INVESTIGATION OF STATIC AND CYCLIC BEARING FAILURE MECHANISMS FOR GR/EP LAMINATES

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SUMMARY

Static, cyclic load (fatigue), and residual strength testing of graphite-epoxy and aluminum pin bearing joints was completed to investigate bearing failure mechanisms. Parameters investigated included static strength, failure mode, fatigue life, hole growth, joint stiffness, and residual strength. Comparative evaluation of these results show that the MIL-HDBK-5 convention for the definition of bearing strength can be used for GR/EP materials while maintaining the same, or improved, level of structural integrity demonstrated for metal joints.

INTRODUCTION

The determination of bearing strength design allowables for advanced composite primary aircraft structure surfaced many questions and concerns. There was no industry accepted consensus or standard for defining bearing strength for GR/EP materials. Also, the permissibility of local damage and the influence of cyclic loading above a load level that created initial damage on structural integrity was a concern.

Bearing allowables that did not permit local damage were initially defined. However, these allowables precluded the potential strength capability and structural efficiency of GR/EP structures from being realized.

Early work was directed toward joints with relatively low $^{e}/D$ ratios typical of splice details. Evaluation of proposed GR/EP structures showed that attachments with high $^{e}/D$ ratios typical of brackets, rib-to-cover, and chord-to-web details had significant impact on structural weight. Consequently, failure mechanisms and allowables for the high $^{e}/D$ details received attention in this evaluation.

A detailed study was initiated to investigate the bearing static strength and cyclic performance. Results of this study were then used to establish a procedure for defining bearing allowables.

SYMBOLS

D	Fastener diameter (inches)
e	End margin; distance from center of hole to end of specimen (inches)
e/D	Ratio of end margin to fastener diameter
FBR	Bearing Stress (KSI)
KSI	Stress (KIPS per square inch)
P	Load (KIPS)
RTD	Room Temperature Dry
t	Thickness (inches)
W	Width (inches)
W/D	Ratio; specimen width to fastener diameter

APPROACH

Definition of the procedures to be used for defining GR/EP bearing strength allowables included 1) a review of existing and proposed bearing strength definitions and then 2) completing a test program to evaluate concerns and potential problem areas.

No industry standards are available which can be used to assess the acceptability of the proposed definition of bearing failure and the resulting design allowables. For this study, standard was selected as the performance level demonstrated by 2024-T3 aluminum. This material has an extensive background of allowables development and successful service experience in the aircraft industry.

Tests for the aluminum material were completed to define a baseline for comparison. Results for the GR/EP material were then compared to those for the aluminum. If the GR/EP performs equal to or better than the known successful aluminum standard, the performance of the GR/EP material should also be acceptable.

The test program was designed to evaluate several concerns. These include:

1) No catastrophic failure at ultimate load

2) Acceptable deformation up to ultimate load

3) No detrimental damage at limit load

4) Acceptable fatigue performance

5) Acceptable residual strength after cyclic loading

6) Acceptable hole growth

   - No joint leaks after cycling

   - Maintain "tight joint"

7) Acceptable change in joint stiffness

   - Maintain design load distribution

The GR/EP material used in this program was T300/934 tape and fabric. Layups consisted of quasi isotropic, 25/50/25, as well as 0/100/0 and 50/0/50. These layups represent a wide range of laminate design and behavior.

CANDIDATE BEARING STRENGTH DEFINITIONS FOR GR/EP MATERIAL

Many proposed definitions for GR/EP bearing strength were investigated. Those considered most viable are summarized in Figure 1. A brief description of these and concomitant advantages and disadvantages are presented in Figures 2 through 5.

TEST PLAN

Specimen geometry and the number and type of tests completed in this program are shown in Figure 6. The geometry selected permits direct comparison between the data generated during this study and bearing strength data generated for other materials in separate test efforts.

The test plan is illustrated in Figure 7. Static test data include failure loads, failure modes, and the load deflection curves to failure. Similar data were obtained for the cyclic test specimens. Load-deflection curves from zero to the maximum cyclic load were periodically recorded. These recordings were typically made at the cyclic lives noted in Figure 7. This information was used to obtain joint stiffness (slope of the elastic portion of the load-deflection curve) and permanent hole deformation.

Special attention was directed to eliminating extraneous variables from influencing test results. Specimen fabrication was monitored carefully. All specimens were tested in the same machine by the same operator. Specimen temperature was continually monitored and cyclic rate controlled to keep the local specimen temperature below 120°F. One engineer monitored all tests and reduced all data.

Steel loading fixtures and a steel pin were used to apply the bearing test load. This is consistent with the ASTM E-238 (Ref 1) test procedure and MIL-HDBK-5 (Ref 2). However, the steel pin (bolt) was installed "finger tight". This provided some restraint to resist "brooming" of the GR/EP laminate at the high bearing area. However, it did not provide any capability to transfer load by friction; all load was transferred by bearing. This provides more representative strength for the GR/EP material than results from the truly untorqued configuration defined in ASTM E-238 (Ref 3). It also provided a configuration that could be used for the cyclic testing thus eliminating a test variable.

A cyclic stress ratio ($R = f^{min}/f_{max}$) of 0.06 was selected for test. This provided the largest stress excursion while eliminating cyclic test problems encountered with load reversal and specimen stability.

It is recognized the load reversal can have a significant effect on fatigue performance and hole growth. However, since cyclic data from this testing will be evaluated on a comparative basis only, the relative performance of the materials should be similar.

A maximum cyclic life of 10,000 cycles was chosen for this test. Since most of the cyclic load levels in this investigation are approaching or above limit stress (67 percent of ultimate), this is considered a severe and sufficient number of cycles.

TEST RESULTS

Influence of Material

A comparison of bearing load-deflection behavior of the investigated GR/EP laminates and aluminum materials is presented in Figure 8. Data are presented in two formats: 1) load vs deflection and 2) percent of typical static failure load vs. deflection. The maximum load sustained by the specimen was considered failure load.

The load-deflection curves shown are for the material test specimens which had the most representative behavior and strength of those tested. Strength and load-deflection performance for each test group were consistent.

As shown in Figure 8, the load-deflection curves for all materials tested were similar. The maximum load capability of the aluminum specimen was low because of the lesser relative specimen thickness (See Figure 6).

Comparison of the normalized load-deflection performance shows similar behavior for all materials. The aluminum experiences non-linear behavior at a lower percentage of ultimate load than do the GR/EP laminates.

