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ABSTRACT

Structural strength reproducibility of graphite-epoxy composite spoilers for the Boeing 737 aircraft was evaluated by statically loading fifteen spoilers to failure at conditions simulating aerodynamic loads. Spoiler strength and stiffness data were statistically modeled using a two-parameter Weibull distribution function. Shape parameter values calculated for the composite spoiler strength and stiffness were within the range of corresponding shape parameter values calculated for material property data of composite laminates. This agreement showed that reproducibility of full-scale component structural properties was within the reproducibility range of data from material property tests.

NOMENCLATURE

Values are given in both U.S. Customary and SI Units. Measurements and calculations were made in U.S. Customary Units. Factors relating the two systems are given in reference 1.

F = Failure load
$P()$ = Probability distribution function
S = Structural stiffness
X = Random variable
α = Weibull shape parameter
μ = Statistical mean
σ = Standard deviation

Superscript
$\hat{}$ = Weibull scale parameter

INTRODUCTION

Several flight service programs are being conducted with composite components on transport aircraft. These include Kevlar 49-epoxy fairing components on Lockheed L-1011 aircraft (ref. 2), boron-epoxy-reinforced wing-box structures on U.S. Air Force C-130 aircraft (ref. 3), graphite-epoxy rudder section on McDonnell Douglas DC-10 aircraft (ref. 4), and graphite-epoxy spoilers on Boeing 737 aircraft (ref. 5). These components are being carefully monitored to determine their ability to withstand the normal day-to-day aircraft environment.

The Boeing 737 composite spoiler (ref. 5), which is the component discussed in this paper, is in flight service with several airlines. To date approximately one million hours of flight time have been accumulated.

Even though considerable composite material property data are in the literature, usually, only one-of-a-kind structural components have been tested. Insufficient data are available for adequate confidence in designs which minimize structural weight. A broader statistical base would aid in this respect. The statistical distribution functions that are normally employed for strength and structural reliability are discussed in references 6 to 10. One of these functions is the Weibull distribution which is described in greater detail in reference 11. In reference 12, this distribution function is used to develop a reliability plan for composite materials static strength based on the macroscopic material properties.

The purpose of the present paper is to report the results of an initial portion of a structural reproducibility evaluation of a composite aircraft component. The entire program consists of structural tests of the component and static tensile, compression, and interlaminar shear tests of the same material as used in the component construction. This paper is restricted to reporting the structural component tests. Fifteen components were evaluated by loading to structural failure. This is the first series of structural strength tests with sufficient replicates for a statistical analysis of a builtup composite structural component fabricated on a production basis. Component stiffness and strength data are examined statistically and are shown to fit a two-parameter Weibull distribution. The two parameters, the shape and scale factors, were computed. In addition, some initial comparisons are made of the Weibull shape parameter for the component tests with shape parameters for material property test data from several NASA contracts.

MATERIALS

The composite materials discussed in this paper were combinations of graphite or aramid fibers and epoxy resins. The specific materials were:

Thornel 300 graphite fibers, manufactured by Union Carbide Corporation

AS graphite fibers, manufactured by Hercules Incorporated

Kevlar 49 aramid fibers, manufactured by E. I. duPont de Nemours & Co., Inc.

Narmco 5209 epoxy resin, manufactured by Narmco Materials, a subsidiary of Celanese Corporation

3501 epoxy resin, manufactured by Hercules Incorporated

EA 9628 epoxy adhesive, manufactured by Hysol, a division of Dexter Corporation.

Identification of commercial products in this report is to adequately describe the materials and does not constitute official endorsement, expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

TEST COMPONENTS

The test articles (fig. 1) were graphite-epoxy aircraft spoilers that were developed for and are being evaluated in the flight service program previously discussed (ref. 5). Spoiler construction was similar to the standard aluminum production spoilers on the Boeing 737 transport aircraft except that graphite-epoxy skins were substituted for the aluminum skins (fig. 2). These composite skins were fabricated from Thornel 300/Narmco 5209 prepreg and were bonded to the substructure with EA 9628 adhesive. The structure was designed for a stiffness criterion and design limit load [3,790 lb (16,858 N)] and design ultimate load [5,685 lb (25,287 N)] criteria were also satisfied. The spoilers tested in this investigation were among the last 25 of a production run of 140 items. Fifteen of these spoilers were loaded to failure. The remaining 10 spoilers will be used in other tests. All spoilers used in this evaluation were new and flight qualified.

PROCEDURES

Spoilers were loaded with a whiffletree arrangement which applied a distributed load to simulate aerodynamic loading. Spoiler loading pads are shown in figure 3 and the test setup, mounted on a rigid backstop, is shown in figure 4. The load was applied to the spoilers by a hydraulic cylinder pulling down on the crossbeam below the spoiler. Through this arrangement, the spoilers were loaded to failure and the values of load, strain, and displacement were recorded on magnetic tape throughout the tests. Strain gage locations and the three points along the trailing edge of the spoiler where displacements were measured are shown in figure 3. The strain gages were located on the upper and lower surfaces near the corners of the hydraulic actuator attachment box where the maximum strains were expected to occur. Displacements were measured using weighted strings turning calibrated, 10-turn, variable resistors. Failure was taken to be the point of maximum load which was also the point at which catastrophic structural failure occurred. Figure 5 shows a failed spoiler in the test rig.

RESULTS

All fifteen spoilers appeared to fail in the same mode. The lower skin (compression side) buckled around the actuator attachment frame and the upper skin (tension side) failed at one or both of the frame aft corners. These failures are shown in figure 6. Trailing edge deflection at the corners of the spoiler at failure was approximately 2.7 in. (69 mm). A typical load-deflection curve is shown in figure 7 and the failure loads and deflection data are given in table 1. Using load-deflection data, comparative initial stiffness values (table 2) were computed. These stiffness values were obtained by dividing the applied load by the associated deflection.

Failure loads of the 15 spoilers are plotted in figure 8 in the sequence tested. The solid line represents the mean failure load of 10,190 lb (45,325 N) for all the tests. The two dashed lines represent an arbitrary ± 10 percent band. All of the data are within this band except for two points which are 12.9 and 14.5 percent below the mean failure load of the spoilers. The lowest failure load of 8,709 lb (38,708 N) is 53 percent above the design ultimate load of 5,685 lb (25,287 N). As indicated in table 1, the standard deviation of the load data is 673 lb (2,994 N).

A test was made for normal distribution of the failure loads by plotting the data on a normal probability scale. If they are normally distributed, the data should fit a straight line. In figure 9, failure loads are plotted in this manner where the ordinate represents the probability of survival. A straight line based on the computed mean and standard deviation is not a good fit of the data.

As previously discussed, references 11 and 12 indicate that experimentally measured parameters may be described by the two-parameter Weibull distribution function

$$P(X) = \exp \left[- \left(\frac{X}{\hat{X}}\right)^{\alpha} \right] \tag{1}$$

where X is the random variable such as failure load, $\hat{X}$ is the scale parameter, and α is the shape parameter. The parameter $\hat{X}$ is the characteristic value or estimate of the mean and α gives the shape of the distribution and some measure of dispersion or scatter. Large values of α are indicative of small scatter in the data. $P(X)$ is the probability of survival and $1-P(X)$ the probability of failure.

The failure load data are replotted in figure 10 on ordinate and abscissa scales such that a Weibull distribution lies along a straight line. The solid line is a least square fit of the data with a slope, α, of 14.70 and a scale parameter, $\hat{F}$, of 10,532 lb (46,846 N). The parameter $\hat{F}$ is an estimate of the mean failure load.

