10	30/60/10	19/76/5
1	+45	+45	+45
2	0	0	0
3	−45	−45	−45
4	0	0	0
5	90	+45	+45
6	0	90	−45
7	+45	−45	+45
8	0	0	−45
9	−45	+45	+45
10	0	−45	−45
℄ 11	—	—	90
Total Plies	20	20	21
Nominal Thickness	0.208	0.208	0.2184

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Figure 3. Graphite/Epoxy (AS/3501-6) Laminate Stacking Sequence

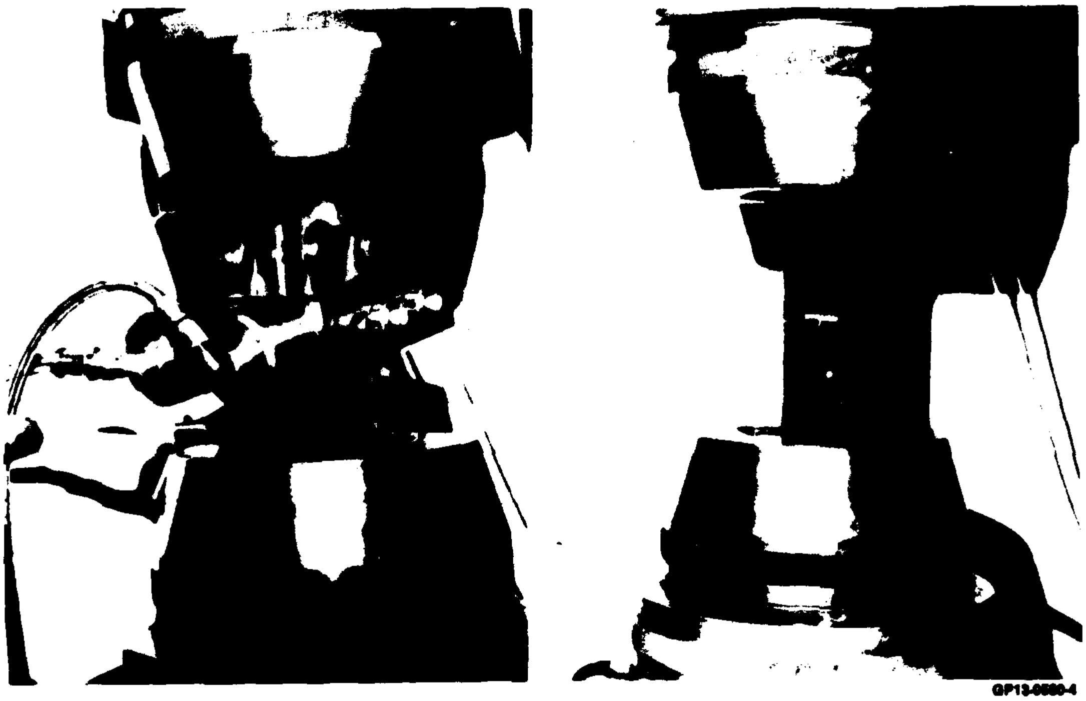

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Figure 4. Bearing/Bypass Test Setup

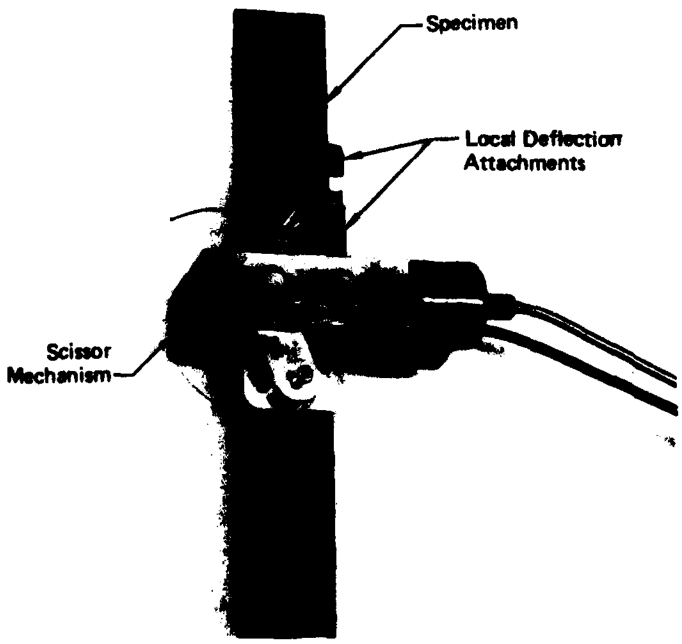

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Figure 5. Scissor Mechanism with Local Deflection Attachments

III. THEORY/TEST CORRELATIONS

Each of the three laminates was analyzed using the BJSFM procedure described in Reference 1. Bearing-versus-bypass strengths were predicted for tests ranging from unloaded hole (no bearing load) to pure bearing (no bypass load). Critical plies and failure locations were identified. The AS/3501-6 graphite-epoxy lamina mechanical properties used in these calculations are listed in Figure 6.

Properties	Room Temperature
Elastic Constants	
• E_1^t (10^6 psi)	18.85
• E_1^c (10^6 psi)	18.20
• E_2 (10^6 psi)	1.90
• G_{12} (10^6 psi)	0.85
• ν_{12}	0.30
Allowables	
• ϵ_1^{tu} (μin./in.)	12,206
• ϵ_1^{cu} (μin./in.)	17,630
• ϵ_2^{tu} (μin./in.)	5,380
• ϵ_2^{cu} (μin./in.)	29,080
• γ_{12} (μin./in.)	20,350
• F_1^{tu} (ksi)	230
• F_1^{cu} (ksi)	321
• F_2^{tu} (ksi)	9.5
• F_2^{cu} (ksi)	38.9
• F_{12} (ksi)	17.3

GP13-0580-6

Figure 6. AS/3501-6 Graphite-Epoxy Lamina Mechanical Properties

Selection of bearing-versus-bypass load interaction ratios for test conditions was based on predicted failure loads, critical plies, and failure location (θ_{cr}). Two types of failure were predicted for each laminate; fiber-critical 0° plies in the net-section region of the fastener hole, and shear-critical 0°, 90° or ±45° plies in the bearing region of the fastener hole. Initial tests were performed at bearing stress levels of 0.0 and 60.0 KSI for all laminates to verify the predicted net-section type of failure. Remaining tests were performed at higher bearing stress levels, 70-100 KSI, to provide data for verification of the second predicted failure mode involving local failures due to shear critical plies in the bearing region. Testing performed at these higher bearing stress levels also permitted verification of the predicted occurrence of combined bearing region and net-section failures if certain loading sequences were used.

Predicted strengths for each laminate are correlated with test data in Figures 7, 8 and 9. Predictions made using the BJSFM procedure were based on the maximum strain and Tsai-Hill failure criteria. These criteria were applied at a characteristic distance (R_c), .02 inch, away from the hole boundary.