Influence of End Margin ($^e/D$)

Load deflection and strength comparisons for a 25/50/25 GR/EP laminate are shown in Figure 9. The load required to obtain permanent deformation is about the same for all end margins tested. However, maximum load carrying capability and deformation at failure increases as the end margin increases.

Influence of Cyclic Loading

Influence of cyclic loading on bearing strength integrity is shown in Figures 10 through 16 for the materials, lay-ups, and end margins investigated. Loads are defined as a percent of the typical ultimate load capability.

A typical load-deflection curve for each material and end margin is shown. The bearing proportional limit and the .02D offset loads are defined. Typical ultimate load is 100 percent; typical limit load can be considered to be 67 percent.

Fatigue test data points are also shown. Fatigue specimens which did not fail prior to 10,000 cycles were tested in static tension to obtain tension residual strength. Specimens experiencing bolt failures were not tested for residual strength.

Hole growth data were reduced and plotted in an S-N curve format. These data show cycles required at a given load level to grow the hole to a deformation defined as a percentage of the fastener diameter.

Bearing stiffness (slope of the elastic portion of the bearing load-deflection curve) was determined. Comments relating relative change of stiffness as a function of cyclic loading are presented.

A summary of the cyclic loading behavior for the investigated materials is presented in Figure 17. This comparison is for a maximum cyclic load which is the lowest of 1) two percent diameter off-set or 2) 67 percent of maximum static load. This can be considered equivalent to a limit load level for a structure designed to the MIL-HDBK-5 allowable bearing stress guidelines.

The GR/EP materials have a higher relative allowable bearing load (based on ultimate load) than do the 2024 material. Consequently, for the cyclic comparison, the GR/EP materials are loaded at a higher percentage of their ultimate load capability than the aluminum material.

Results of this comparison show that all materials have good fatigue performance. No fatigue failures were experienced during 10,000 cycles of limit load.

The GR/EP materials typically did not experience any reduction in residual strength after cycling. The 2024 and 0/100/0 fabric ($e/D=8.0$) did experience minor residual strength reductions. However, the number of data points available to support this observation is limited.

Cycles required to grow the hole a distance of 0.04 diameters was significantly greater for GR/EP than for the 2024 aluminum. No growth was experienced on the 50/0/50 or the 25/50/25 GR/EP laminates for end margins of 2.5 diameters.

Bearing stiffness for the aluminum was found to increase with cycling. No significant change in stiffness was noted for the GR/EP laminates.

COMPARISON OF BEARING SPECIMEN AND JOINT SPECIMEN STRENGTH

A limited test effort was conducted to assess the applicability of using bearing allowables derived from untorqued specimens for defining strength of torqued joints typical of aircraft structure.

Results presented in Figure 18 show that the torqued joint exhibits higher bearing stress than the non-torqued bearing specimen. This increased strength is probably due to the added local stability and friction load carrying capability provided by the torque-up. This should provide a small amount of conservatism in joints sized with allowables determined from non-torqued test specimens.

CONCLUSIONS

A wide range of GR/EP laminates was tested to define bearing strength. The resulting strength values were assessed to compare performance relative to 2024-T3 aluminum. Results of this study show that:

a) The bearing behavior of GR/EP is dependent on laminate design and end-margin ($^e/D$).

b) Using MIL-HDBK-5 (Ref 2) definition of bearing, the GR/EP laminates can be designed to a higher percentage of their ultimate strength capability than can 2024-T3 aluminum.

c) Fatigue performance of GR/EP laminates loaded in bearing is equal to or better than that of 2024 aluminum.

d) Hole growth for GR/EP laminates subjected by cyclic loading is less than that for 2024 aluminum.

e) Residual strength of GR/EP laminates does not decrease during 10,000 cycles of design limit bearing load.

f) Bearing stiffness of GR/EP does not change significantly with cyclic loading.

g) Fully torqued joints designed for bearing failure exhibit slightly higher load carrying capability than untorqued joints.

Based on these findings, the following conclusion is derived.

> The MIL-HDBK-5 (Ref 2) convention for defining bearing strength for metals can be used for GR/EP materials while maintaining the same, or improved, level of structural integrity demonstrated for metal joints.

The results of the testing was specifically directed to Fiberite T300/934 GR/EP material, manufactured by Fiberite Corporation. Other material systems may behave in a different manner and should be investigated. The presented scheme for comparison of significant design parameters against known successful production material is recommended for that determination.

REFERENCES

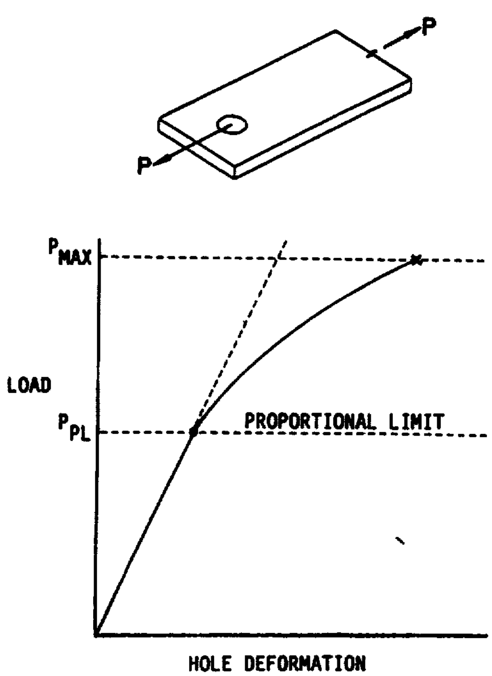
1. Standard Method for Pin-Type Bearing Test of Metallic Materials ASTM Designation: E238-84. Part 3 of Annual Book of ASTM Standards, 1984.

