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ACCELERATION, STRESS, AND DEFLECTION MEASUREMENTS ON THE XB-15 BOMBER IN GUSTY AIR

By H. A. Pearson

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Corps

ACCELERATION, STRESS, AND DEFLECTION MEASUREMENTS ON THE XB-15 BOMBER IN GUSTY AIR

By H. A. Pearson

Acceleration measurements in gusty air have been accumulated over a period of years in order to determine the loads to which airplanes may be subjected. Most of these data have been obtained with the V-G recorders that have been installed in Army, Navy, and commercial airplanes. Theoretical studies of the load variation while flying through various types of gusts have indicated that the "effective" gust velocities, as obtained from the V-G records, must be supplemented by data on the gust gradients. Consequently, some tests have been made on two airplanes, the Martin XBM-1 and the Aeronca C-2N, in gusty air to gain some information of the gradients to be expected. Although the number of flying hours in these tests is small as compared with the V-G total, they were sufficient to indicate that the critical gust gradient depended upon airplane size, a factor which had been given no particular consideration at that time.

Theoretical studies had also indicated that an additional factor called "dynamic overstress" might be of importance in the design of large projected airplanes. For these airplanes it appeared that the relationship between wing period, lag in lift, and gust gradient might be such that the wings in gusts would deflect considerably more than for the case of a static load of the same magnitude. The higher deflections would naturally be accompanied by higher stresses in some of the members of the structure.

It thus appeared desirable to conduct experiments on larger airplanes both for the purpose of determining gust gradient distances and for determining the existence of the dynamic overstress which the theory indicates. The Army Air Corps agreed to cooperate in this project by allowing suitable equipment to be installed in their large XB-15 bomber.

This report presents the results of these tests which cover a total of about 70 flying hours on this airplane. These measurements were made under authority granted by the Air Corps in October 1938.

Acknowledgements are due to members of the Air Corps who made these tests possible and in particular to Major C. V. Haynes and Sgt. A. Cattarius for their cooperation.

AIRPLANE AND INSTRUMENTS

Airplane.- The XB-15 bomber (fig. 1) is metal-covered except for the fabric-covered portion of the wing aft of the rear spar. The wing is of two-spar construction, the rear spar being straight and the front spar swept back. All gas and oil is carried within the wings, the gas tanks being located as shown in figure 2. Figure 2 also shows the estimated dead-weight distribution (tanks full) including both the distributed as well as the concentrated-weight items. The wing structural dead-weight distribution has been adjusted so that the total integrated weight is equal to 8,000 pounds. Other pertinent dimensions of the airplane are listed in table I.

Drum instruments.- The following standard N. A. C. A. photographically recording instruments were used in these tests:

(1) Air-speed recorder located in the nose of the airplane and connected to a swiveling pitot head 12 feet forward of the nose. (See fig. 1.)

(2) Accelerometer mounted on the catwalk in the bomb bay near the center of gravity.

(3) Accelerometer mounted in the wing 29 feet 1 inch out from the airplane center line.

(4) Control position recorders on the aileron and elevator. These instruments were used mainly to guard against confusion of gust accelerations and accelerations that might be due to control manipulation.

In addition to the above, a D. V. L. optograph mounted rigidly in the top gun turret was used. This instrument was equipped with two telephoto lenses which recorded photographically the deflection of three 50-candlepower lights mounted along the rear spar. The installation is shown diagrammatically in figure 3.

Strain gages.- Four N. A. C. A. and four D. V. L. scratch recording strain gages were used. The N. A. C. A. gages were of the intermittent drive type and had a gage length of 10 cm. while the D. V. L. gages had a continuous drive and a gage length of 20 cm. The N. A. C. A. gages were located on the top chord member of the front spar at stations 5 feet 11 inches and 39 feet 9 inches out from the center line of the airplane. These stations were approximately at the wing root and at the end of the outer gas tank. The D. V. L. gages were located on the diagonal members below the N. A. C. A. gages and all gages were positioned so as to be in the middle of their respective bays. The gages were mounted in pairs at each station and all of the gages, with the exception of the two on the root chord member, were mounted on duralumin. The strain-gage locations are shown in figures 3 and 4.