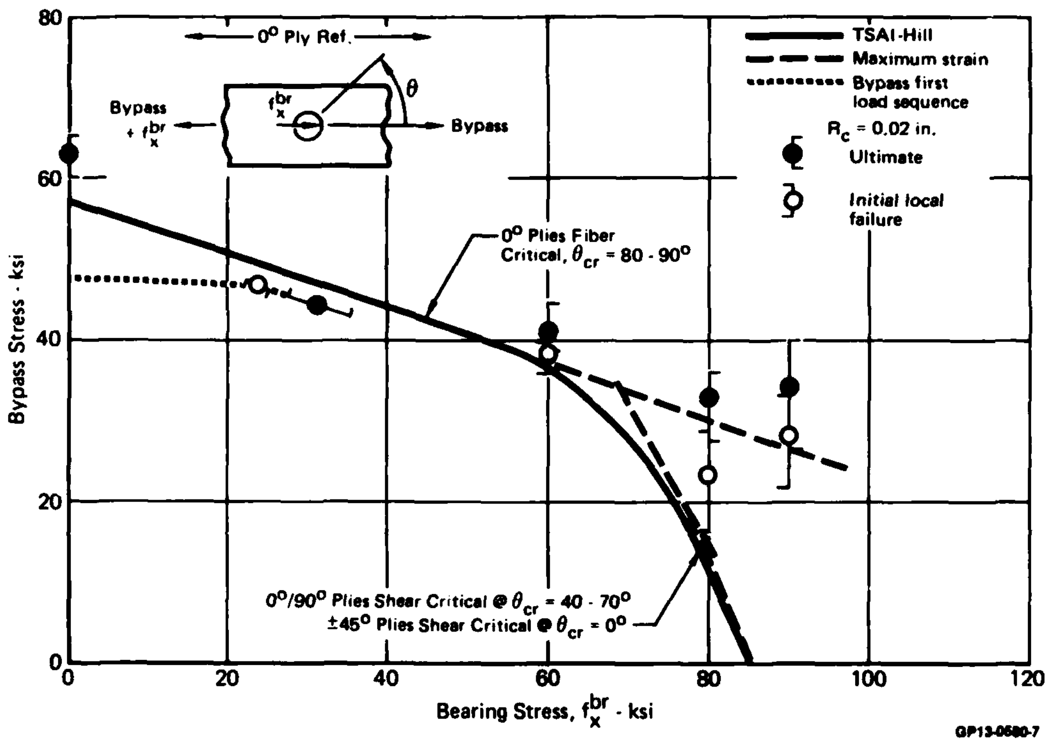


Figure 7. Theory/Test Correlations for 50/40/10 Layup

For the 50/40/10 laminate, representative bypass load versus overall specimen deflection data is presented in Figure 10. Each curve was obtained after bearing loads were applied to the specimens. Initial failure loads were defined to have occurred at the onset of discontinuous or significant load-deflection behavior; ultimate failure loads were defined to have occurred at the highest load attained. Solid and open symbols used in Figure 10 indicate the ultimate and initial failure load levels which were used in Figure 7 to show correlation of theory with test data. Square symbols on the graphs represent predicted net-section failure of the 0° plies due to fiber rupture. As predicted, data indicated that laminate bypass strength decreased as bearing stresses increased and that net-section failures occur.

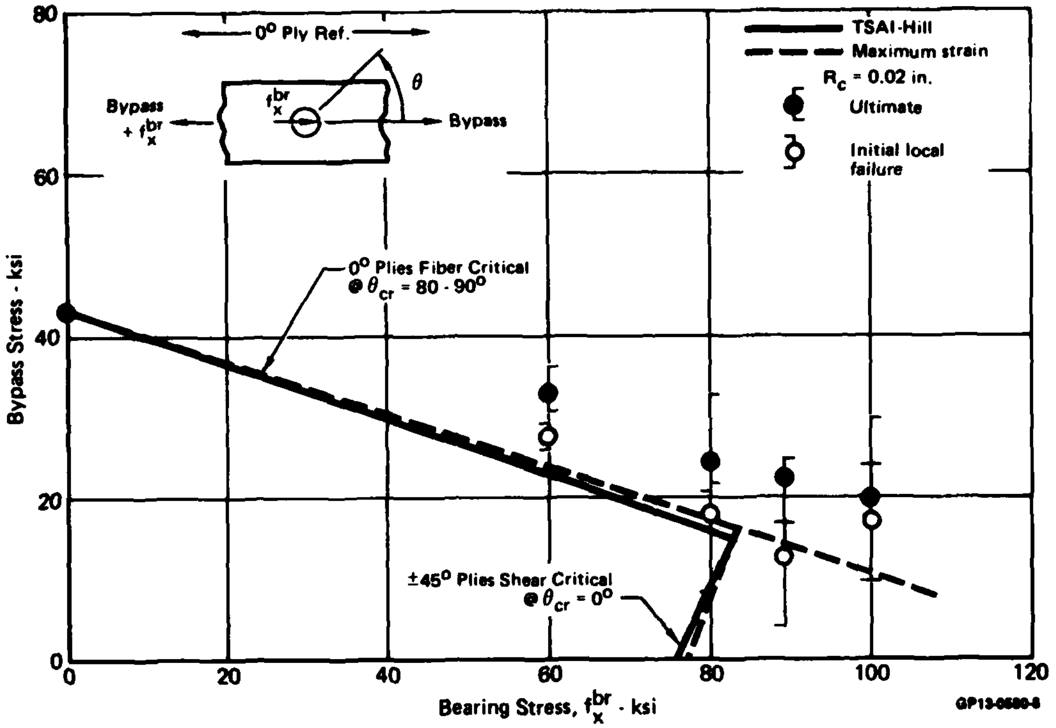


Figure 8. Theory/Test Correlation for 30/60/10 Layup

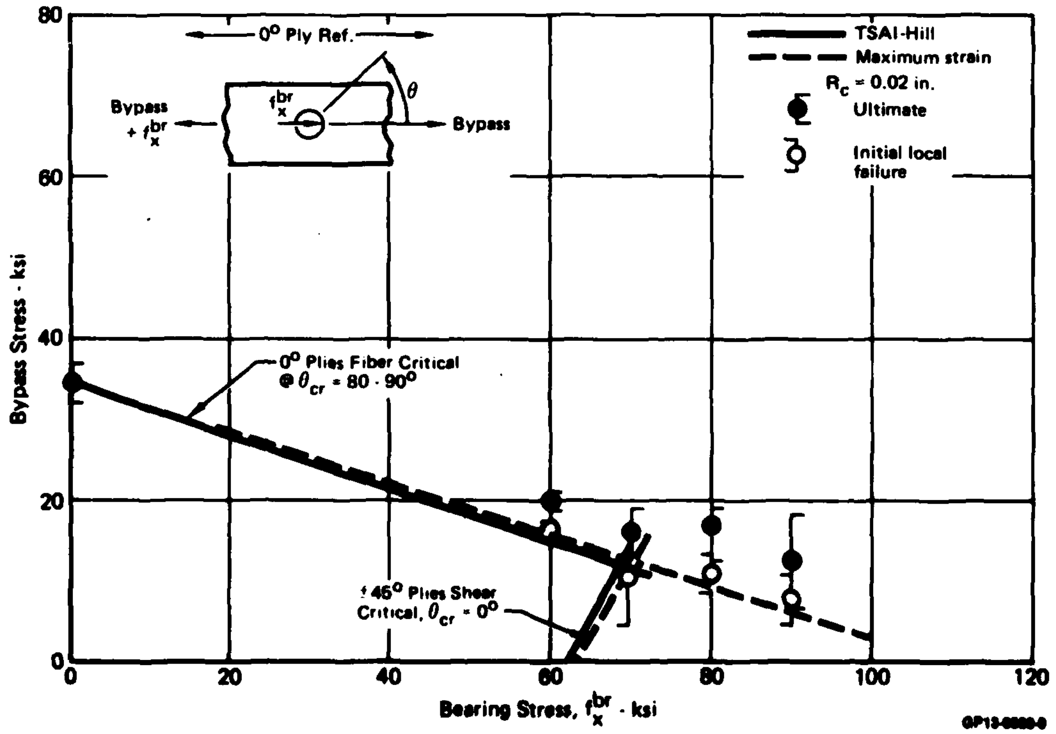


Figure 9. Theory/Test Correlation for 19/76/5 Layup

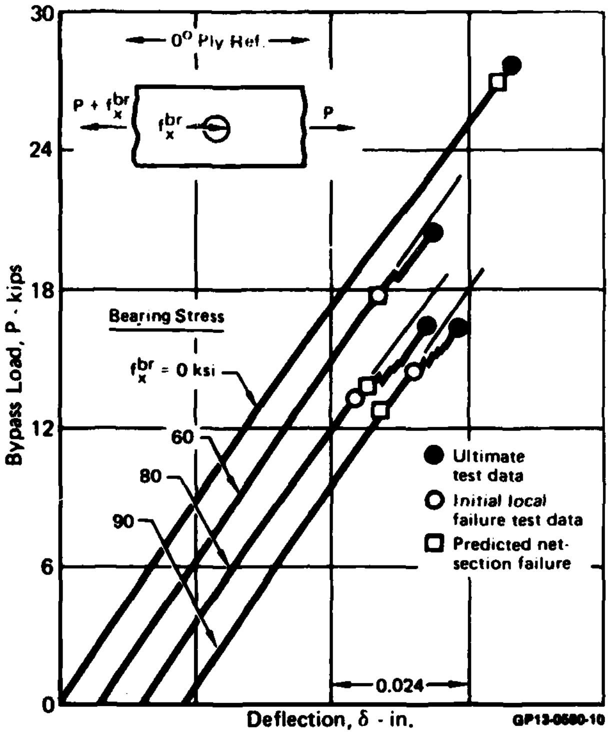


Figure 10. Representative Load-Deflection Data for 50/40/10 Layup

For the bearing stresses above 85 KSI, it was predicted that application of pure bearing alone would exceed the shear capability of the $\pm 45°$ plies (reference Figure 7) and thus result in a local bearing failure of the laminate. Subsequent application of bypass loads in conjunction with the maintained bearing loads would then result in additional net-section failures. These predictions were verified by load-deflection data similar to that in Figure 10, and by a sequence of C-scans taken of the same specimen after each load application, as illustrated in Figure 11.