2. Military Handbook-5E, June 1987, Metallic Materials & Elements for Aerospace Vehicle Structures

3. Standard Test Method for Bearing Strength of Plastics ASTM Designation: D953-84, Part 8 Annual Book of ASTM Standards, 1984

CRITERIA OR METHOD	REFERENCE	CRITERIA LOAD FOR	
		YIELD	ULTIMATE
PROPORTIONAL LIMIT	-	P @ BEARING PROPORTIONAL LIMIT	P_{MAX}
ASTM STANDARD FOR PLASTICS	ASTM D953-84a (REF. 3)	-	P AT 4% DIA. TOTAL BEARING DEFORMATION
VARIATION OF ASTM STANDARD FOR PLASTICS	-	-	P AT 4% DIA. PLASTIC BEARING DEFORMATION
MIL-HDBK-5 STANDARD FOR METALLIC STRUCTURES	MIL-HDBK-5 SECTION 1.4.7.2 (REF. 2) (REF. 1)	P AT 2% DIA. PLASTIC BEARING DEFORMATION	P_{MAX}

FIGURE 1. SUMMARY - BEARING STRENGTH CRITERIA



CRITERIA

(1) DETERMINE PROPORTIONAL LIMIT AND P'_{MAX} FROM LOAD DEFORMATION CURVE

(2) DESIGN FOR $f_{BR_{ULT}}$ AS LOWEST OF:

- $f_{BR_{ULT}} = P_{MAX}/tD$
- $f_{BR_{ULT}} = \left[P_{PL}/tD\right] \times 1.5$

ADVANTAGE

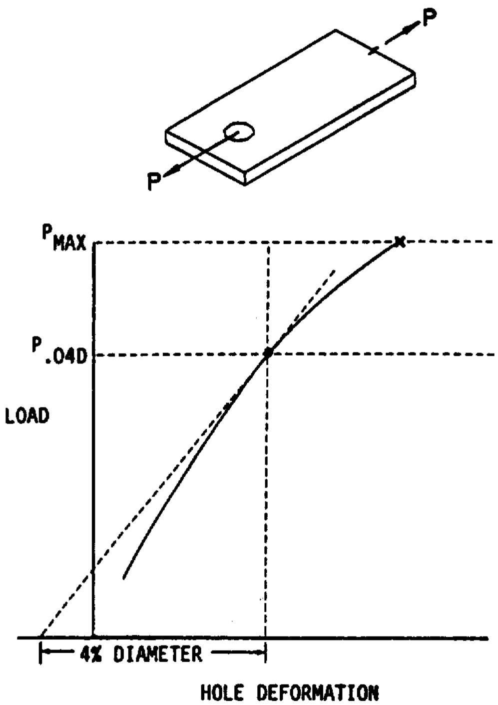
(1) MINIMUM LAMINATE DAMAGE AT LIMIT LOAD

DISADVANTAGES

(1) RELATIVELY LARGE VARIATION IN DETERMINING PROPORTIONAL LIMIT

(2) PROVIDES CONSERVATIVE (LOW) VALUES FOR LAMINATES WITH HIGH e/D VALUES OR HIGH PERCENTAGE OF ± 45 DEGREE PLIES

FIGURE 2. PROPORTIONAL LIMIT BEARING STRENGTH METHOD



CRITERIA

(1) DETERMINE LOAD AT WHICH BEARING HOLE DEFORMATION IS 4% OF HOLE DIAMETER

(2) DESIGN FOR $f_{BR_{ULT}}$ AS:

- $f_{BR_{ULT}} = P_{.04D} / tD$

ADVANTAGES

(1) ATSM STANDARD D953-84A (REF. 3) THAT CONSIDERS TOTAL HOLE DEFORMATION

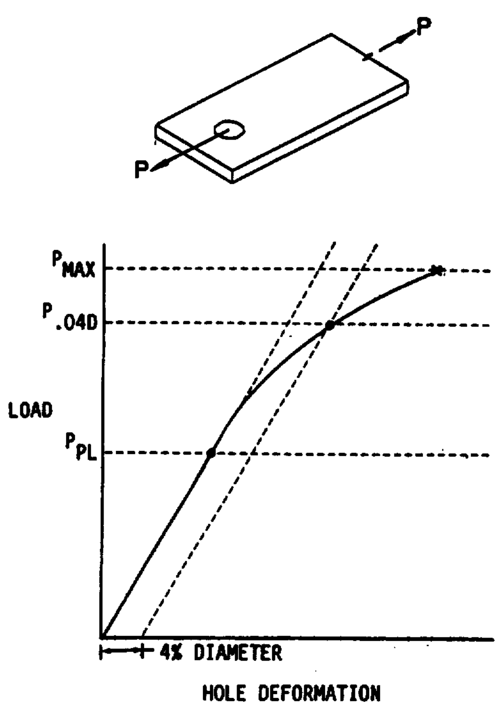
(2) LIMITS TOTAL DEFORMATION OF HOLE

DISADVANTAGES

(1) DOES NOT CONSIDER ELASTIC DEFORMATION

(2) PROVIDES CONSERVATIVE (LOW) VALUES FOR LAMINATES WITH HIGH e/D VALUES OR HIGH PERCENTAGE OF ± 45 DEGREE PLIES

FIGURE 3. ASTM D953-84A BEARING STRENGTH METHOD



CRITERIA

(1) DETERMINE MAX FAILURE LOAD AND LOAD AT PLASTIC HOLE DEFORMATION EQUAL TO 4% OF FASTENER DIAMETER

(2) DESIGN FOR $f_{BR_{ULT}}$ AS LOWEST OF:

- $f_{BR_{ULT}} = P_{MAX} / tD$
- $f_{BR_{ULT}} = P_{.04D} / tD$

ADVANTAGE

(1) RECOGNIZES ELASTIC CAPABILITY OF MATERIAL

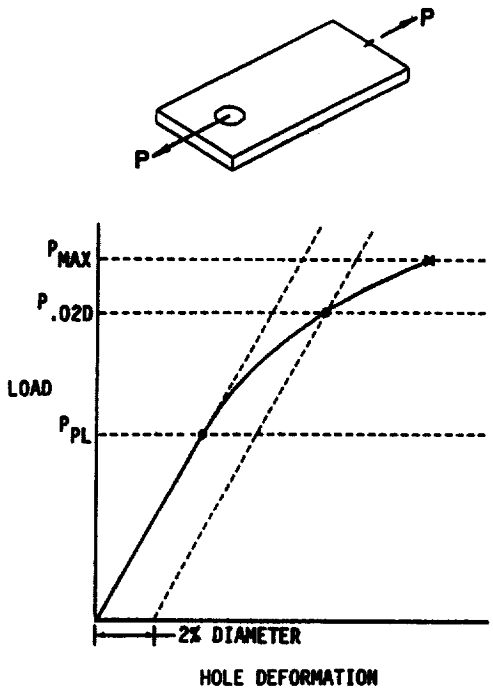
(2) LIMITS PLASTIC DEFORMATION OF HOLE

DISADVANTAGES

(1) RELATIVELY LARGE VARIATION IN DETERMINING PROPORTIONAL LIMIT

(2) PROVIDES CONSERVATIVE (LOW) VALUES FOR LAMINATES WITH HIGH e/D VALUES OR HIGH PERCENTAGE OF ± 45 DEGREE PLIES

FIGURE 4. FOUR PERCENT OFFSET BEARING STRENGTH METHOD



CRITERIA

(1) DETERMINE MAX FAILURE LOAD AND LOAD AT PLASTIC HOLE DEFORMATION EQUAL TO 2% OF FASTENER DIAMETER

(2) DESIGN FOR $f_{BR_{ULT}}$ AS LOWEST OF:

- $f_{BR_{ULT}} = P_{MAX}/tD$
- $f_{BR_{ULT}} = 1.5P_{.02D}/tD$

ADVANTAGE

(1) RECOGNIZES ELASTIC CAPABILITY OF MATERIAL

(2) LIMITS PLASTIC HOLE DEFORMATION AT LIMIT LOAD

(3) ACCEPTED MIL-HDBK-5 STANDARD (REF. 2) FOR METALLIC MATERIALS

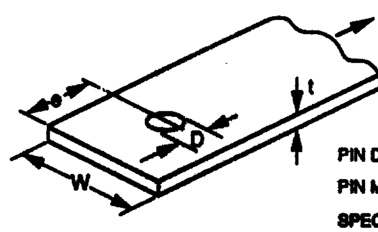
DISADVANTAGES

(1) NO LIMIT FOR MAX HOLE DEFORMATION AT ULTIMATE LOAD

FIGURE 5. MIL-HDBK-5 BEARING STRENGTH METHOD

W/D = 8.0

ENVIRONMENT = RTD



PIN DIAMETER = 0.25 NOMINAL

PIN MATERIAL = H-11 STEEL, 125 KSI SHEAR STRENGTH

SPECIMEN HOLE DIAMETER = $0.25^{+.003}_{-0}$

MATERIAL	NOMINAL t (IN)	e/D	NUMBER OF TEST SPECIMENS		
			STATIC	FATIGUE	RESIDUAL 1
ALUMINUM					
2024-T3	0.10	2.5	3	3	2
2024-T3	0.10	4.0	3	3	3
GRAPHITE/EPOXY 2					
25/50/25 TAPE	0.25 3	2.5	8	3	1
50/0/50 TAPE	0.25 3	2.5	3	3	2
0/100/0 TAPE	0.25 3	2.5	6	4	3
0/100/0 FABRIC	0.25 4	2.5	6	4	2
0/100/0 FABRIC	0.25 4	8.0	3	5	3
		TOTAL	32	25	16

1 RESIDUAL STRENGTH TESTS CONDUCTED ON SELECTED FATIGUE TEST SPECIMENS

2 FIBERITE T300/934 MATERIAL (TAPE t/PLY = .0078, FABRIC t/PLY = .0156)

3 28 PLIES OF TAPE; SUFACE PLIES ARE FABRIC (t = .2496)

4 16 PLIES OF FABRIC (t = .2496)