Comparative initial stiffness values (table 2) are plotted on a normal probability scale in figure 11. The data fit a straight line based on the computed mean and standard deviation. These results indicate that the computed initial stiffness data, which have very little scatter, are normally distributed.

Figure 12 is a Weibull plot of the stiffness data. The shape parameter value of 69.19 is indicative of a small amount of scatter in the initial stiffness of the spoilers.

To compare the shape parameters for the spoiler failure load and stiffness with material data, values of α were calculated for data from several test programs performed under NASA contracts and are given in table 3. The calculated shape parameters for failure load and stiffness of the spoilers (figs. 10 and 12) fall within the range of α values in table 3. Note that the scatter in the structural component data is less than that in the material property data. The reproducibility of the structural components strength was better than that of the composite material from which they were built.

CONCLUDING REMARKS

Fifteen graphite-epoxy spoilers were tested to determine failure load and stiffness reproducibility at static loads simulating aerodynamic loading. All spoilers exhibited the same mode of failure; the lower skin (compression side) buckled around the actuator attachment box and the upper skin (tension side) failed in tension at one or both of the frame corners. The load standard deviation was 6.6 percent of the mean failure load indicating only a small variation in failure load. The spoiler failure load and stiffness data fit a two parameter Weibull distribution model. Shape parameters for spoiler failure loads and stiffness values were larger than all but one of the shape parameters calculated for the composite materials' property data. These results indicate that the scatter of the full scale structural components was less than that of the composite material.

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TABLE I. - Failure loads and trailing edge deflections of spoilers.

Test number	Failure load		Displ. of left corner		Displ. of Center		Displ. of right corner	
	lb	N	in.	mm	in.	mm	in.	mm
1*	9946	44242	-	-	-	-	-	-
2	9543	42449	2.404	61.06	0.907	23.03	2.3[illegible]	59.69
3	10921	48579	2.993	76.02	1.181	30.00	3.060	77.72
4	10848	48254	2.939	74.65	1.074	27.28	2.887	73.33
5	10736	47756	2.938	74.63	1.180	29.97	2.953	75.01
6	8709	38740	2.178	55.32	0.878	22.30	2.261	57.43
7	10153	45163	2.698	68.53	1.064	27.03	2.867	72.82
8	10296	45799	2.663	67.64	1.027	26.09	2.657	67.49
9	10404	46279	2.817	71.55	1.088	27.64	2.753	69.93
10	10304	45834	2.727	69.27	1.084	27.53	2.685	68.20
11	10400	46261	2.867	72.82	1.048	26.62	2.979	75.67
12	10813	48099	2.881	73.18	1.195	30.35	3.008	76.40
13	10408	46297	2.644	67.16	1.048	26.62	2.727	69.27
14	10549	46924	2.694	68.43	0.963	24.46	2.790	70.87
15	8875	39478	2.161	54.89	0.818	20.78	2.281	57.94

Mean failure load = 10190 lb (45325 N)
Standard deviation = 673 lb (2994 N)
Weibull shape parameter = 14.7
Mean corner deflection at failure = 2.711 in. (68.85 mm)
* No deflection data on first test

TABLE II. - Spoiler trailing corner stiffness

Test number	Stiffness					
	Left corner		Right corner		Mean	
	lb/in.	kN/m	lb/in.	kN/m	lb/in.	kN/m
1*	-	-	-	-	-	-
2	4153	727	4212	738	4183	733
3	4259	746	4160	729	4209	737
4	4194	734	4338	760	4266	747
5	4160	729	4198	735	4179	732
6	4389	767	4224	740	4307	754
7	4320	757	4012	703	4166	730
8	4197	735	4299	753	4248	744
9	4273	748	4304	754	4289	751
10	4216	738	4430	776	4323	757
11	4191	734	4093	717	4142	725
12	4392	769	4154	727	4273	748
13	4397	770	4302	753	4350	762
14	4337	760	4099	718	4218	739
15	4357	763	4101	718	4229	741

Mean stiffness = 4242 lb/in. (743 kN/m)
Standard deviation = 63 lb/in. (11 kN/m)
Weibull shape parameter = 69.2
* No deflection data on first test

TABLE III. - Material property test conditions and shape parameters (Tests performed under NASA contracts).

Material	Type of Test	Ply orientation or load direction	Test temp.	Moisture	Failure load shape parameter
Graphite/epoxy (T300/5209) NASA Contract No. NAS1-11668	compression	0°	room temp.	-	10.5
	compression	90°	room temp.	-	7.7
	compression	0°	room temp.	100% RH	16.9
	short beam shear	0°	room temp.	-	11.0
	short beam shear	0°	room temp.	-	81.7*
	short beam shear	0°	room temp.	100% RH	15.2
	tension	0°	room temp.	-	7.3
	tension	90°	room temp.	-	7.4
Graphite/epoxy (T300/5209) NAS1-14000	compression	$[\pm45/0/\pm45_2]_s$	room temp.	dry	15.3
	compression	$[\pm45/0/\pm45_2]_s$	room temp.	wet	40.6
	compression	$[\pm45/0/\pm45/0_3]_s$	room temp.	dry	7.0
	compression	$[\pm45/0/\pm45/0_3]_s$	room temp.	wet	7.5
Graphite/epoxy (AS/3501) NAS1-12308	tension	90°	250°F (394K)	-	8.6
	tension	90°	250°F (394K)	-	9.7
Boron/aluminum (5.6mil/6061) NAS1-12308	tension	90°	room temp.	-	12.1
	tension	90°	room temp.	-	11.9

*Repeat of immediately preceding test.