All instruments were synchronized by a timer connected into the circuit. The timing interval was 2.28 seconds for all the instruments except the N. A. C. A. gages which were operated once every 6.84 seconds.

FLIGHTS

The following flights were made with N. A. C. A. equipment on board.

No.	Date	Destination	Flying time, hrs.	Instrument time, min.
1[1]	8-29-38 8-31-38	Langley, Selfridge, Mitchell, Langley	8-1/2	28
2	11-29-38 -30	Langley, Bolling, Chanute, Wright	10-1/4	22
3	12-6-38	Langley, Maxwell, Langley	7	0
4	12-12-38	Langley, Kittyhawk, Langley	2	0
5	12-15-38	Langley, Amarillo, Tex.	10-3/4	0
6	12-16-38	Amarillo, March Field, Cal.	7-1/4	24
7	12-21-38	March, Hamilton	3-1/4	0

[1]No strain gages installed on this flight.

No.	Date	Destination	Flying time, hrs.	Instrument time, min.
8	12-22-38	Hamilton, Mt. Shasta, March	5-1/2	20
9	12-23/-24-38	March, Okla. City, Langley	13-1/4	22
			67-3/4	116

Although the total number of flying hours is small compared to the total flown, it includes a stretch of the roughest flying that this particular airplane had encountered to date. This stretch of rough air occurred during flight No. 8 while proceeding in a southerly direction at about 8,500 feet between Pasadena and Mt. Wilson, Cal. The gustiness was apparently due to mechanical atmospheric turbulence caused by winds blowing across the mountain tops. An examination of the flight notes for all the flights made (except for some of the accelerations measured in flight 1 where the airplane was flown through the edge of a number of cumulus clouds) reveals that the recorded accelerations were due to mechanical turbulence encountered while flying through passes in the Rocky Mountains or while flying over mountainous country.

If during a particular flight it appeared likely that acceleration increments of over ±1/4g would be encountered, the instruments were turned on until the roughness died down. Thus, during any one flight a number of runs at different airplane weights and altitudes were obtained some of which did not yield particularly large accelerations. These runs were nevertheless evaluated; however, for this memorandum it is only necessary to refer particularly to the results obtained in the flights given in the table below. The others are omitted mainly because the combination of airplane weight and the small accelerations encountered were amply covered by those that were included. Their omission changes none of the conclusions and their inclusion would only result in a mass of undistinguishable points clustered around the origin.

Flight No.	Run No.	Estimated airplane weight	Remarks
2	6	50,000	Fairly severe accelerations
6	1	60,000	
8	4	52,000	Most severe accelerations
9	1	65,000	Greatest weight

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Although the accelerations encountered in flights 6 and 9 are moderate with respect to 2 and 8, they are included mainly because the weights at the time of the run were considerably different from the usual 50,000 to 55,000 pounds. In the only flight (No. 5) in which the full gross weight of over 69,000 pounds was equaled, the air was perfectly smooth and no records were taken.

METHOD AND RESULTS

In evaluating the records to obtain gust velocities and gust gradients, the following method was used: For each center-of-gravity accelerometer record (roughly 20 feet of film) all peaks, indicating accelerations of approximately 0.2g or over, were read. These values of acceleration were then converted to effective gust velocities, U_e, from the equation

$$U_e = \frac{2\,\Delta n\,\frac{W}{S}}{\rho m V} \tag{1}$$

where Δn is acceleration increment from 1 g.

W, estimated weight at time of run.

S, wing area, square feet.

ρ, mass density of air at altitude.

m, slope of lift curve, taken as 4.76.

V, true air speed, feet per second.

The evaluation of the records in this manner yielded 560 effective gust velocities ranging from 1.7 to 17.5 feet per second. These gusts and the number in the various ranges are summarized in table II.