FIGURE 6. STATIC AND FATIGUE TEST SPECIMENS

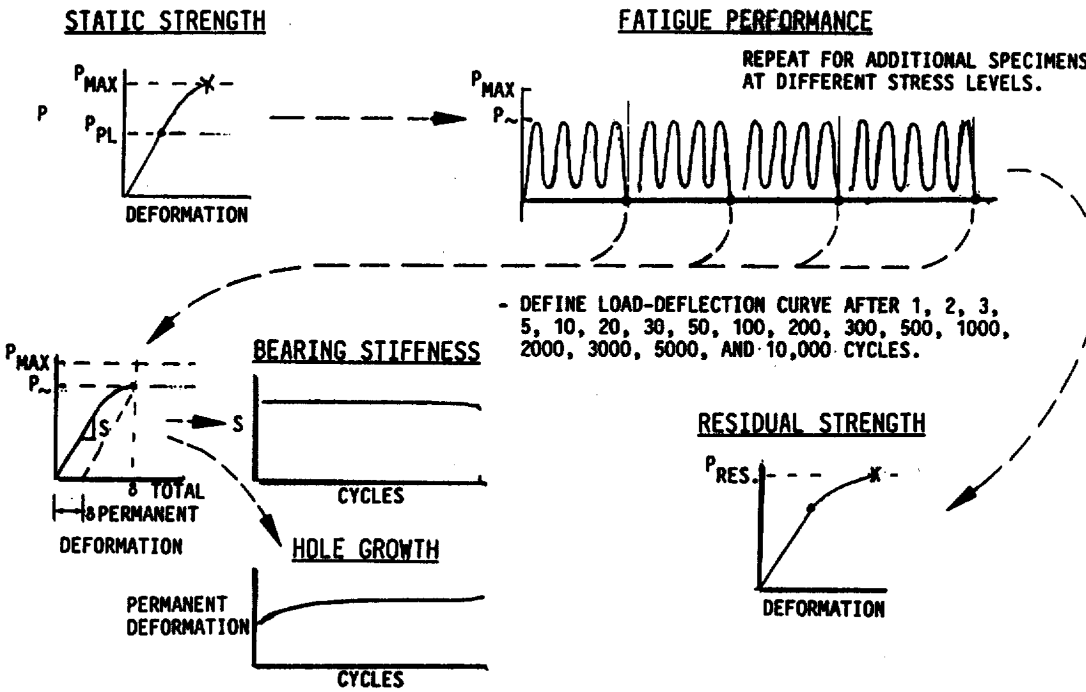


FIGURE 7. TEST PLAN

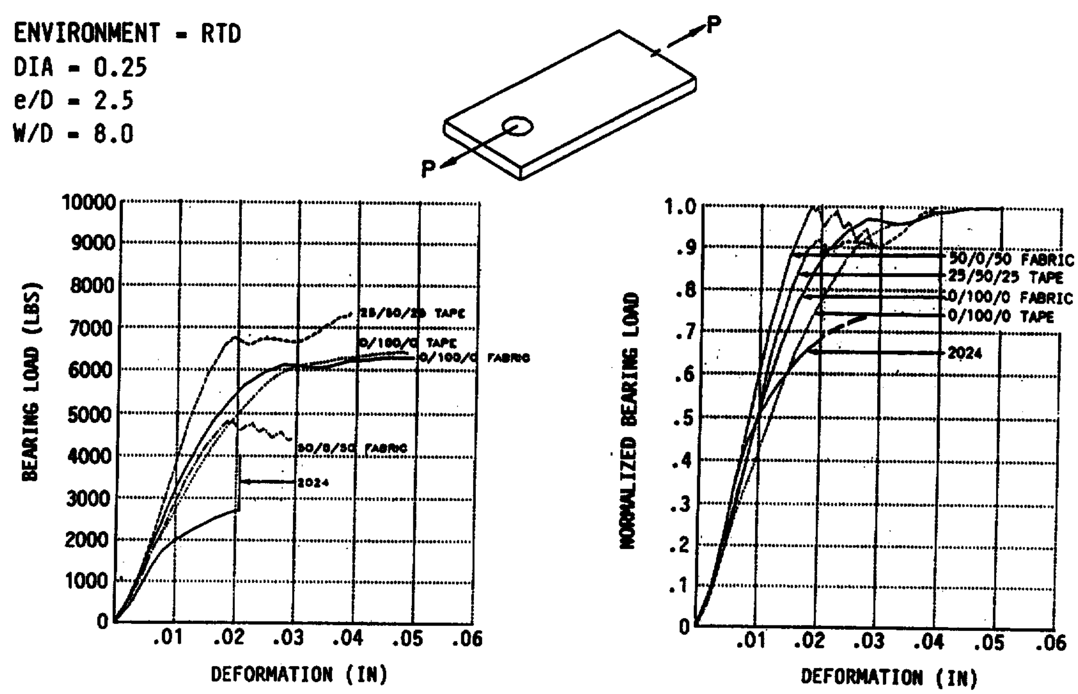