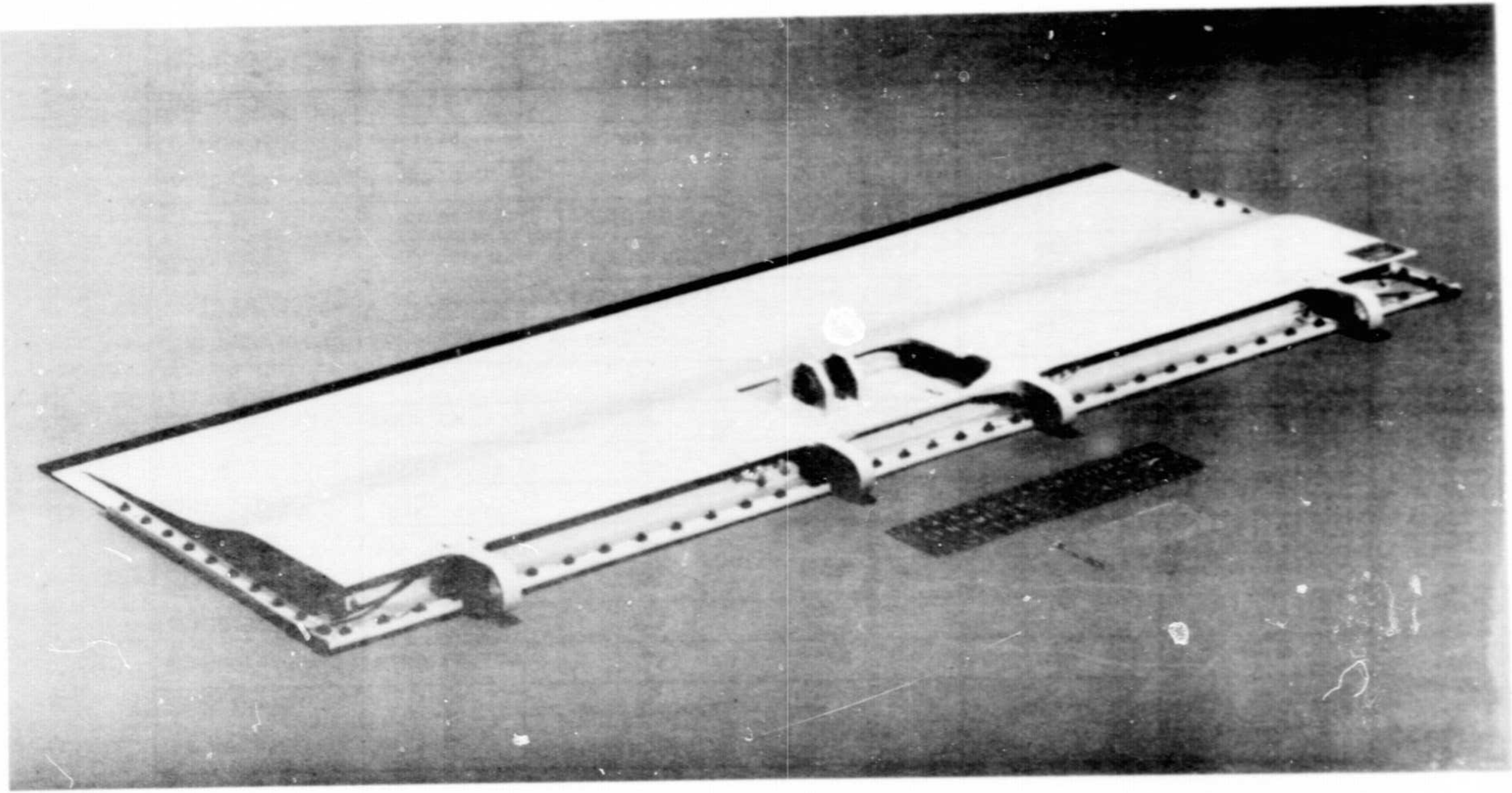

Figure 1. - Boeing 737 composite spoiler.

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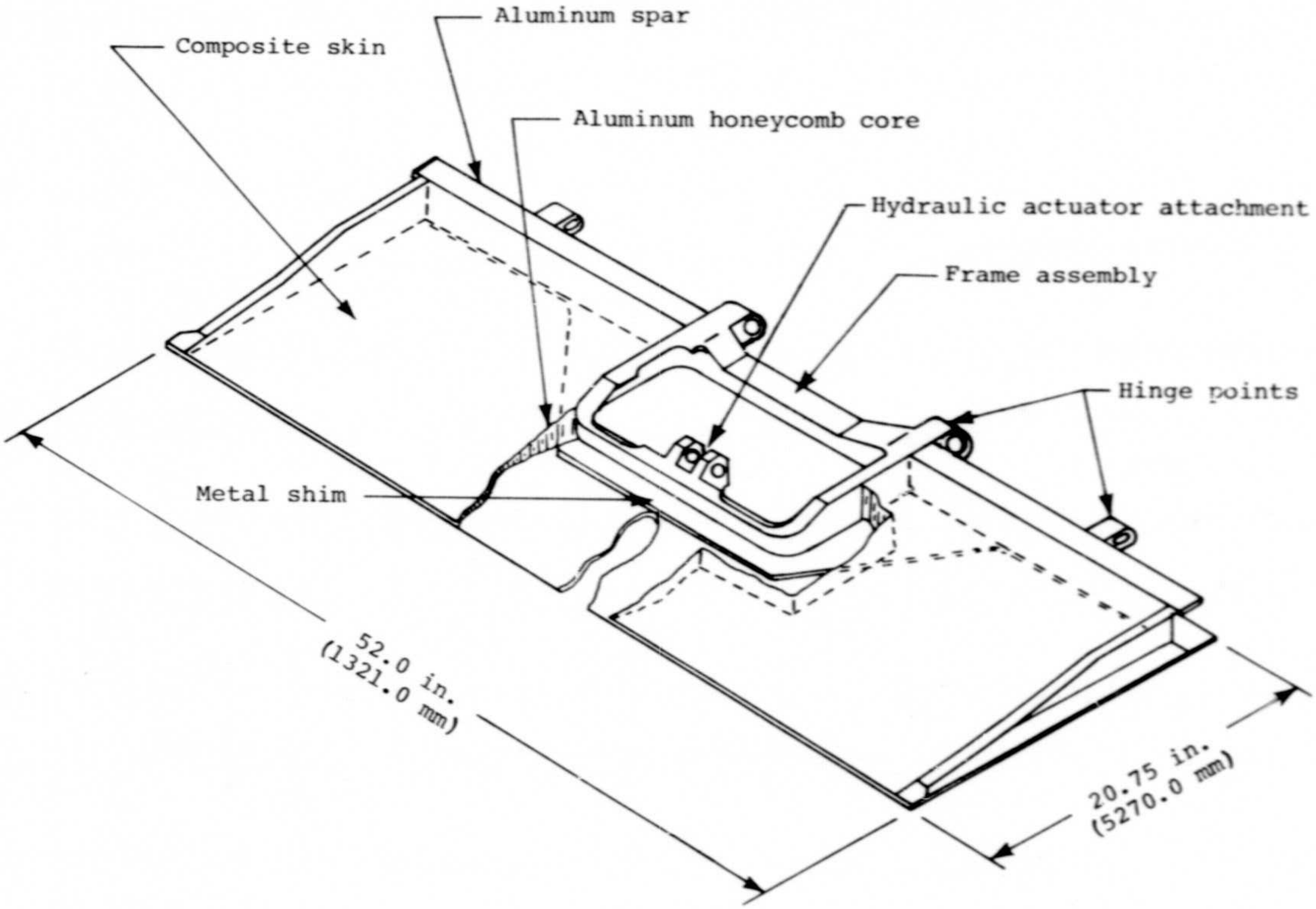

Figure 2. - Spoiler structural arrangement.