To obtain the C-scans in Figure 11, the specimen was loaded in pure bearing to 80 KSI stress levels and then removed from the test apparatus for ultrasonic inspection. The specimen was again loaded in pure bearing to 90 KSI and the inspection repeated. Finally, the specimen was loaded in pure bearing to 90 KSI and then bypass load was applied until initial failures were indicated on the bypass load-deflection curves. A final ultrasonic inspection was performed. The same inspection procedure was used for all specimens except bearing and bypass load levels were varied.

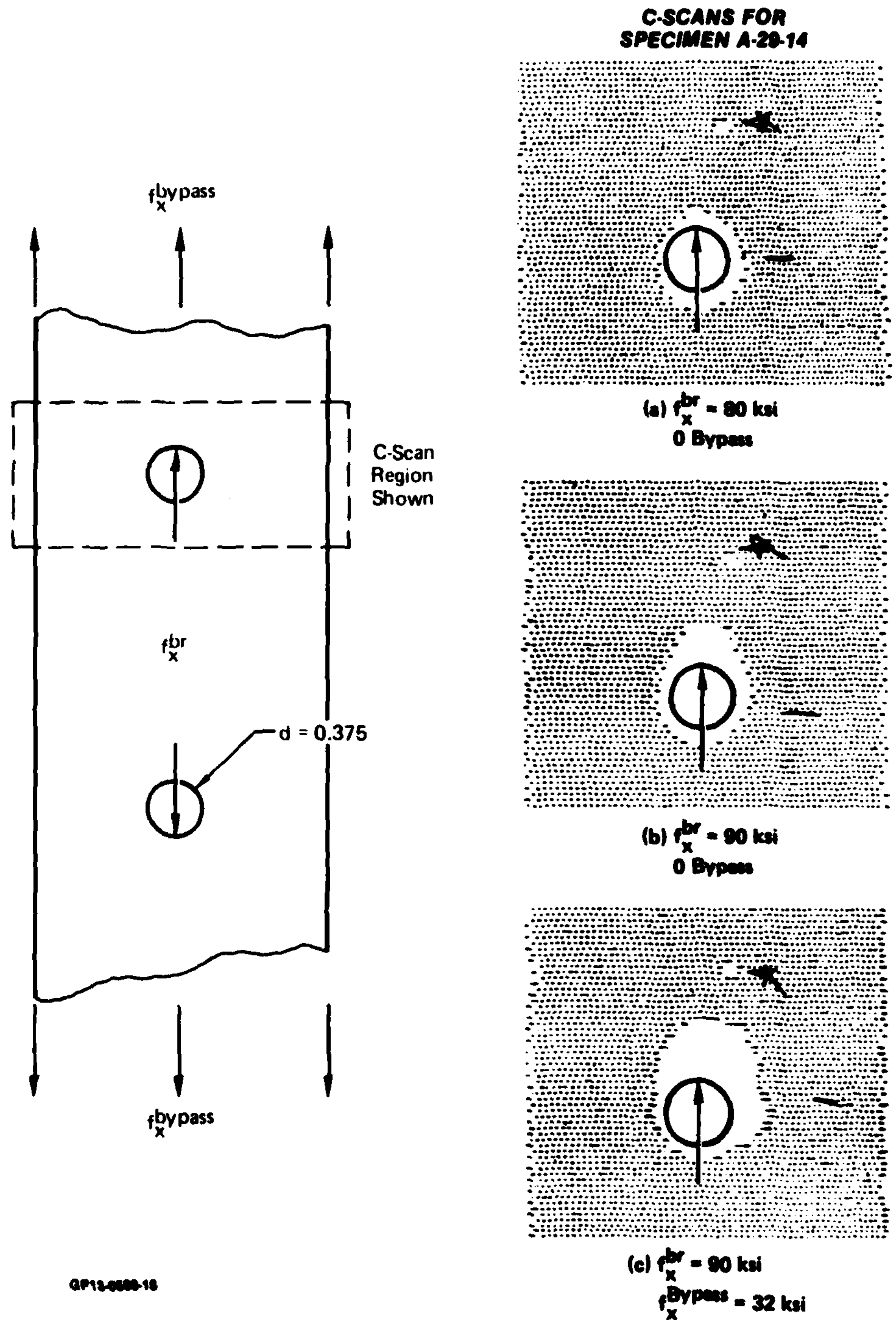


Figure 11. C-Scans of Same Specimen After Different Bearing-to-Bypass Loadings 50/40/10 Layup

Using load-deflection data and C-scans permitted verification of predicted strengths, failure location, and failure interactions. Initial discontinuous or non-linear load-deflection behavior correlated with the predicted bypass strengths of Figure 7. C-scans and local (Figure 5) load-deflection data verified the predicted pure bearing strengths.

The ability to predict load-dependent failure sequences, using the BJSFM ply-by-ply failure analysis, was also verified. Figures 11(a) and 11(b) indicate a significant local bearing failure has occurred between 80-90 KSI under pure bearing load conditions. Figure 11(c) indicates additional net-section damage occurs when bypass loads are applied in conjunction with these high bearing loads. This sequence of failures was predicted (Figure 7). Similar conclusions were reached for the 30/60/10 and 19/76/5 layups. Representative bypass load-deflection data and C-scans for these respective layups are presented in Figures 12 and 13, and Figures 14 and 15.