FIGURE 8. BEARING STATIC STRENGTH BEHAVIOR MATERIAL COMPARISON

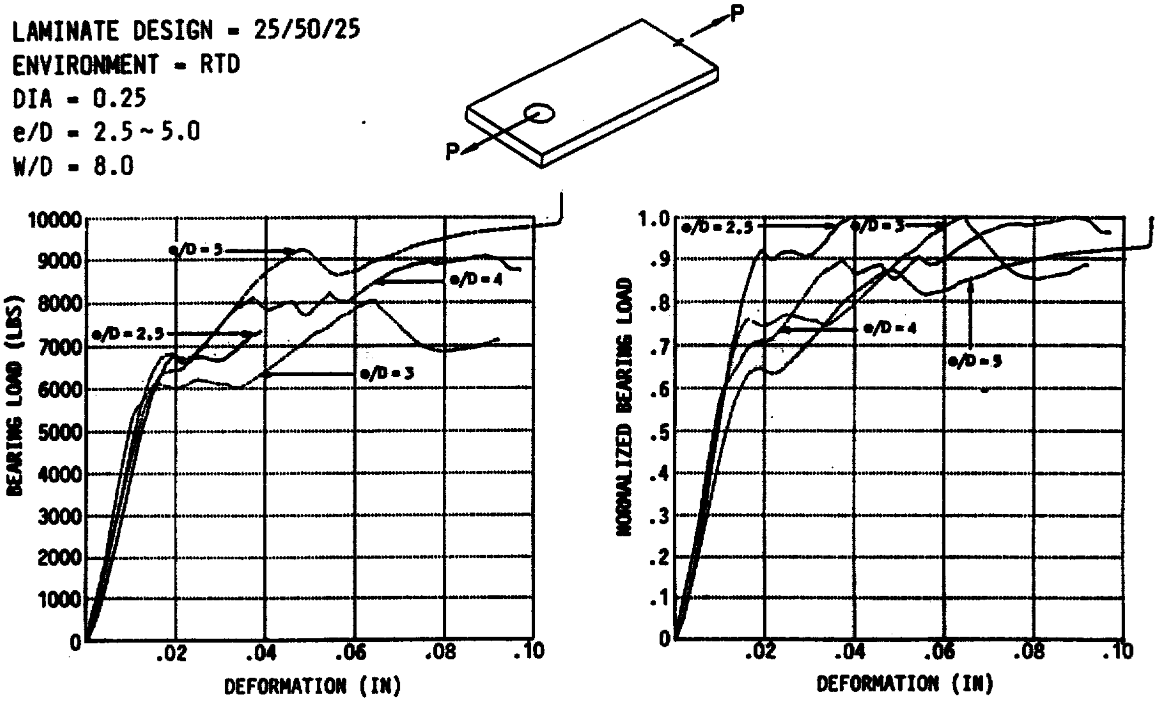
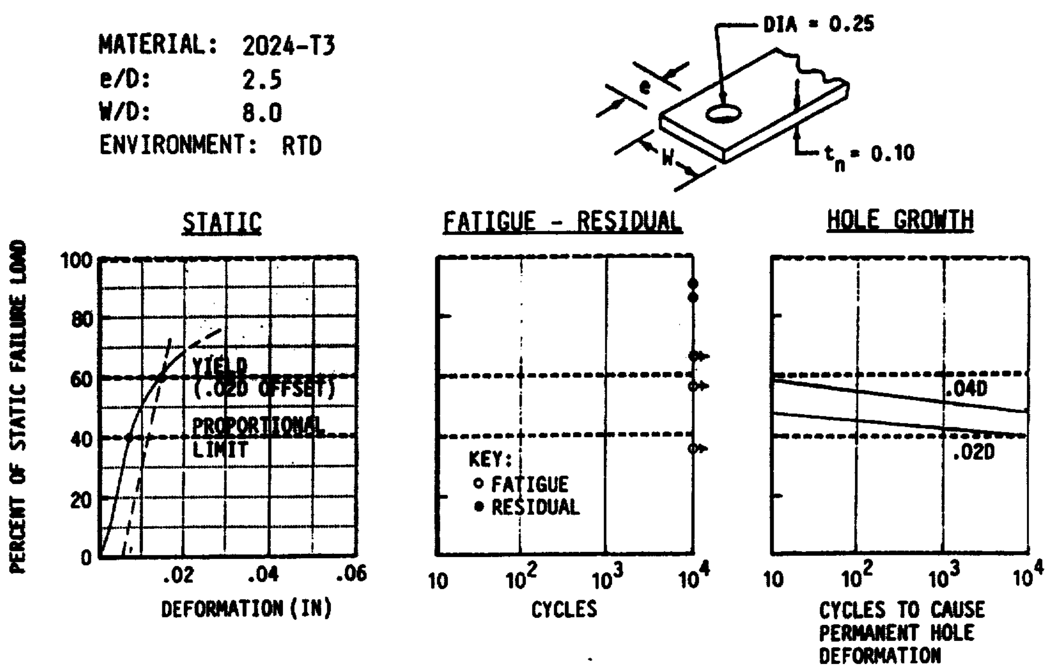
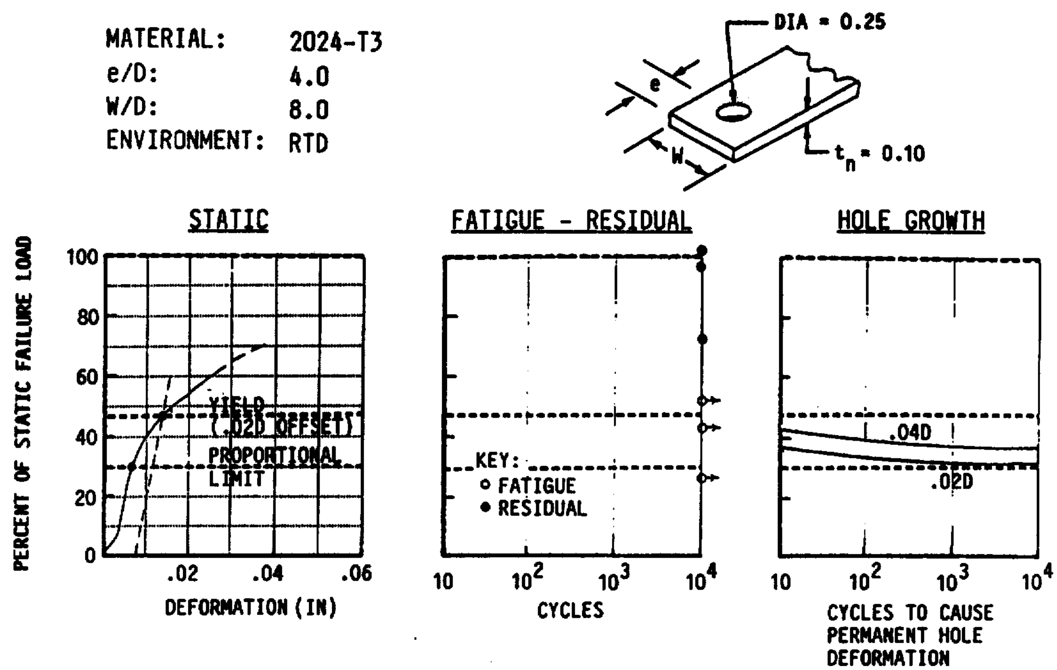