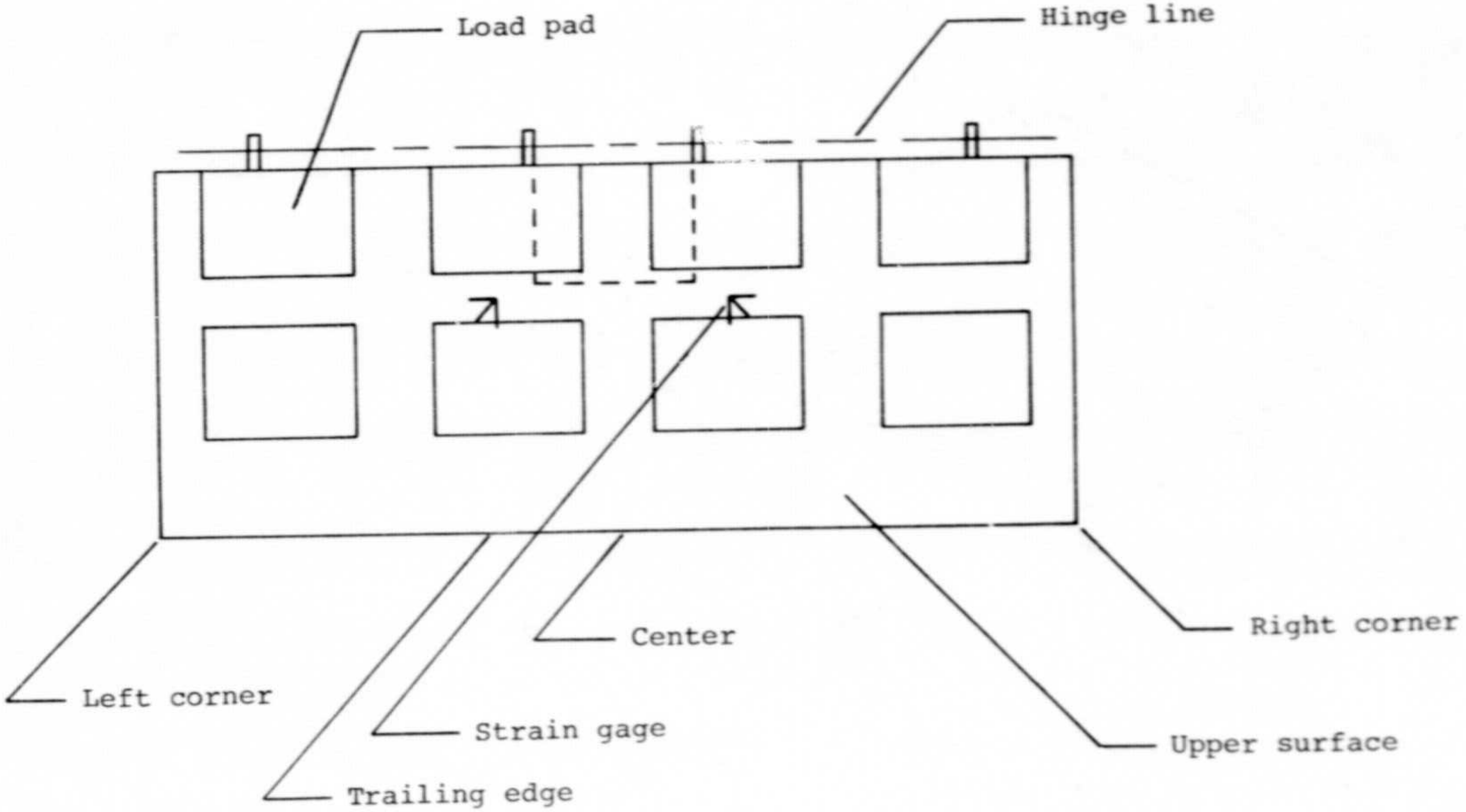

Figure 3. - Spoiler loading pad and instrumentation locations.

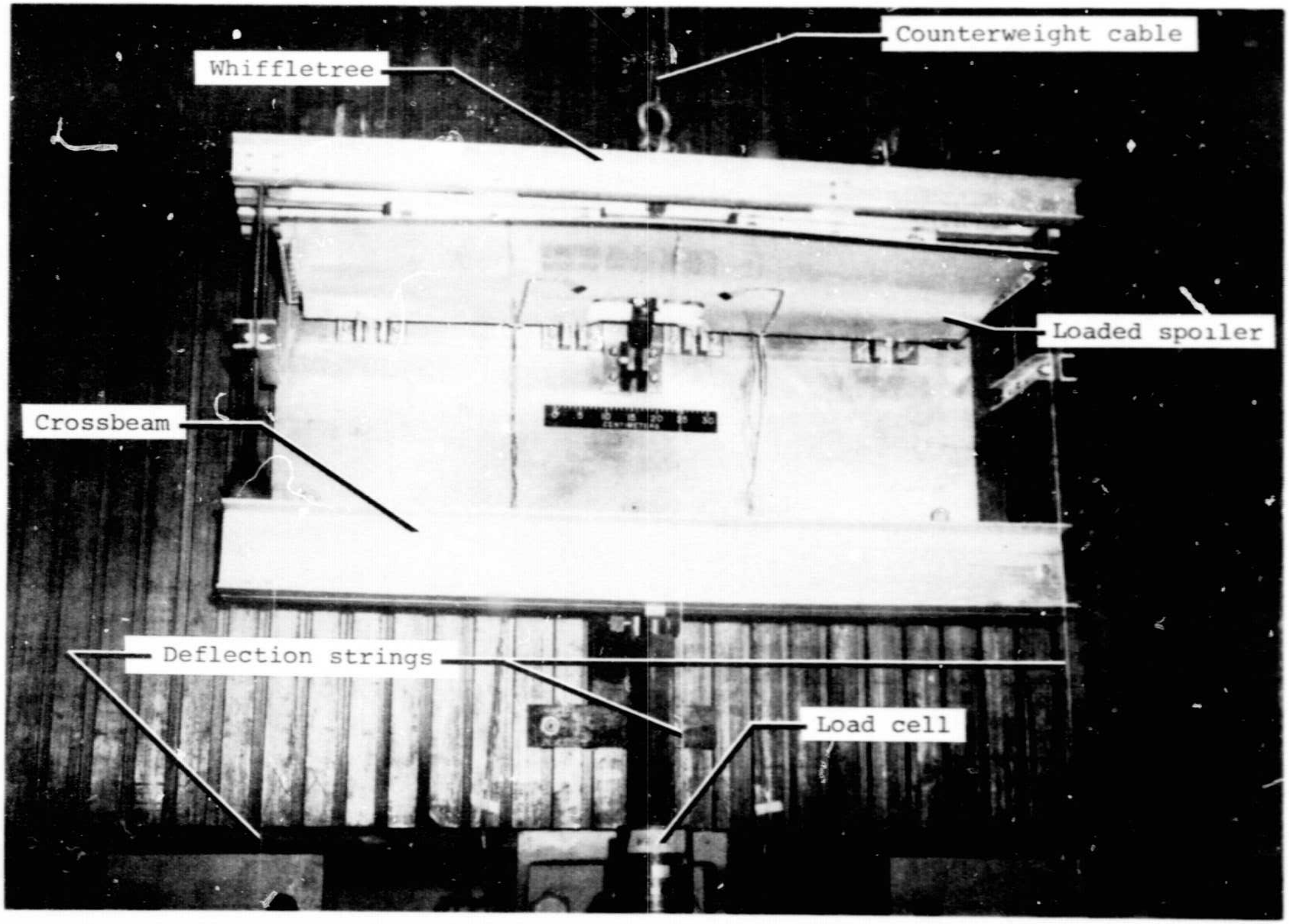

Figure 4. - Spoiler during loading in test rig.