Of the above gusts, only 111, however, were usable for determining the gust gradient distance and the true gust velocities. The criterion used in selecting the gusts to be evaluated for gradient distance was (1) that the acceleration be 0.15g or over and (2) that the acceleration peak be immediately preceded by a reasonably steady flight portion (i. e., 1 g reading) of at least 2 seconds duration which, at the speeds that the XB-15 usually flies, corresponds to 25-30 chord lengths. Some such procedure is required

since it is necessary to eliminate the effects of any previous gusts and motions of the airplane on the acceleration measurement. Thus, many of the larger peaks encountered during flight 8 could not be used because the above criterion was not met with.

The gradient distance H in which the gust reaches a maximum value was determined by multiplying the time elapsing from the start to the peak of the acceleration by the true air speed as obtained from the air-speed record. Theoretical studies (references 1 and 2) indicate that such a procedure is justified since for the gusts encountered in the atmosphere the gradients are apparently such that there is little if any lag between the point of maximum acceleration and that of maximum gust velocity.

The true gust velocities that are associated with these accelerations were obtained by dividing the effective gust velocities of equation 1 by the "alleviating" factor $U_s = \frac{\Delta n_t}{\Delta n_s}$ whose value is given by

$$U_s = \left(A - \frac{2B}{2M + s}\right) \frac{s}{Hb} \tag{2}$$

where $M = \frac{2Wb}{\rho g S^2} + \frac{1}{4}$

A and B, theoretical factors given in reference 2.

s, distance from edge of gust to point at which acceleration is computed, chord lengths.

H, gradient distance, feet.

b, wing span, feet.

Δn_t, true acceleration.

Δn_s, the acceleration computed from the usual sharp-edge gust assumption for a gust velocity equal to the maximum of the gust for which Δn_t is determined.

The factor U_s thus corrects for the proportion of the gust velocity that is acquired by the airplane in traversing the gradient distance H. The true gust velocities, evaluated in this manner, are shown in figure 5 plotted against the

gust gradient distance H. Table III gives the number of gusts occurring within a given gradient distance.

The peak values on each of the D. V. L. strain gages and on the optograph were, with few exceptions, read only at the times which obviously corresponded to similar peaks on the center-of-gravity accelerometer record at which effective gust velocities were obtained. The variation of the stress and wing-deflection measurements with acceleration are shown in figures 6 to 17. Figure 6 shows the measured deflection of the tip light with acceleration at the airplane center for two different airplane weights while figures 7 and 8 show the same for the middle and inner lights. In these figures, as well as in those which follow, it is necessary to use 1 g as a datum since it was not possible to obtain a true zero stress or zero deflection reading. This was due to the fact that the wing must support its own weight which, as may be seen from figure 2, is considerably different from the air load acting over it. Figures 9 to 11 show the stress variation as recorded by the D. V. L. gages that were mounted on the outer diagonal while figure 12 shows the stress variation in the upper chord member. These results are all taken from flight 8 run 4. Figures 13 to 15 show similar measurements taken at the outer station for flight 2 run 6.

Figures 16 and 17 give the stress variation measured at the front and rear of the top chord member near the root on these same flights. No reliable stress measurements were obtained on the diagonal member at the root because of a complete failure of one of the gages and a partial failure of the other on both of the flights where the most severe accelerations were encountered. Thus, it was possible to obtain only the stresses at the absolute maximum and minimum accelerations that were encountered. The rate of change of stress as determined in this manner was only 850 pounds per square inch per load factor. The strain-gage records for this station on other flights on which the gage operated properly indicated such extremely low stresses in this member that no better value than that given above could be obtained because the scattering of points was of the same order of magnitude as the measured stresses. This unanticipated low stress variation may be due either to an oversize member at this station or to a failure of all of the expected load to pass through the member. Values of E equal to 10,300,000 and 30,000,000 pounds per square inch were used with duralumin and steel, respectively, in the evaluation of the strain-gage records.

Several time histories of some of the measured quantities are shown in figure 18 for three of the largest bumps encountered on flight 8. These time histories are included mainly to show the character of the variations obtained in gusty air.