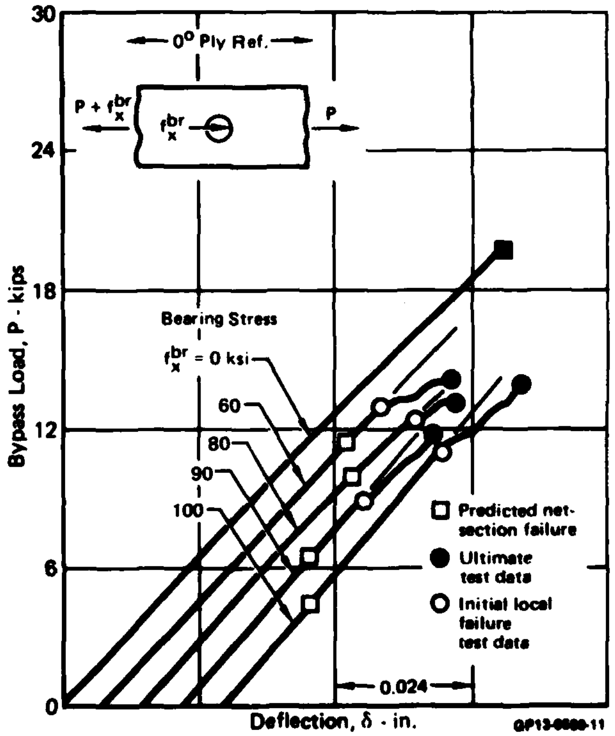


Figure 12. Representative Load-Deflection Data for 30/60/10 Layup

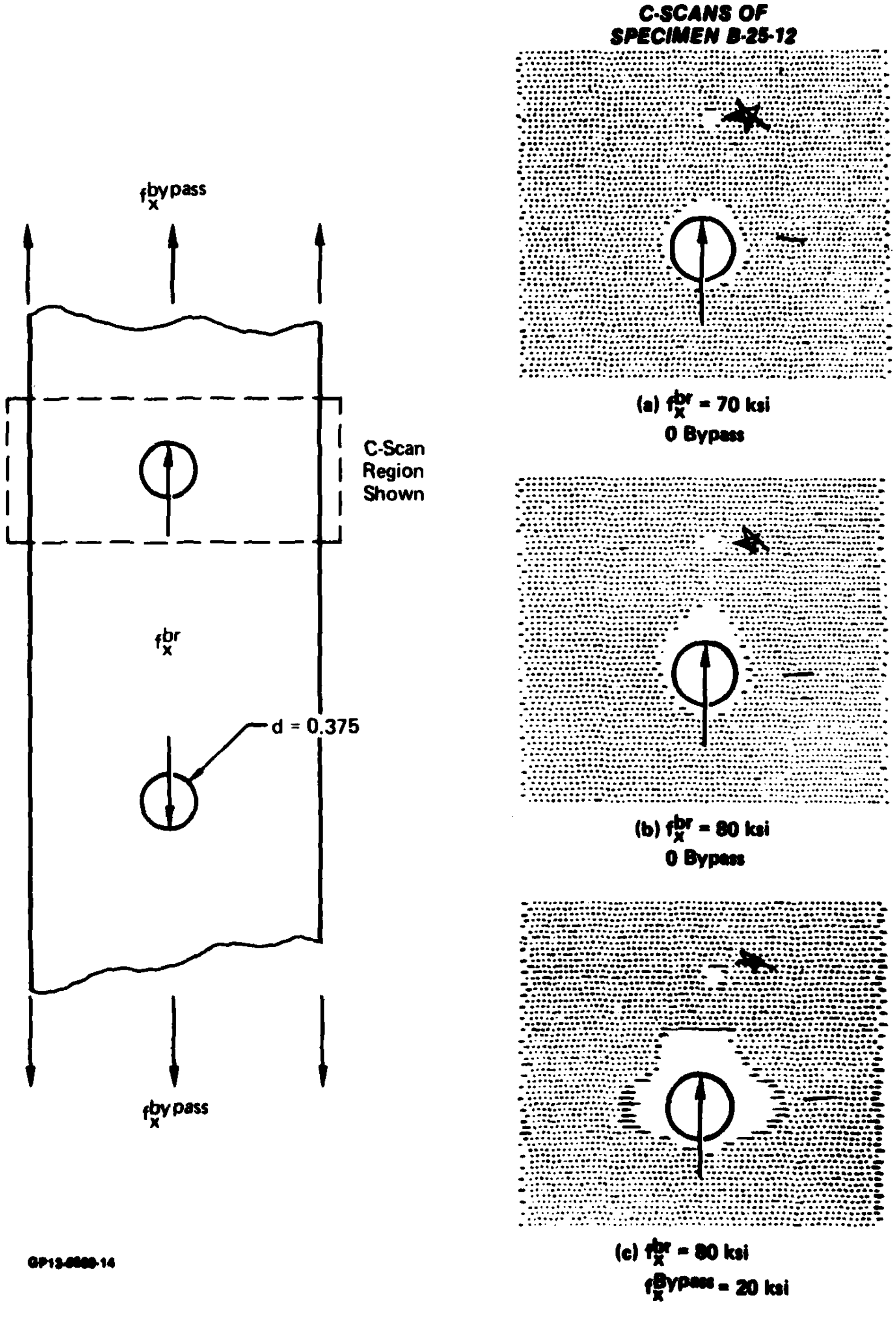


Figure 13. C-Scans of Same Specimen after Different Bearing-to-Bypass Loadings 30/60/10 Layup

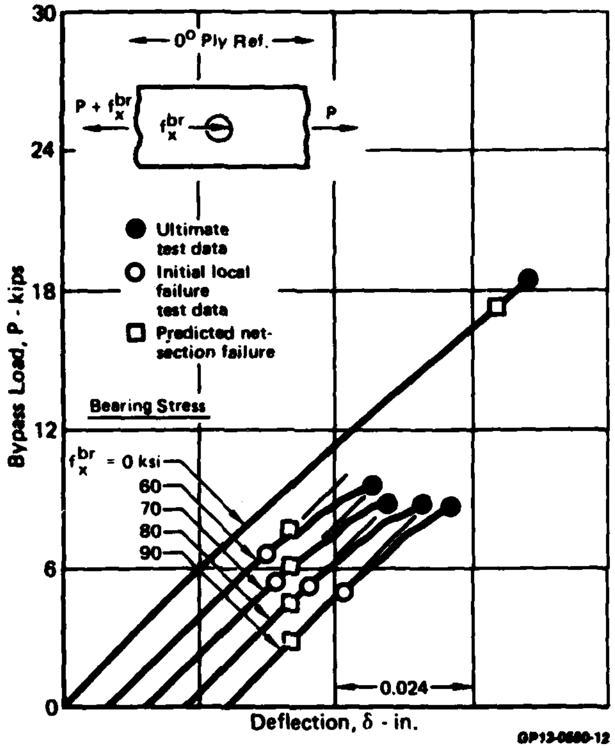


Figure 14. Representative Load-Deflection Data for 19/76/5 Layup

To permit a clearer example of the insight gained by using the BJSFM ply-by-ply failure analysis, the 50/40/10 laminate analysis was used to create contour plots of constant strain levels for critical plies at predicted failure loads. These contour plots are shown in Figure 16 with a C-scan of a specimen tested to the analyzed pure bearing load. Numbers next to contours indicate constant strain levels normalized to tenths of unnotched ply allowables. The C-scan indicates local failure in front of the bearing face of the bolt, and correlates with the predicted shear failure area of 0°, 90° and ±45° plies.

For the same specimen, bypass loads were now added to the high bearing load and a second C-scan made. For this combined bearing-bypass load condition, analysis was performed and constant strain contour plots of critical plies were again drawn. The C-scan and contour plots for this combined bearing plus bypass load condition are shown in Figure 17. The prediction of new failures in the net-section region because of fiber failure of 0° plies correlates with the C-scan indications.