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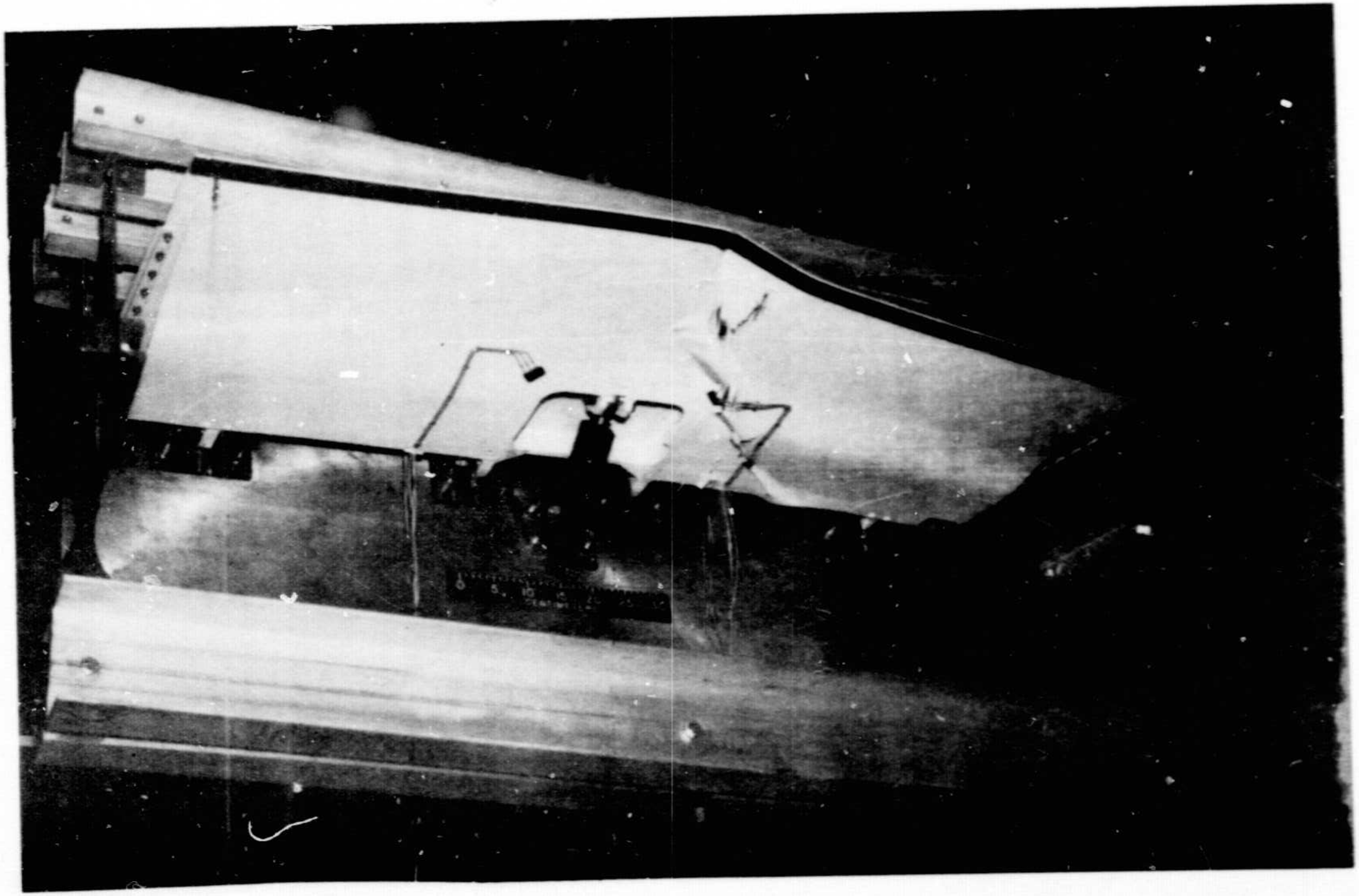
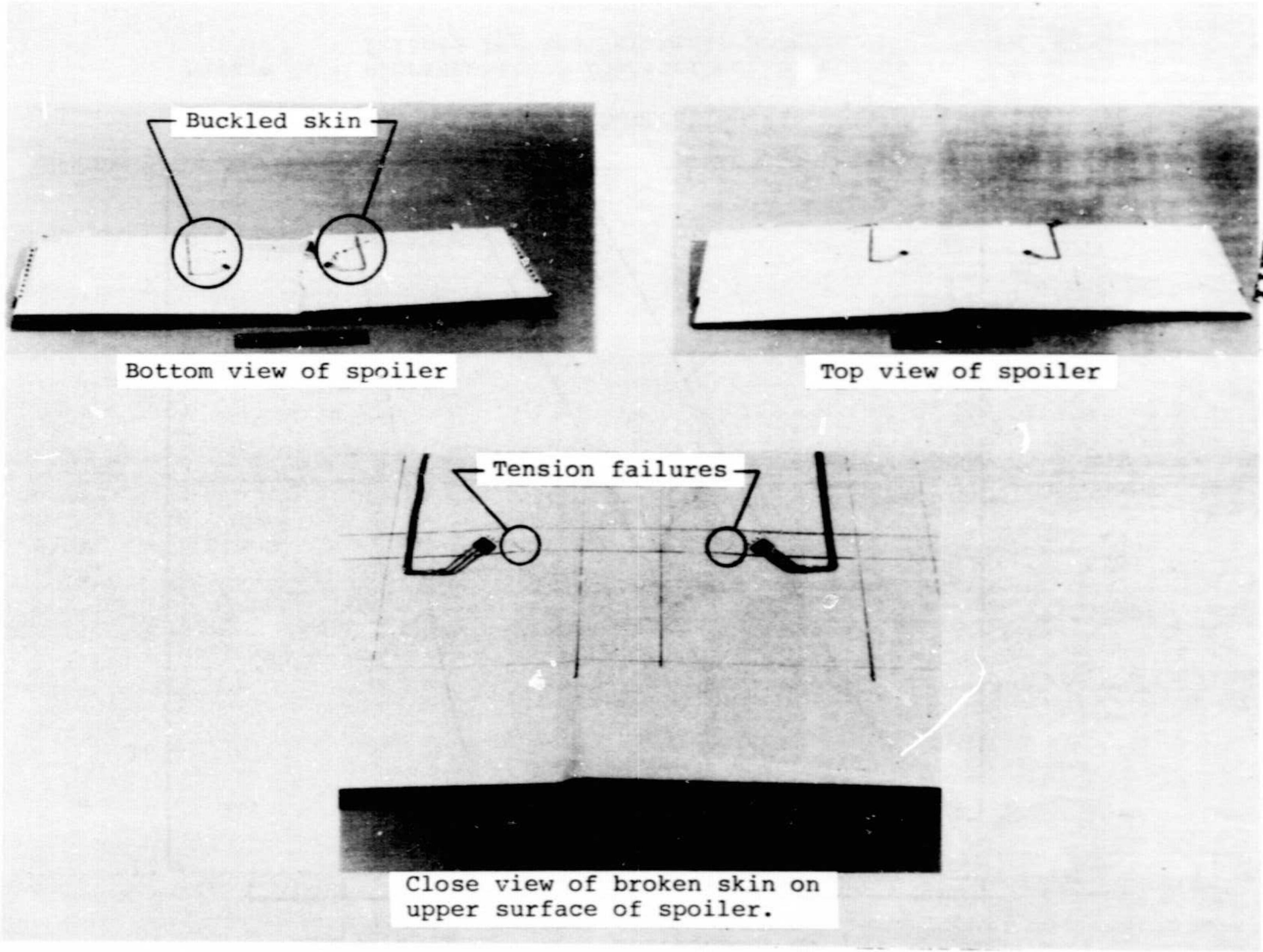


Figure 5. - Structural failure of spoiler.



Bottom view of spoiler

Top view of spoiler

Close view of broken skin on upper surface of spoiler.

Figure 6. - Views of failed spoiler showing extent of damage.