PRECISION

The following are estimates of the accuracy to which the various quantities may be relied upon:

Acceleration (c. g.)	±0.05g
Acceleration (wing)	±0.1g
Air speed	±1 m. p. h.
Airplane weight	±2 percent
Deflection (outer light)	±1/2 in.
Deflection (middle light)	±1/4 in.
Deflection (inner light).	±1/8 in.
Stress (all D. V. L. gages).	±200 lb./sq.in.
Stress (N.A.C.A. gages on dural)	±400 lb./sq.in.
Stress (N.A.C.A. gages on steel)	±800 lb./sq.in.

The above limits for wing deflection and stresses apply when all records are read at peak values or at the synchronization marks where the correspondence among the various records is obvious. It may be seen from figure 18, however, that the synchronization between timer marks (every 2.28 seconds) for the D. V. L. gages and for the optograph records may be off as much as ±0.15 second indicating that larger errors than those listed above would exist in the time histories. In the case of the D. V. L. strain gages, the poor synchronization was due principally to the uneven running of the motors which drove the targets through extension shafts and universal joints. For the optograph the slight fore and aft motion of the wing with changes in the chordwise forces was known to cause a lack of synchronization in the records. However, since most of the results given in this report are obtained by reading the various quantities at peaks which obviously correspond, the lack of synchronization between timer marks is of small importance.

DISCUSSION

Although these tests included a stretch of the roughest air that the XB-15 had encountered, the maximum effective gust velocity measured was only 17.5 feet per second. This value is only one-half of that which has been measured on overland transports and about two-thirds of that measured on the Clipper ships. (See reference 1.) It is necessary, however, to point out that the values given in reference 1 have in all cases been conservatively computed using the gross weight of the airplane. Such a procedure in the present case would give a maximum effective gust velocity nearly equal to the maximum measured on the Clipper ships. An interesting observation in connection with the maximum measured gust velocities obtained to date is that they appear to decrease with an increase in airplane span. This variation may be a true trend or it may be due to the fact that the number of flying hours for which records are available varies inversely with airplane size.

Figure 5 in conjunction with table III indicates that the largest number of gusts evaluated for gradient distance as well as the maximum true gust velocity occur within a distance of 150 to 200 feet, a distance slightly more than the wing span. Previous tests on the XBM-1 and the Aeronca C-2N airplanes appear to indicate that the maximum true gust velocities are associated with gradient distances slightly larger than the respective wing spans. Such a result is partly in keeping with the hypothesis advanced in reference 1 which gives the result that the maximum gust velocity varies as the cube root of the gradient distance, the lateral extent being approximately the same as the gradient distance, H. In order to produce a fairly large normal acceleration, the gust should at least envelop the whole wing which would call for a gradient distance equal to or greater than the wing span.

An envelope of the points of figure 5 would give approximately the variation predicted in reference 1 up to a gradient distance slightly greater than the wing span, but beyond that point the true velocities appear to decrease. This variation may be due to the fact that fewer gusts were available for evaluation with large gradient distances, but it is felt that the neglected pitching motion of the airplane is mainly responsible. It is apparent that if an airplane is at all stable it will tend to pitch into the gust and relieve its effect, the amount of pitch, of course, depending both upon the gradient distance and the amount of stability.

Wing deflection.- Median lines through the points of figures 6 to 8 indicate that in the range of accelerations covered the wing deflection at each of the measured points is proportional to the acceleration at the airplane center. Since there is no guaranty that the angle-of-attack change across the span stays the same for a given acceleration, the scattering of points is greater than that indicated in the discussion of Precision. The mean line, however, should, according to probability, represent the case for symmetrical loading.

From these figures the rates of change of wing deflection with load factor, i. e. $\partial\delta/\partial n$, are as follows:

Weight	52,000	65,000
Tip light	8.5 in.	8.0
Middle light	3.0 in.	2.5
Inner light	1.0 in.	1.0

The values for weight 52,000 are the more reliable because of the greater range of load factors that was covered. Apparently for the weight conditions of the flights, large changes in weight have small effect on the wing deflection. Since it was customary to empty the inner fuel tanks first and then to switch to the outer tanks, the difference between 65,000 and 52,000 pounds would be represented approximately by both the inner and outer tanks being full in the one case and only the outer tanks being full in the other. No bombs were carried on any of the flights so that any weight variation may be attributed to differences in the amount of fuel carried.