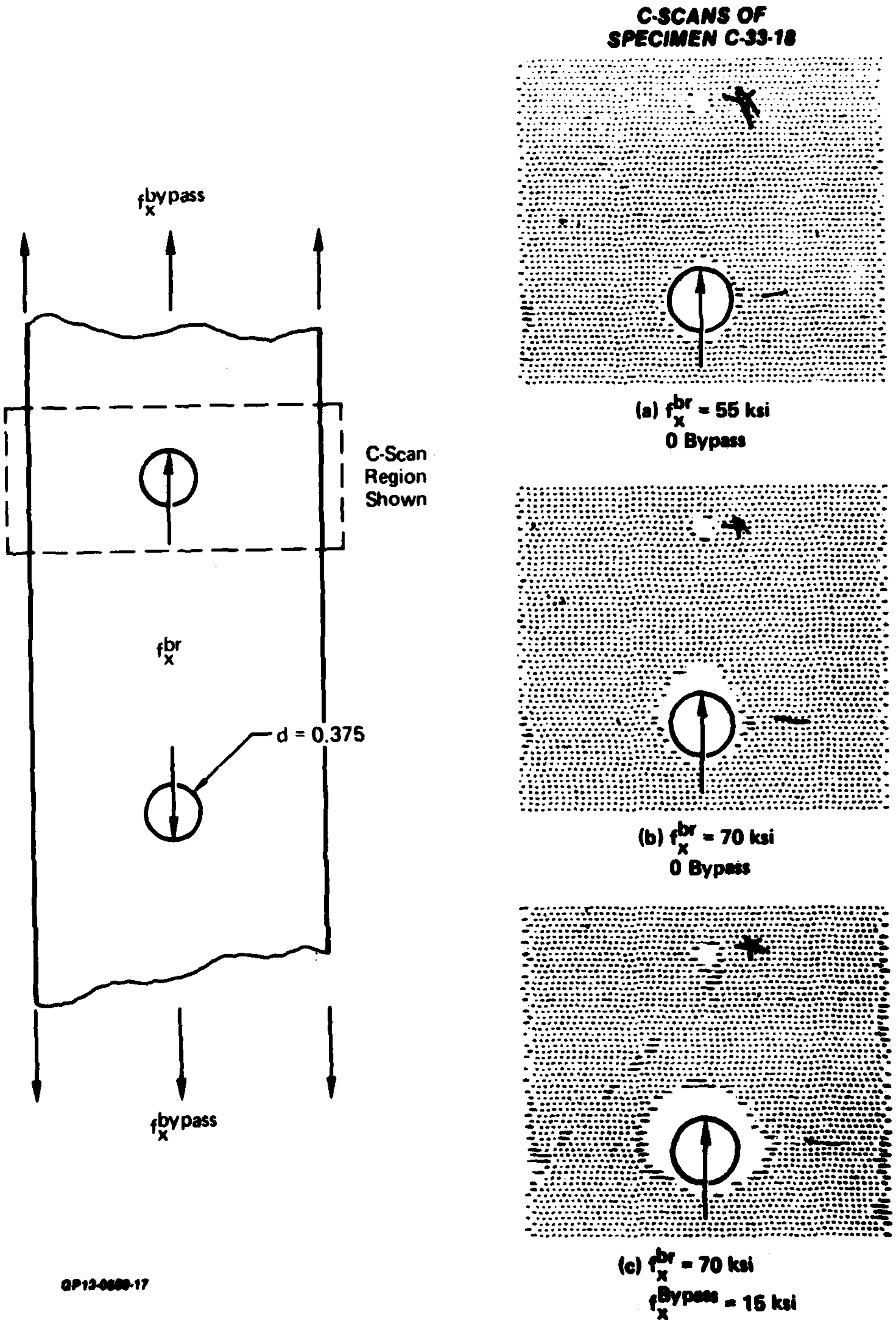


Figure 15. C-Scans of Same Specimen after Different Bearing-to-Bypass Loadings 19/76/5 Layup