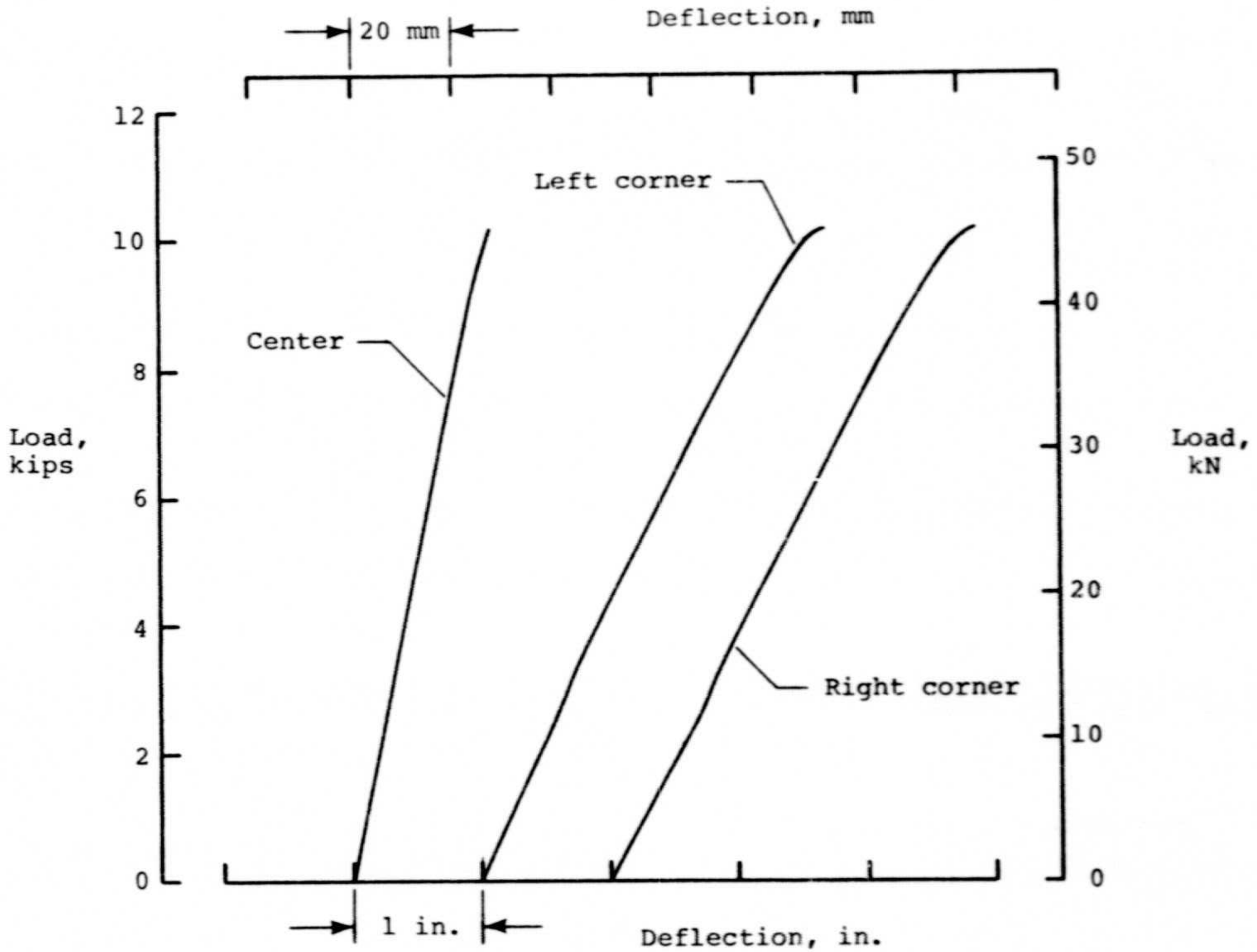


Figure 7. - Representative load-deflection curves to failure for spoiler trailing edge.

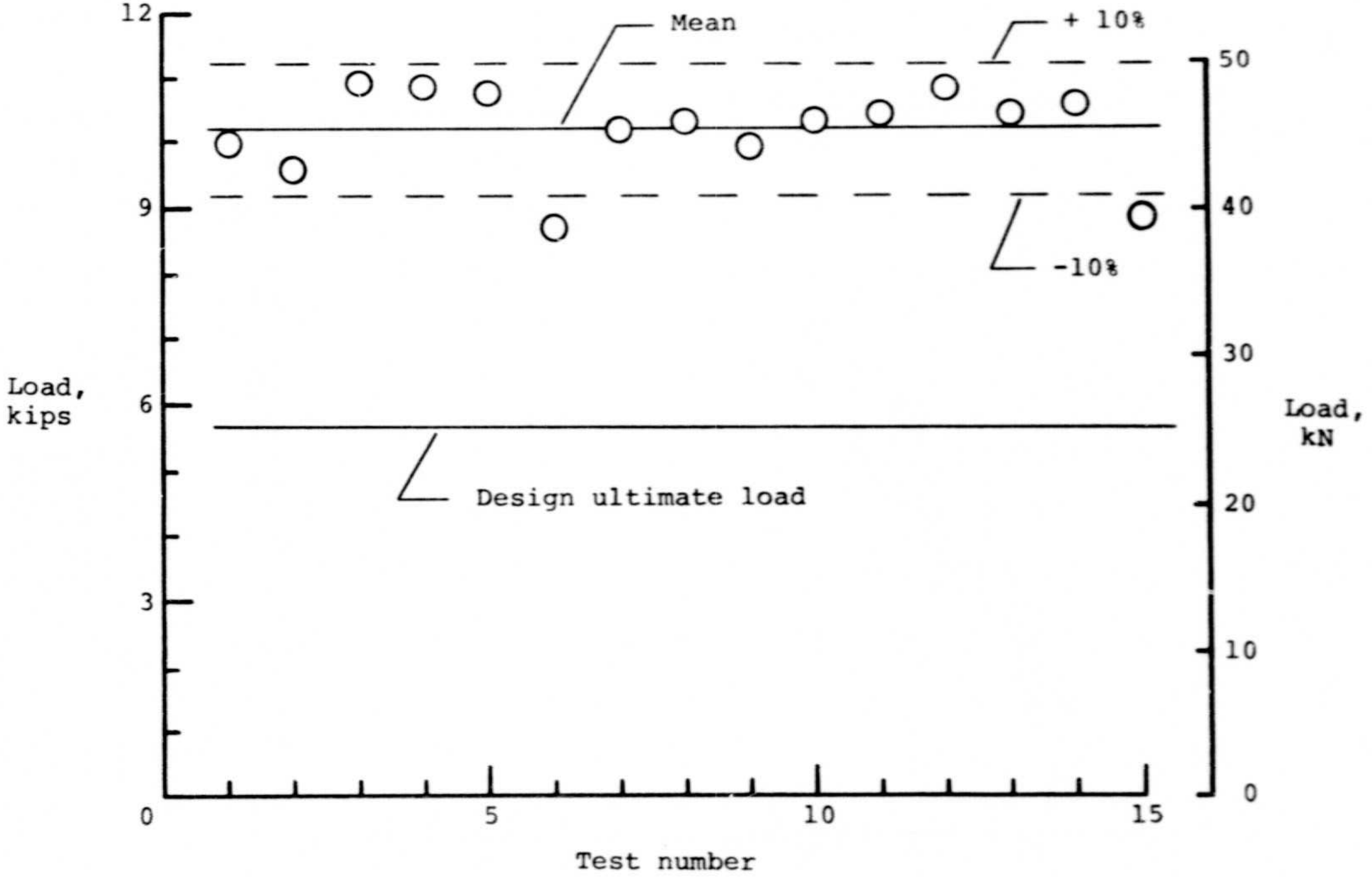


Figure 8. - Strength reproducibility of graphite-epoxy spoilers.