Static tests made by Boeing of the outer wing panel and of the center section in which rear spar deflection was measured were pieced together and the following values of $\partial\delta/\partial n$ were obtained.

Tip light	13.6 in.
Middle light	4.7 in.
Inner light	1.5 in.

These apply for a weight of approximately 67,000 pounds but the dead-weight load distribution condition is not known.

The above deflections per load factor are considerably more than those obtained in flight and would certainly indicate that no dynamic overstress was obtained in the flight tests. Assuming that the static-test results applied to the case with all the useful load housed in the fuselage (i. e., no gas or oil) so that there would be some justification for reducing the above values of $\partial\delta/\partial n$ in the ratio 52,000/67,000, the reduced values would still remain above the listed flight values. It is admitted that the piecing together of the static deflection curves is liable to error; however, in the present case, two persons using different methods arrived at very nearly the same values of $\partial\delta/\partial n$ at each of the lights. After considering the above possibilities, it can be said that the wing deflection in flight is no more than and is probably less than the deflection for a static load of the same magnitude. Thus, the indication is that there is no dynamic overstress on the XB-15.

Stress measurements.- Median lines through the stress curves of figures 9 to 11 for the outer diagonal member indicate a direct proportionality (as measured from 1 g) between the stress and the load factor either when the gages are considered separately or when their results are averaged. Strain gages on this same member during the static tests indicated an average rate of change in stress (between -2.5 and 3g) of 5,700 pounds per square inch per load factor for the weight tested. Correcting this value, as previously, to 52,000 pounds gives 4,400 as against an average of 4,700 from the flight tests.

For the chord member at the outer station (fig. 12) the average value of $\partial\delta/\partial n$ is 3,500 pounds per square inch per load factor. This value is to be compared with the corrected value of 3,700 as given by the static tests.

The results from figures 13 to 15 do not show any really definite changes from the previous figures, i. e., 9-12, even though the weight is slightly different for the two flights. In fact, the results of figure 13 for the outer diagonal shear member indicate a slightly larger value of $\partial\delta/\partial n$ with a slightly lower airplane weight. This would indicate that the method of correction that was applied to the static test results was too conservative and that the corrected static values should be higher. Thus, the stress measurements at the outer station apparently indicate that, as far as the XB-15 is concerned, dynamic overstress is either not present or is sufficiently small so that both the instrument accuracy and the amount of instrumentation must be increased in order to detect it.

For the stresses in the steel root chord member (figs. 16 and 17) the average value of $\partial\sigma/\partial n$ is 14,800 pounds per square inch per load factor. This compares with an uncorrected value of 21,600 obtained for this same member in the static tests and a "corrected" value of 16,700. The corrected value would presumably apply in the case where all the useful load was carried in the fuselage.

The time histories of figure 18 call for no particular comment other than to point out that the accelerometer records, wing deflections, and stresses show quite similar variations except that the minor variations appear to be smoothed out in the strain-gage results.

Although it was not intended to measure the wing frequency in flight, it could readily be obtained from the wing deflection records and was found to be about 3.4 c. p. s. at the tip and middle light. This frequency is included principally because it is approximately one-half that obtained in the routine vibration tests that have been conducted on this airplane.

CONCLUSIONS

1. The most critical gradient distance for this airplane is between 150 and 200 feet or of about the same order as the wing span. Gusts encountered with lower gradient distances apparently have insufficient energy to produce large accelerations while for the stronger gusts of longer gradient distance the pitching action of the airplane relieves the load.

2. The maximum true gust velocities measured were just over 30 feet per second and the maximum effective sharp-edge gust velocity measured was 17.5 feet per second. These values were obtained in the roughest air this airplane has encountered to date.

3. Both the wing deflection and strain-gage measurements indicate that there was very little, if any, dynamic overstress induced in the wings by the type of gusts encountered. Since this is in accordance with somewhat similar measurements taken on the M-130 airplane, it may be said that dynamic overstress will probably be negligible on airplanes with spans of less than 150 feet flying at speeds less than about 200 miles per hour.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 16, 1939.