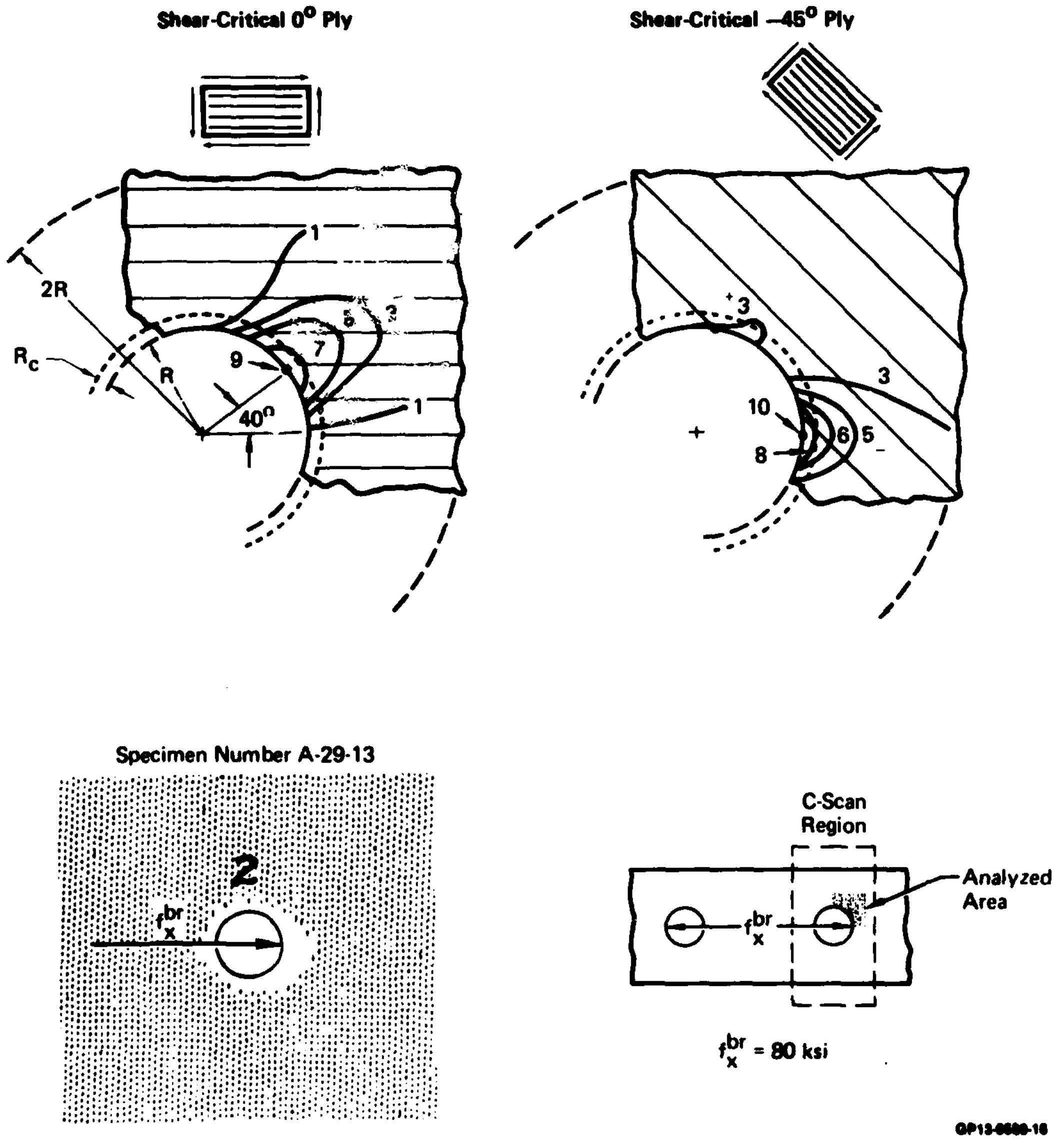


Figure 16. C-Scan Correlates with Predicted Pure Bearing Ply Failures

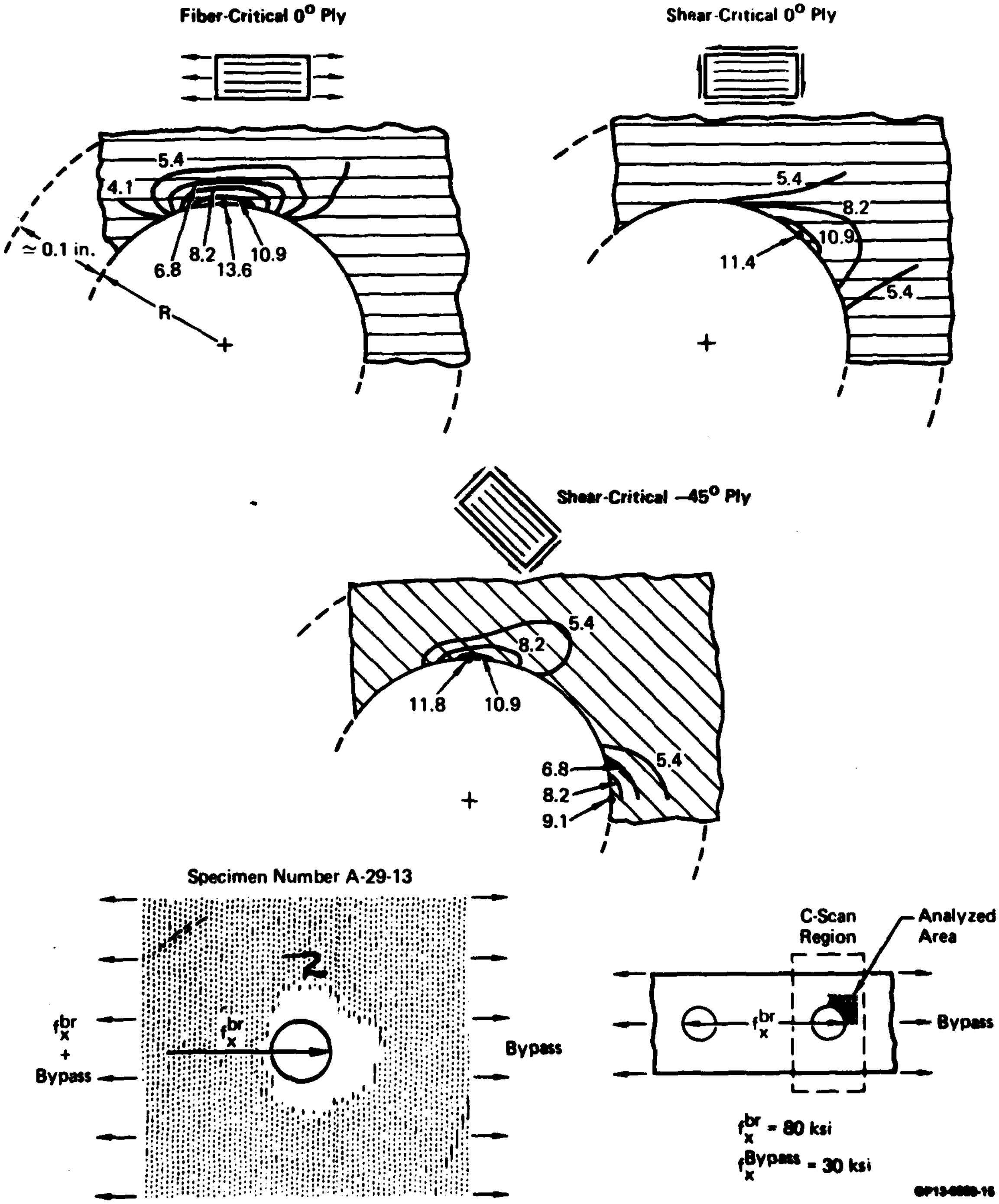
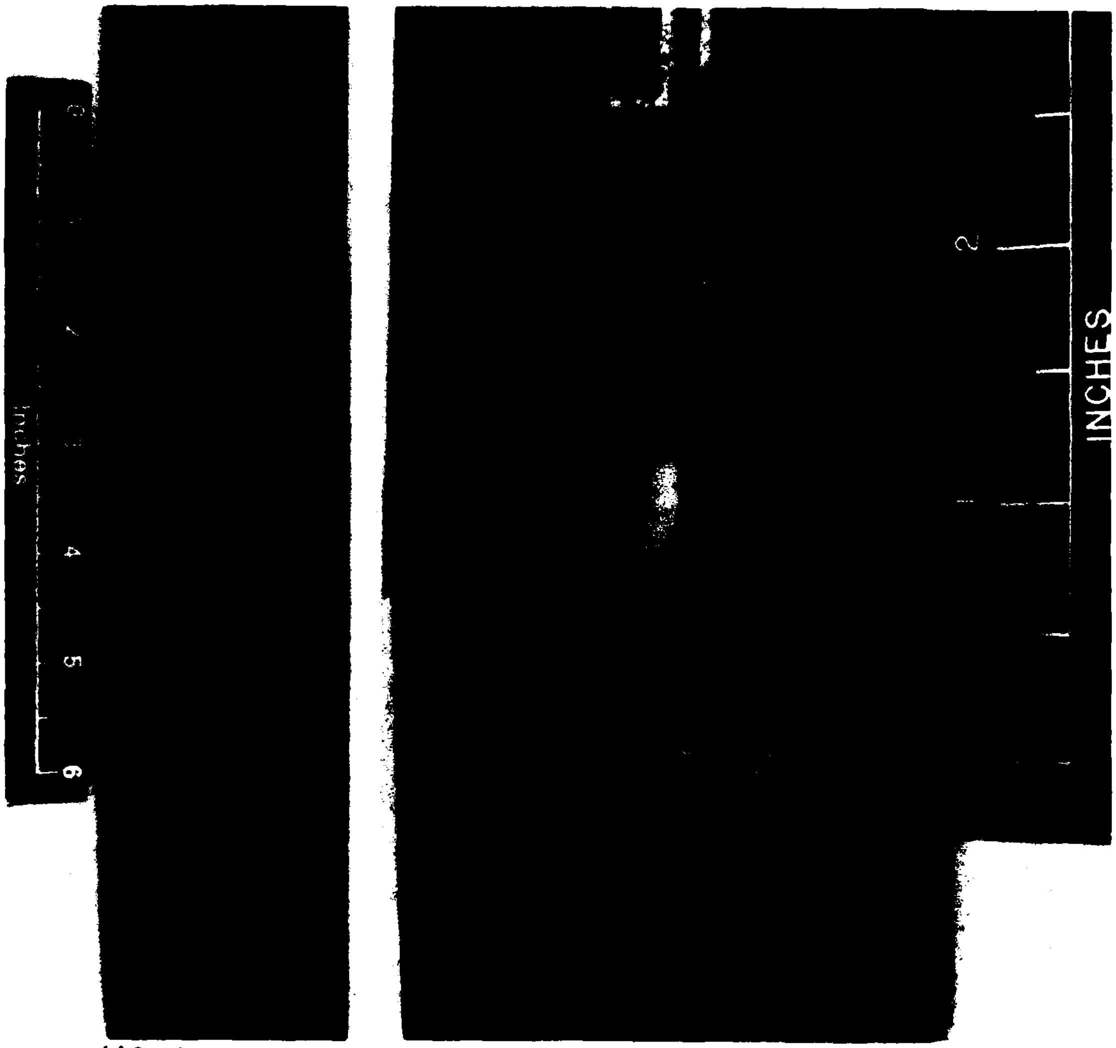