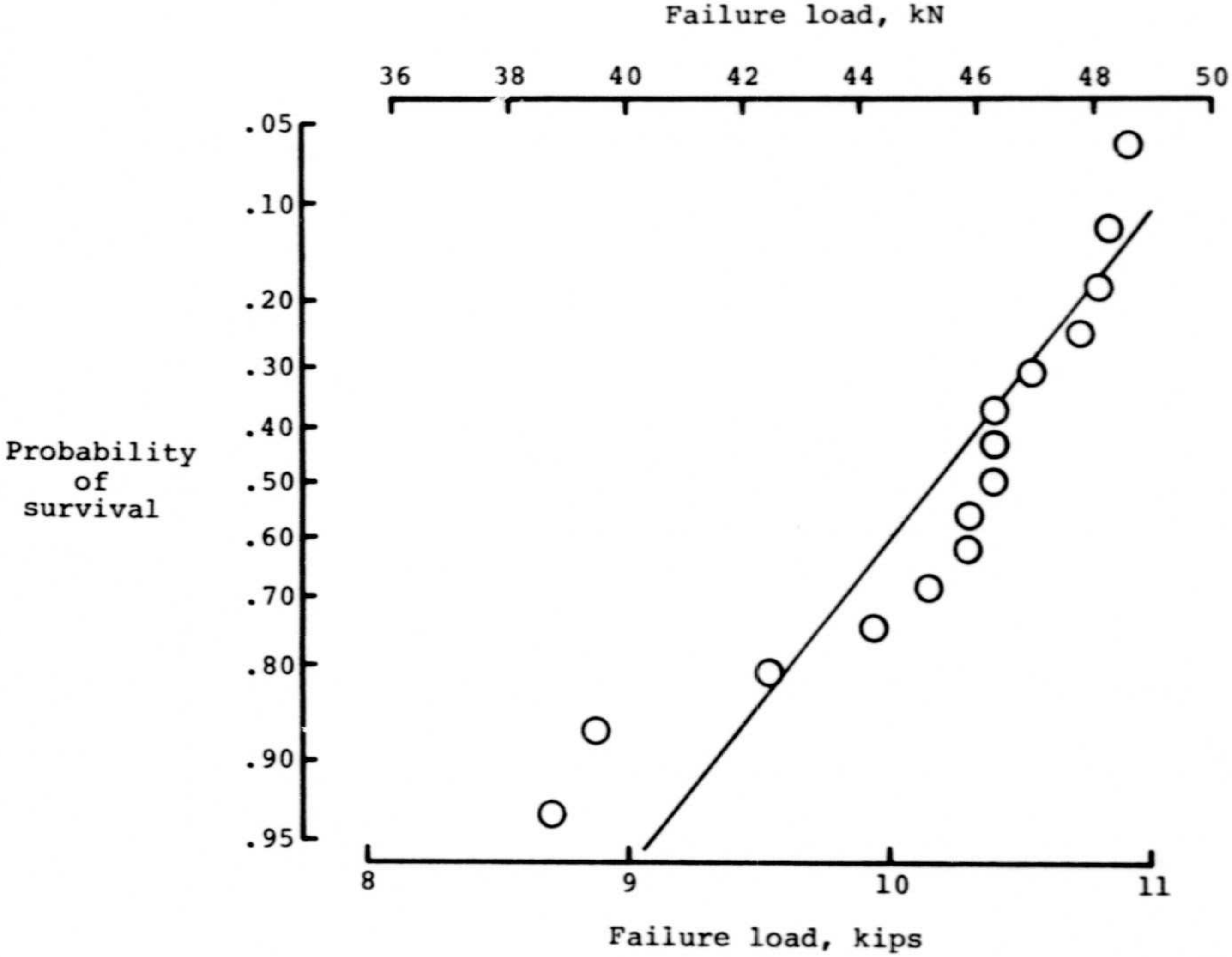


Figure 9. - Test for normal distribution of composite spoiler strength data.

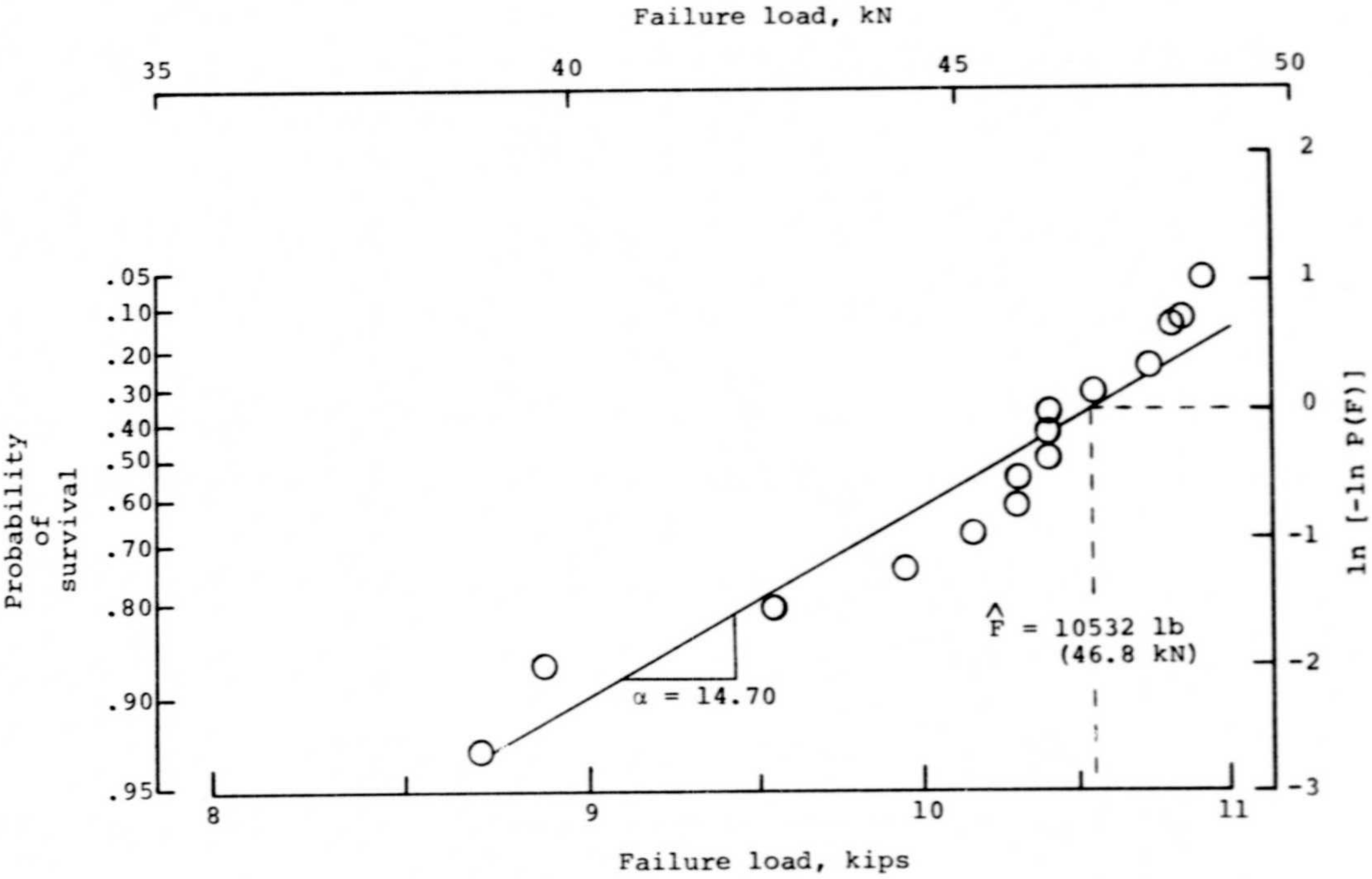


Figure 10. - Weibull distribution of composite spoiler failure loads.