FIGURE 9. BEARING STATIC STRENGTH BEHAVIOR e/D COMPARISON



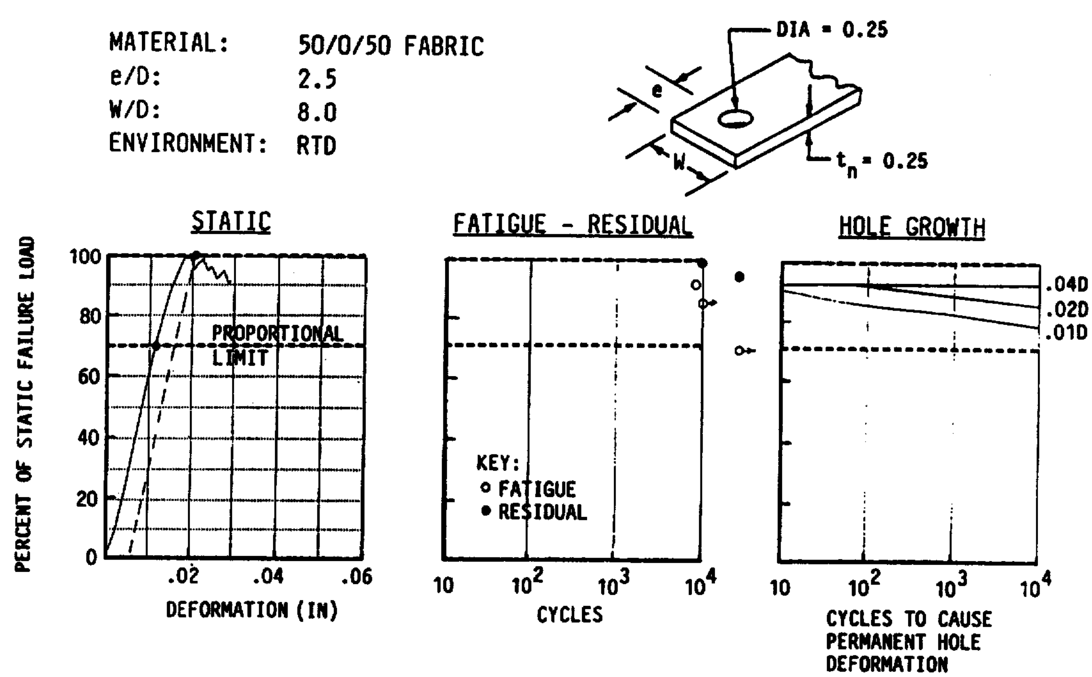
- BEARING STIFFNESS INCREASED DURING CYCLIC TESTING

FIGURE 10. BEARING BEHAVIOR, 2024-T3, e/D = 2.5



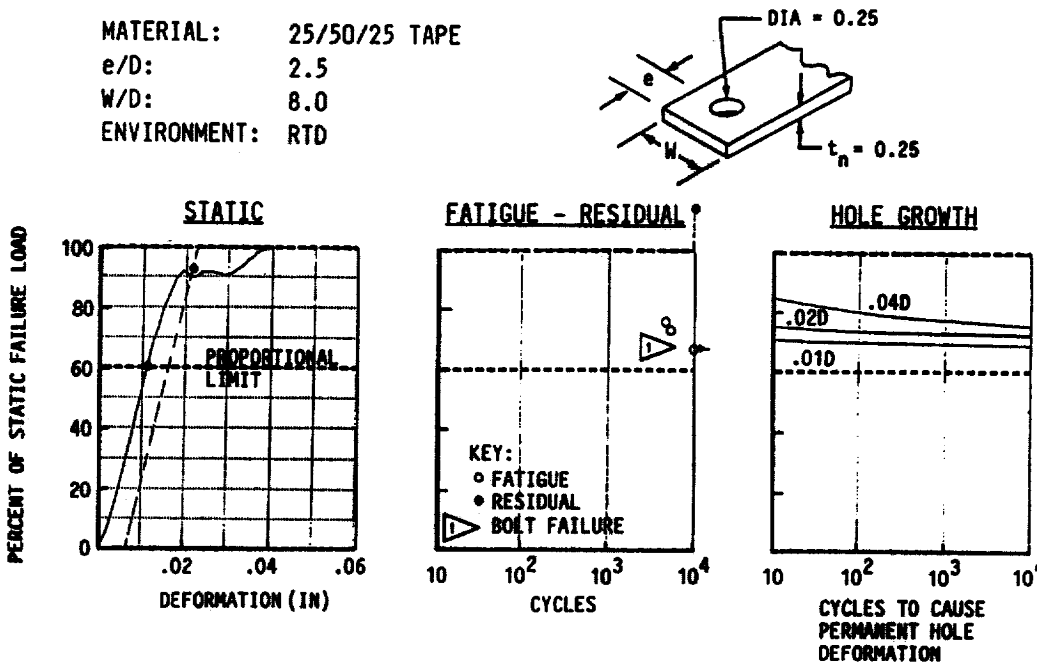
- BEARING STIFFNESS INCREASED DURING CYCLIC TESTING

FIGURE 11. BEARING BEHAVIOR, 2024-T3, e/D = 4.0



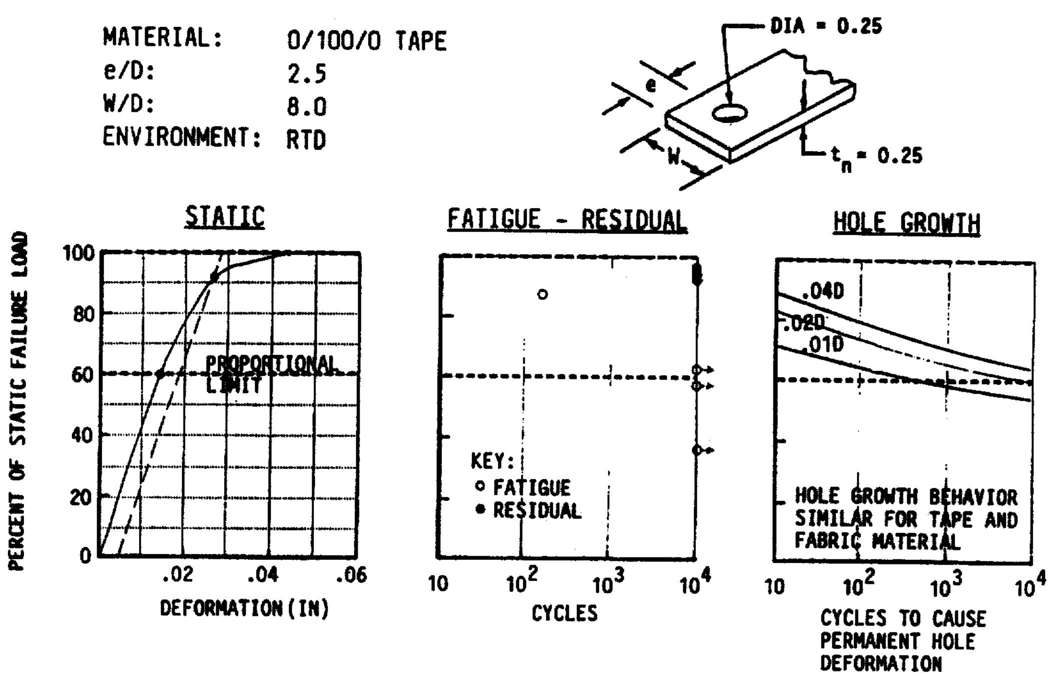
- BEARING STIFFNESS DID NOT CHANGE SIGNIFICANTLY DURING CYCLIC LOADING.

FIGURE 12. BEARING BEHAVIOR, 50/0/50 FABRIC, e/D = 2.5



- BEARING STIFFNESS DID NOT CHANGE SIGNIFICANTLY DURING CYCLIC LOADING.

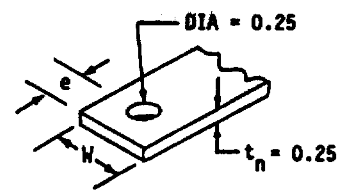
FIGURE 13. BEARING BEHAVIOR, 25/50/25 TAPE, e/D = 2.5

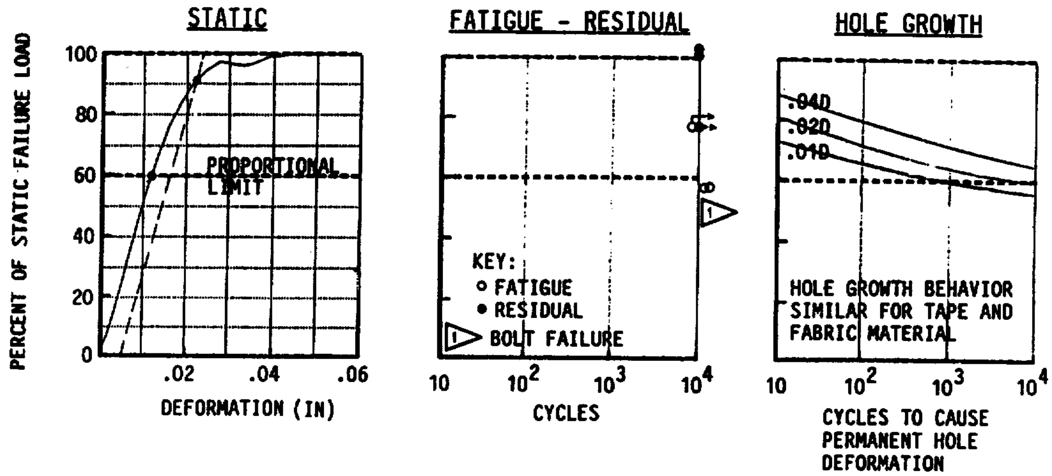


- BEARING STIFFNESS DID NOT CHANGE SIGNIFICANTLY DURING CYCLIC LOADING.