Figure 17. C-Scan Correlates with Predicted Bearing and Net Section Ply Failures

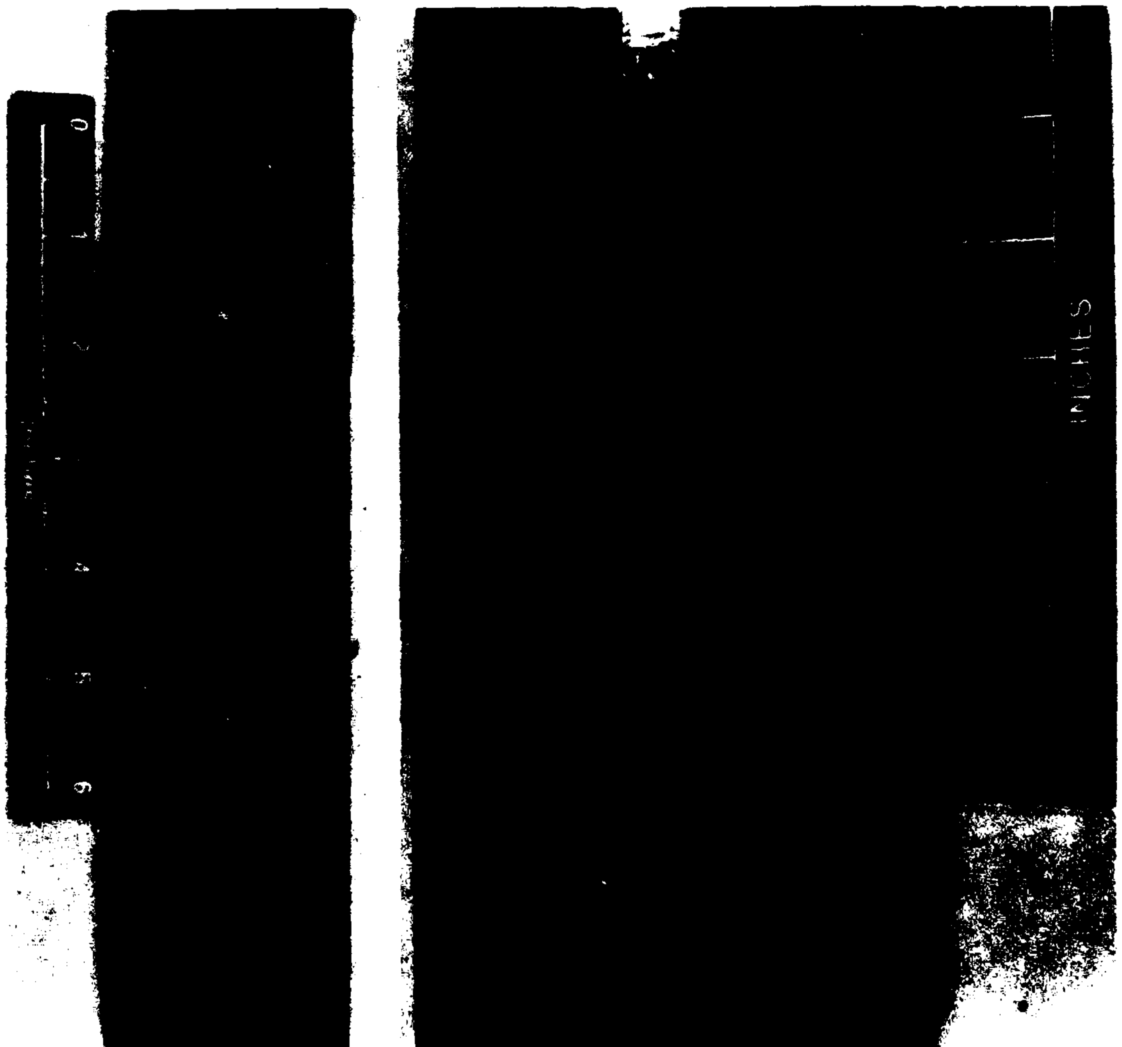
Further review of C-scan data tends to explain specimen load carrying capability after initiation of pure bearing failures. Below initiation of pure bearing failure, data (and theory) indicate that bypass strength decreases as bearing stress levels increase. However, it can be observed from Figures 7, 8, and 9 that ultimate bypass strength does not continue to decrease with ever increasing bearing stress levels; bypass strengths actually increased at the highest bearing stress levels tested. A correlation of C-scans with the predicted contour plots of failure locations offers a possible explanation of this phenomenon. Because bearing failures are localized and result in ply damage in front of the bolt bearing surface, the effective geometry of the fastener hole becomes elliptical in shape with the major axis forming parallel to bypass load directions. Ellipses of this orientation are less of a stress concentration than circular holes, and in conjunction with a softened laminate stiffness in the damaged area leads to higher bypass strength capability. For example, in infinite isotropic plates, circular holes result in a stress concentration of 3.0 under uniaxial loading, while for an elliptical hole this stress concentration is reduced by the ratio of its minor axis to its major axis.

Pictures of failed specimens for all three laminates are shown in Figure 18.



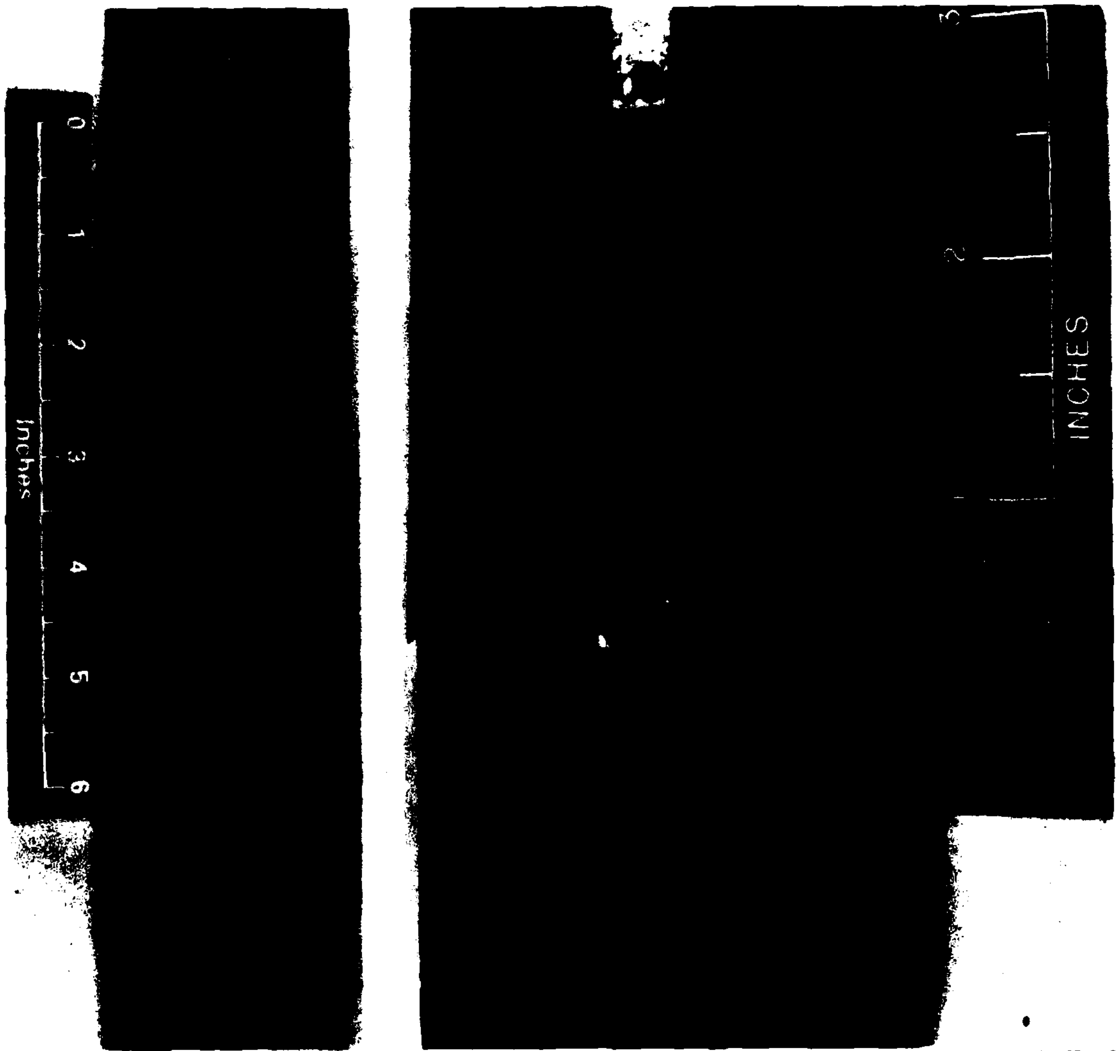
(a) Specimen **(b) Enlargement of Hole No. 1** GP13-[illegible]-13

Figure 18. Pictures of Typical Failures
50/40/10 Layup



(a) Specimen (b) Enlargement of Hole No. 2 GP13-0899-22

Figure 18 (Continued). Pictures of Typical Failures
30/60/10 Layup



(a) Specimen (b) Enlargement of Hole No. 1 GP13-0580-23

Figure 18 (Concluded). Picture of Typical Failures
19/76/5 Layup

IV. SUMMARY AND CONCLUSIONS

An experimental program was performed to provide strength data for three laminates from the family of 0°, ±45°, and 90° ply orientations previously evaluated in Reference 1. These laminates were tested over a wide range of bearing load and bypass load combinations. All specimens were fabricated from AS/3501-6 graphite-epoxy and tested at room temperature in the as-manufactured condition. Data were correlated with strength predictions obtained using the BJSFM procedure reported in Reference 1.

Failure loads, critical plies, and failure locations were predicted for all three layups. Predictions were based on using either the maximum strain or Tsai-Hill failure criterion at a characteristic dimension of 0.02 inch away from the hole boundary. Two types of laminate failure were identified; net-section failure of fiber-critical 0° plies and bearing failures of shear-critical 0°, ±45°, or 90° plies.

Laminate load-deflection behavior and failure characteristics observed in tests were: (1) bypass strength decreases as bearing stress increases prior to local bearing failures, (2) nonlinear or discontinuous load-deflection behavior occurs prior to ultimate failure, (3) initiation of nonlinearity coincides with predicted ply fiber or shear failures, and (4) at high bearing stress, local ply damage relieves stress concentrations; consequently bypass strengths level off or actually increase.