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1. Rhode, Richard V.: Gust Loads on Airplanes, S. A. E. Trans., March 1937, pp. 81-88.

2. Küssner, Hans Georg: Stresses Produced in Airplane Wings by Gusts. T. M. No. 654, N. A. C. A., 1932.

Table I

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General Dimensions of XB-15

Overall span	149'0"
Overall length	87'7"
Overall height	25'10"
Tread	25'
Wing	
Section NACA 0018 (root) NACA 0010 (tip)	
Chord (root)	29'0"
Incidence	4°30'
Dihedral 3° (upper) 6°30' (lower)	4°45'
Area (including ailerons)	
net	2480
gross	2760
Flap area	252
Ailerons	
Area to hinge ℄	125
Area of balance (Frise)	37.8
Horizontal Stabilizer	
Span	45.0
Area to hinge ℄	276.0
Elevator	
Area to hinge ℄ (includes trim tabs)	162.1
Area balance	

Table I (con'd)

Area control tabs	14.8
Area trim tabs	9.2
Total Area	180.5
Vertical Stabilizer	
Area to hinge ℄	60.70
Rudder	
Area to hinge ℄ including trim tab	78.2
Area of control tab	4.00
Area of trim tab	4.00
Area of balance	2.2
Total Area	82.2
Engines	
4- R-1830-11 P+W Twin Wasp B	
Gear Ratio	3:2
Blower Ratio	10 to 1
1000 HP @ 2450 38" Hg (take off)	
850 HP @ 2450 31" Hg @ 6000 ft	

TABLE I (con'd)

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Weights

Weight Empty	37709
Crew + parachutes (13 @ 200)	2600
Baggage (est)	400
Fuel Main 1900 Aux 2290	25140
Oil (309 gals)	2318
Flares	274
Rations + utensils	145
Bomb racks + controls	212
Engine covers	49
NACA instruments	300
Special navigating instruments (est)	50
Total	69,197

TABLE II

SUMMARY OF EFFECTIVE GUST VELOCITIES, U_e

Gust velocity f.p.s	Number encountered
1-2	24
2-3	97
3-4	153
4-5	111
5-6	64
6-7	51
7-8	23
8-9	10
9-10	10
10-11	7
11-12	4
12-13	1
13-14	1
14-15	1
15-16	1
16-17	1
17-18	1
	560

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TABLE III

SUMMARY OF GUST GRADIENTS

Gradient Distance, H	Number Evaluated
50 – 75	5
75 – 100	12
100 – 125	17
125 – 150	13
150 – 175	25
175 – 200	12
200 – 225	8
225 – 250	5
250 – 275	1
275 – 300	3
300 – 325	2
325 – 350	2
350 – 375	0
375 – 400	3
400 – 450	1
450 – 500	1
500 – 650	1
Total	111