FIGURE 14. BEARING BEHAVIOR, 0/100/0 TAPE, e/D = 2.5

MATERIAL: 0/100/0 FABRIC
e/D: 2.5
W/D: 8.0
ENVIRONMENT: RTD

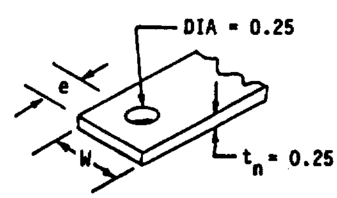


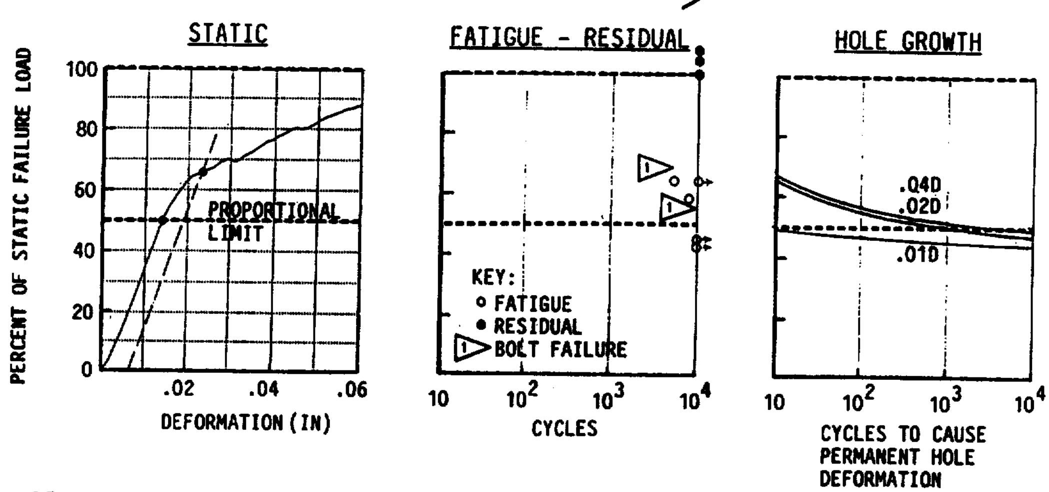


- BEARING STIFFNESS DID NOT CHANGE SIGNIFICANTLY DURING CYCLIC LOADING.

FIGURE 15. BEARING BEHAVIOR, 0/100/0 FABRIC, e/D = 2.5

MATERIAL: 0/100/0 FABRIC
e/D: 8.0
W/D: 8.0
ENVIRONMENT: RTD





- BEARING STIFFNESS DID NOT CHANGE SIGNIFICANTLY DURING CYCLIC LOADING.

FIGURE 16. BEARING BEHAVIOR, 0/100/0 FABRIC, e/D = 8.0

MATERIAL OR GR/EP LAMINATE DESIGN	e/D	PERFORMANCE AT LOWEST OF 2% DIAMETER OFF-SET LOAD OR 0.67 x MAX STATIC LOAD				
		LOAD LEVEL (% OF MAX STATIC)	FATIGUE FAILURES BEFORE 10,000 CYCLES	RESIDUAL STRENGTH REDUCTION AFTER 10,000 CYCLES	CYCLES TO GROW HOLE TO .04 DIA	BEARING STIFFNESS CHANGE AFTER 10,000 CYCLES
2024-T3	2.5	60	NO	YES (10%)	<10	INCREASE
2024-T3	4.0	47	NO	NO	<10	INCREASE
50/0/50 FABRIC	2.5	67	NO	NO	>>10,000	NONE
25/50/25 TAPE	2.5	67	NO	NO	>>10,000	NONE
0/100/0 TAPE	2.5	67	NO	YES (5%)	1,000	NONE
0/100/0 FABRIC	2.5	67	NO	NO	1,000	NONE
0/100/0 FABRIC	8.0	66	NO	NO	10	NONE

ENVIRONMENT: RTD
W/D: 8.0

FIGURE 17. SUMMARY - BEARING BEHAVIOR OF GR/EP AND 2024 ALUMINUM MATERIALS

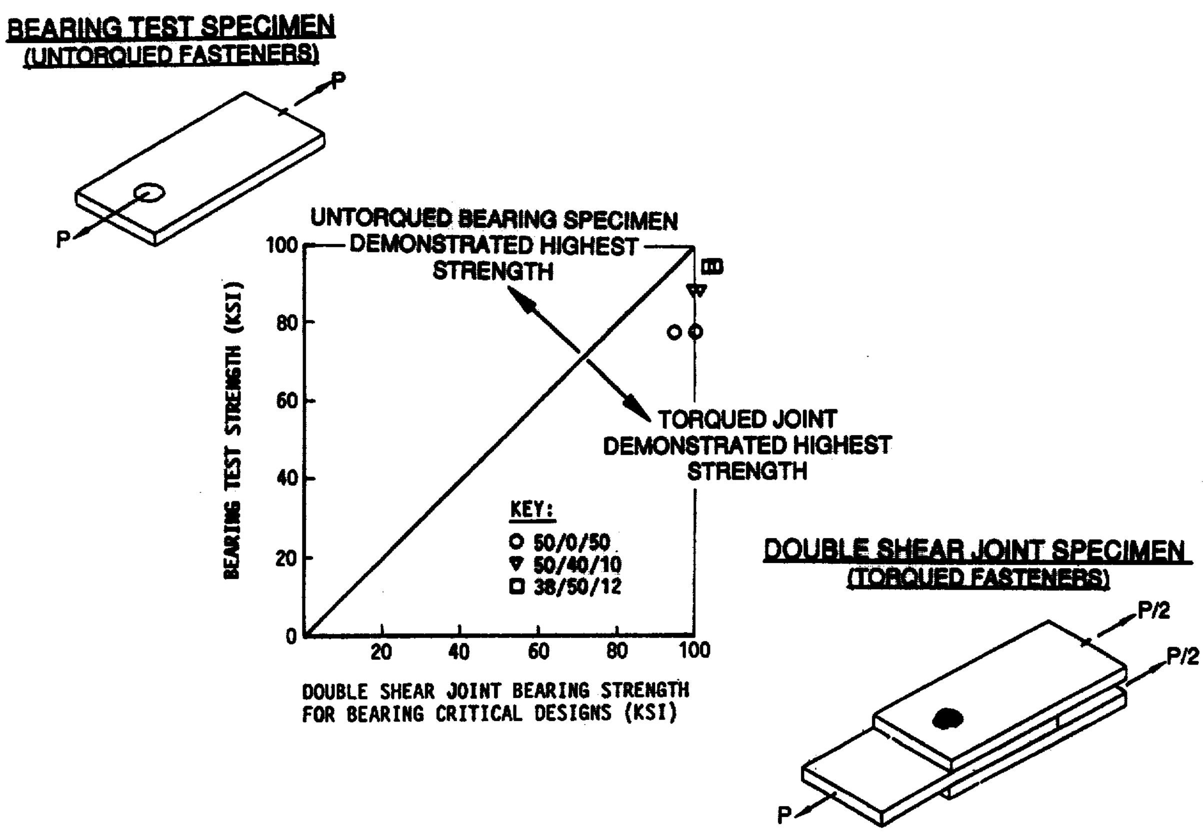


FIGURE 18. COMPARISON OF BEARING STRENGTH FOR BEARING AND JOINT TEST SPECIMENS