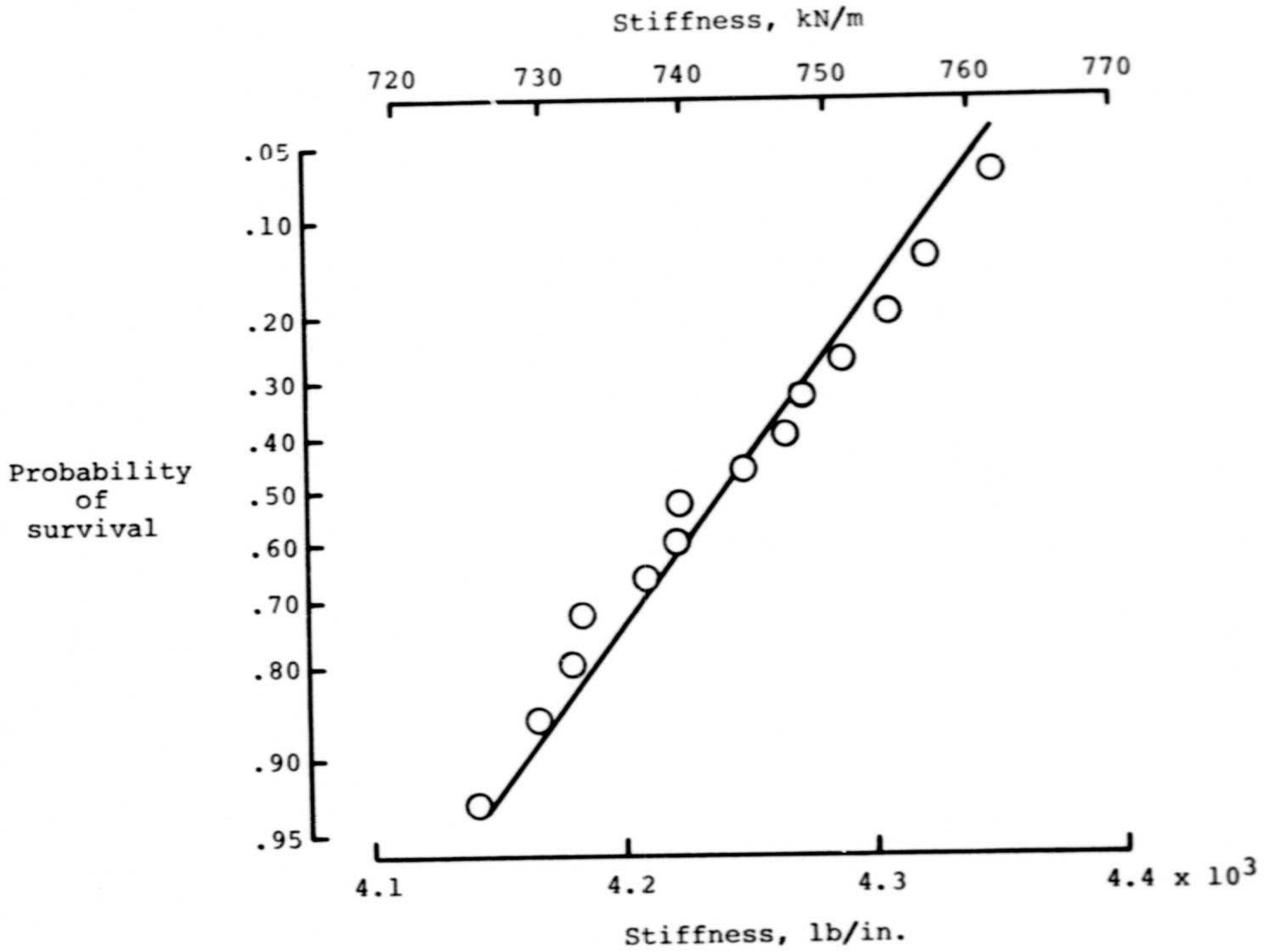


Figure 11. - Test for normal distribution of composite spoiler stiffness data.

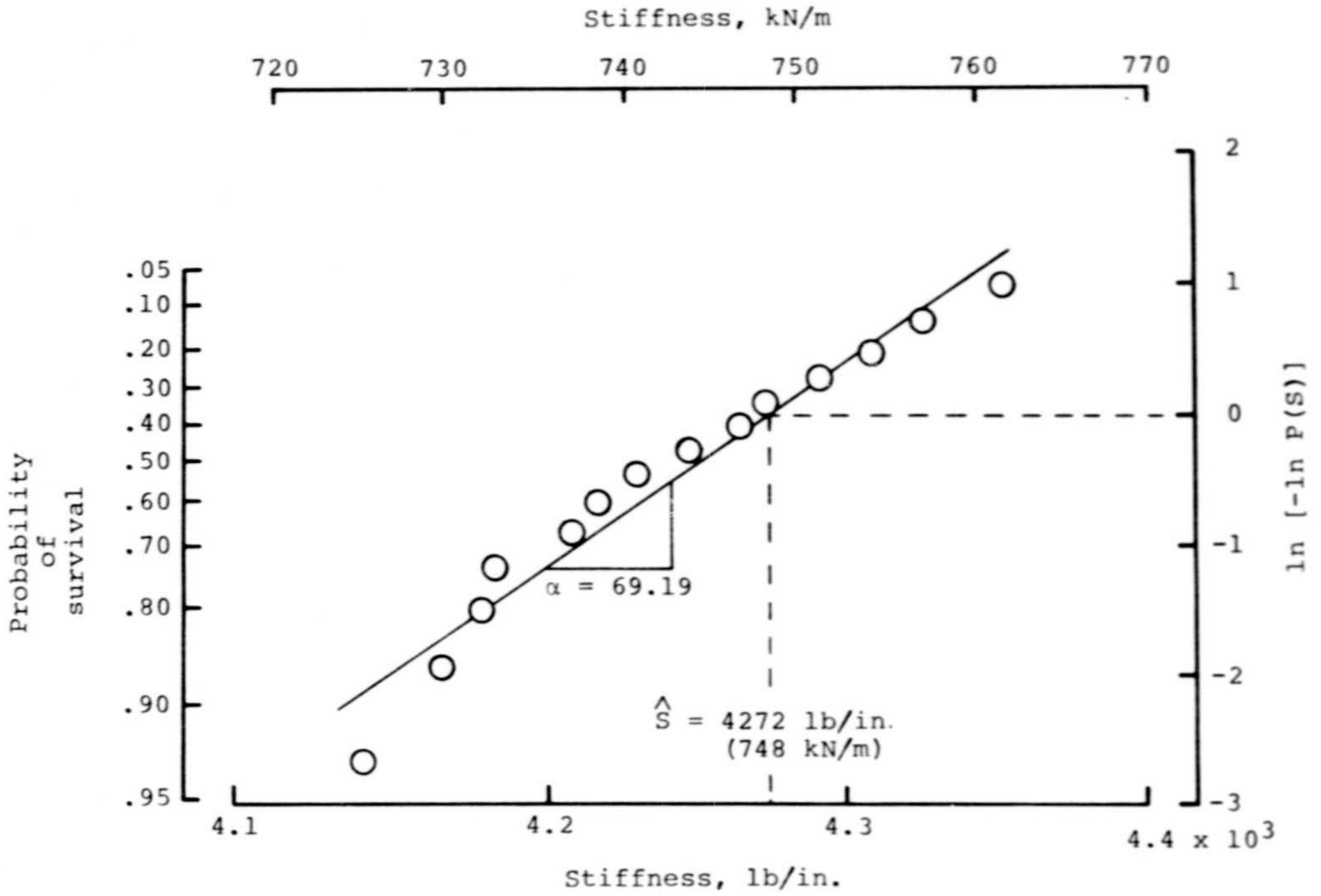


Figure 12. - Weibull distribution of composite spoiler corner stiffness.