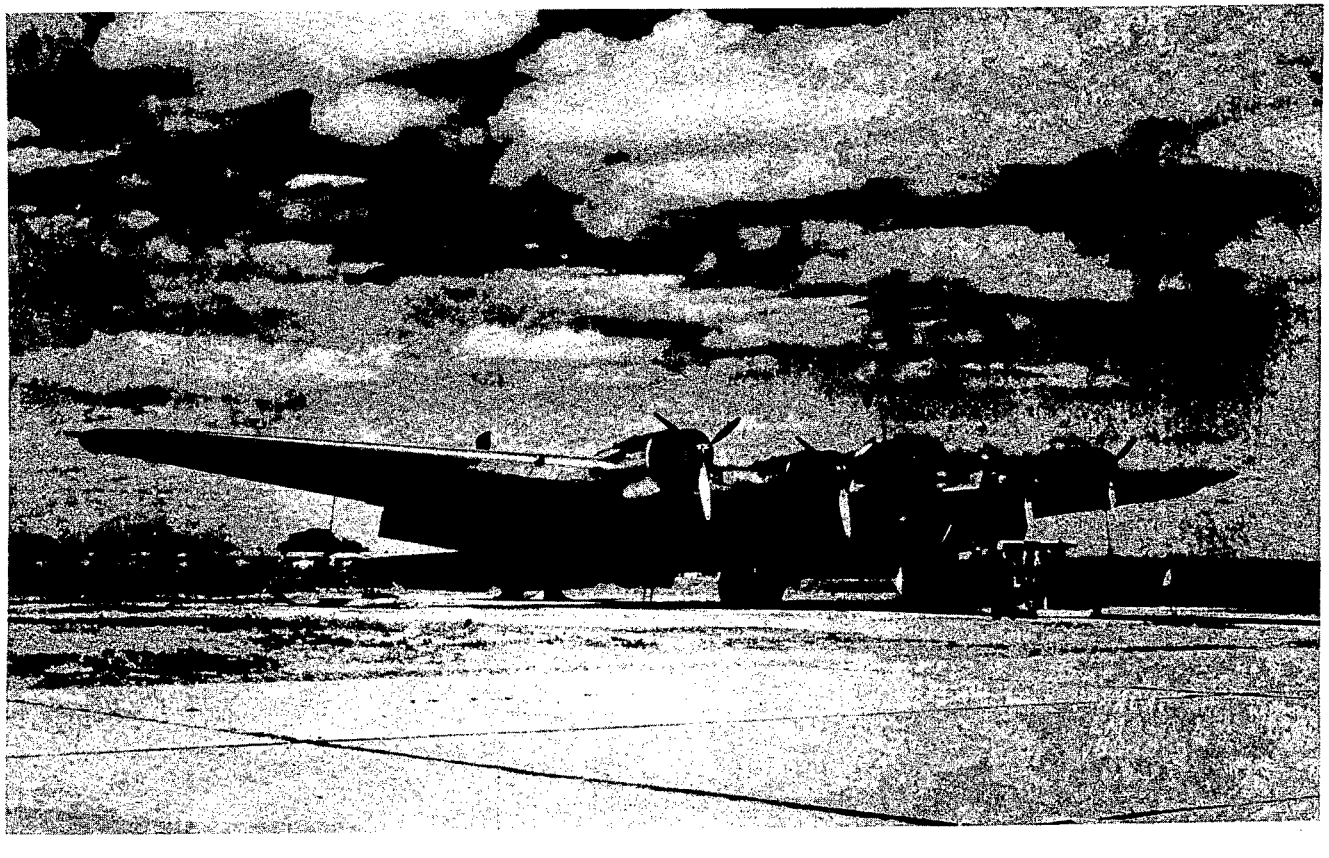

Figure 1.- Three-quarter front view of XB-15 airplane.

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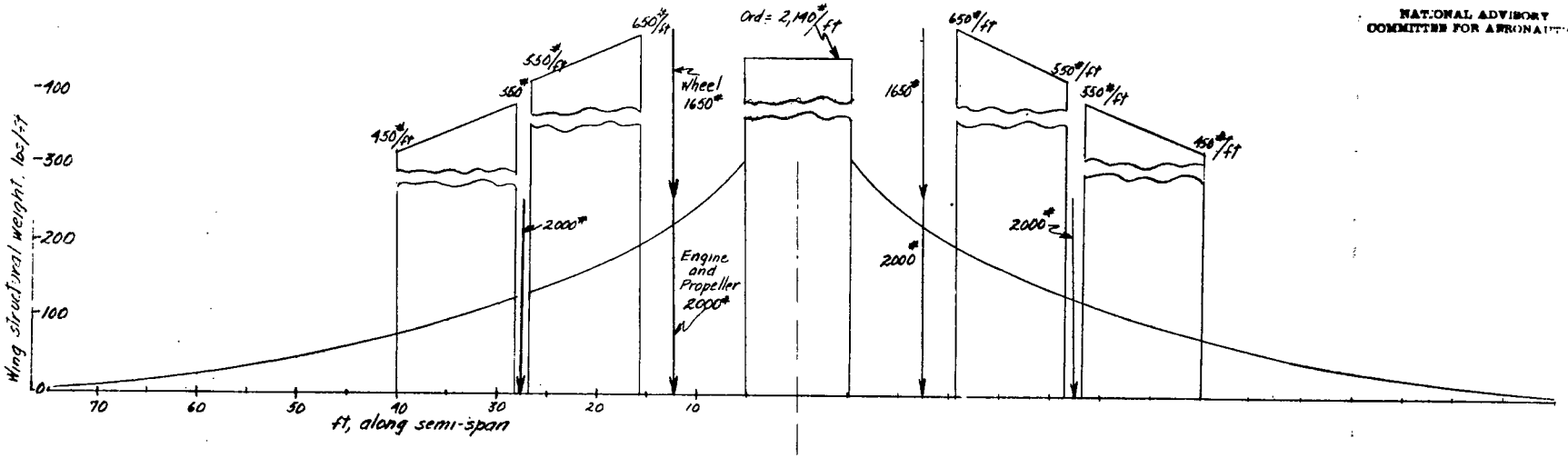