Ply failures predicted using the BJSFM procedure correlated with the onset of initial nonlinear or discontinuous load-deflection behavior. Evaluation of ultrasonic C-scan data further verified these predictions of ply failures and illustrated the need and utility of the detailed stress and failure analysis.

REFERENCES

1. Garbo, S.P. and Ogonowski, J.M., "Effect of Variances and Manufacturing Tolerances on the Design Strength and Life of Mechanically Fastened Composite Joints", AFWAL-TR-81-3041, Volumes 1, 2 and 3, April 1981.

APPENDIX

TEST DATA SUMMARY

All specimen test data have been summarized in the following three tables:

TABLE	TITLE
A1	TEST DATA FOR 50/40/10 LAYUP
A2	TEST DATA FOR 30/60/10 LAYUP
A3	TEST DATA FOR 19/76/5 LAYUP

TABLE A1. TEST DATA FOR 50/40/10 LAYUP

Specimen Number	Bypass Load (lb)	Bypass Strain (μin./in.)	Head Deflection (in.)	Axial Modulus (10^6 psi)	Thickness (in.)	Bearing Stress (ksi) [4]	Initial Nonlinearity	
							Bypass Load (lb)	Bypass Strain (μin./in.)
A-29-1	18,700	3,444	0.0623	11.45	0.2231	60	18,000	3,360
A-29-2	17,350	3,178	0.0525	11.45	0.2275	60	16,125	2,982
A-29-3	20,850	3,696	0.0582	12.02	0.2092	60	18,150	3,248
A-29-4	19,250	3,472	0.0630	11.73	0.2257	60	18,000	3,276
A-29-5	15,300	2,800	0.0432	11.45	0.2268	80	12,750	2,352
A-29-6	16,800	3,164	0.0504	11.73	0.2270	80	13,500	2,576
A-29-7	30,700	5,376	0.0888	12.31	0.2271	0	30,700	5,376
A-29-8	28,300	5,068	0.0804	11.73	0.2213	0	28,300	5,068
A-29-9	18,800	3,444	0.0570	11.88	0.2141	90	15,300	2,800
A-29-10	16,600	3,024	0.0480	12.21	0.2273	90	14,850	2,688
A-29-11	12,450	2,310	0.0330	11.59	0.2114	80	7,500	1,386
A-29-12	12,150	2,212	0.0315	11.83	0.2227	90	12,150	2,212
A-29-13	16,050	2,940	0.0411	11.88	0.2262	80 [1]	8,625	1,568
A-29-14	15,200	2,772	0.0372	11.88	0.2254	90 [2]	10,125	1,862
A-29-15	22,230	4,060	0.0591	11.73	0.2300	24 [3]	21,000	3,808
A-29-16	22,230	4,200	0.0605	11.45	0.2266	28	21,000	3,948
A-29-17	22,230	4,060	0.0585	11.83	0.2278	22	21,150	3,808
A-29-18	22,230	4,088	0.0599	11.83	0.2230	23 [3]	21,300	3,864

GP13-0660-19

[1] C-scans taken after applied bearing stress reached 70 and 80 ksi

[2] C-scans taken after applied bearing stress reached 80 and 90 ksi

[3] Deflection controlled; bypass load applied first followed by bearing load

[4] Based on nominal thickness and bolt diameter

TABLE A2. TEST DATA FOR 30/60/10 LAYUP

Specimen Number	Bypass Load (lb)	Bypass Strain (μin./in.)	Head Deflection (in.)	Axial Modulus (10^6 psi)	Thickness (in.)	Bearing Stress (ksi) 4	Initial Nonlinearity	
							Bypass Load (lb)	Bypass Strain (μin./in.)
B-15-1	14,350	3,808	0.0609	7.73	0.2049	60	13,200	3,612
B-15-2	16,550	4,172	0.0651	8.20	0.2128	60	12,300	3,192
B-15-3	15,400	3,836	0.0606	8.01	0.2095	60	13,500	2,584
B-21-4	15,500	4,088	0.0636	7.82	0.1989	60	12,300	3,304
B-21-5	13,500	3,584	0.0534	8.01	0.1983	80	9,000	2,436
B-21-6	15,300	3,668	0.0600	8.59	0.2008	80	12,300	3,108
B-25-7	20,250	5,460	0.0783	7.92	0.2088	0	20,250	5,460
B-25-8	11,900	2,772	0.0441	8.30	0.2139	90	8,400	2,128
B-25-9	11,700	2,800	0.0486	8.16	0.1982	90	6,000	1,596
B-25-10	7,725	2,037	0.0284	8.01	0.2075	80	3,825	1,015
B-25-11	7,725	2,009	0.0255	8.11	0.2266	90	2,175	560
B-25-12	8,850	2,296	0.0297	8.11	0.2250	80 1	7,500	1,960
B-25-13	9,760	2,562	0.0324	8.11	0.2210	90 2	6,225	1,680
B-25-14	5,000	1,302	0.0165	8.21	0.2133	100 3	5,000	1,302
B-25-15	13,860	3,542	0.0516	7.63	0.1972	100	11,200	3,052
B-25-16	13,740	3,640	0.0507	7.82	0.2027	100	10,900	2,968
B-25-17	5,000	1,344	0.0171	7.95	0.2025	100	5,000	1,344

GP13-0580-20

1 C-scans taken after applied bearing stress reached 70 and 80 ksi

2 C-scans taken after applied bearing stress reached 80 and 90 ksi

3 C-scans taken after applied bearing stress reached 90 and 100 ksi

4 Based on nominal thickness and bolt diameter

TABLE A3. TEST DATA FOR 19/76/5 LAYUP

Specimen Number	Bypass Load (lb)	Bypass Strain (μin./in.)	Head Deflection (in.)	Axial Modulus (10^6 psi)	Thickness (in.)	Bearing Stress (ksi) △4	Initial Nonlinearity	
							Bypass Load (lb)	Bypass Strain (μin./in.)
C-32-1	10,200	—	—	—	0.2144	60	7,650	—
C-32-2	10,250	3,220	0.0483	6.00	0.2248	60	8,550	2,828
C-32-3	9,300	2,884	0.0444	6.18	0.2195	60	7,050	2,296
C-32-4	9,900	3,108	0.0474	6.00	0.2213	60	7,800	2,604
C-32-5	4,770	1,680	0.0189	5.78	0.2156	90	4,770	1,680
C-32-6	9,250	2,800	0.0426	6.18	0.2227	70	5,550	1,820
C-33-7	8,900	2,660	0.0414	6.45	0.2225	80	5,400	1,708
C-33-8	8,400	2,520	0.0420	6.09	0.2248	80	5,100	1,708
C-33-9	— (Damaged in Grips) —			—	—	70	—	—
C-33-10	18,550	5,908	0.0825	6.45	0.2426	0	18,550	5,908
C-33-11	17,550	5,768	0.0795	6.36	0.2450	0	17,550	5,768
C-33-13	8,900	2,632	0.0420	6.63	0.2372	90	5,250	1,596
C-33-14	7,850	2,576	0.0378	6.09	0.2272	90	4,350	1,456
C-33-15	5,775	1,890	0.0240	6.18	0.2188	80	4,725	1,540
C-33-16	2,850	910	0.0108	6.45	0.2401	90	2,250	700
C-33-17	7,020	2,282	0.0276	6.04	0.2431	90 △1	4,725	1,596
C-33-18	7,360	2,338	0.0288	6.27	0.2378	70 △2	5,550	1,820
C-33-19	8,680	2,884	0.0333	6.09	0.2369	80 △3	6,225	2,072
C-33-20	4,875	1,638	0.0210	6.00	0.2238	70	2,700	892

GP13-0580-21

△1 C-scans taken after applied bearing stress reached 80 and 90 ksi

△2 C-scans after applied bearing stress reached 55 and 70 ksi

△3 C-scans after applied bearing stress reached 70 and 80 ksi

△4 Based on nominal thickness and bolt diameter

*U.S.Government Printing Office: 1981 — 559-005/4013

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