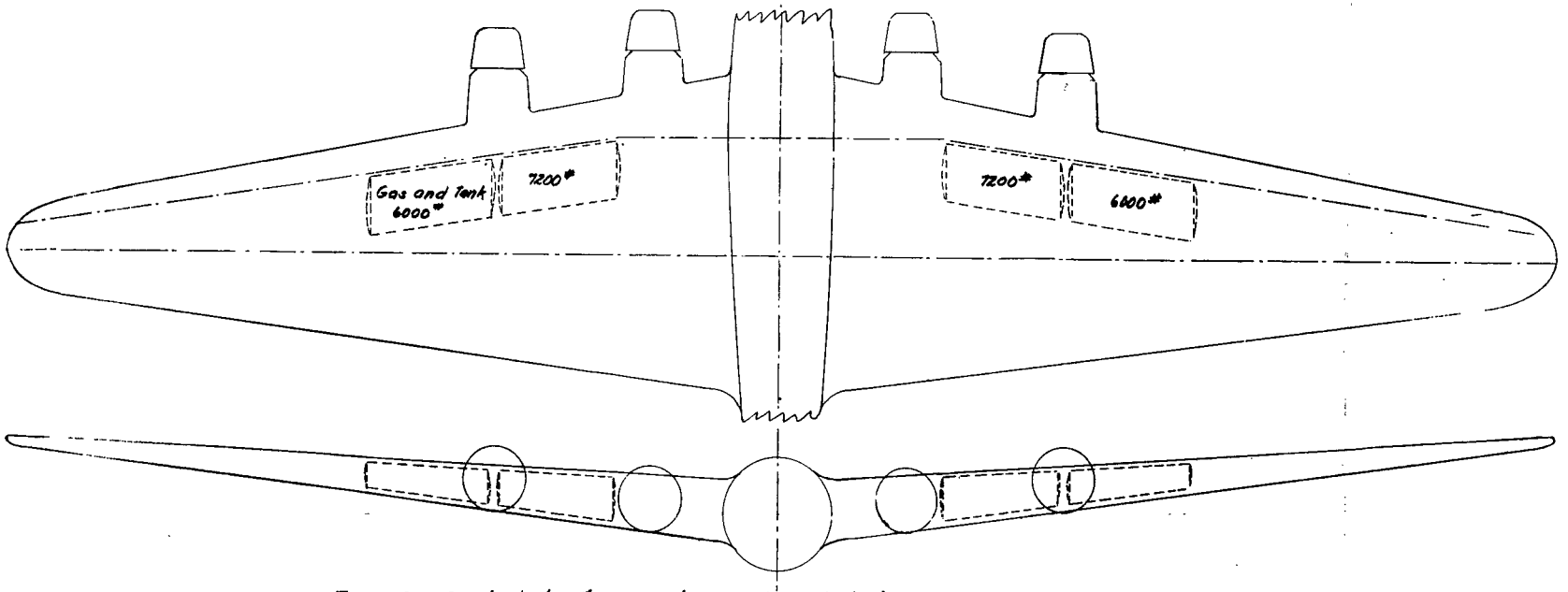

Figure 2.– Gas tank location and weight distribution of XB-15 (estimated)

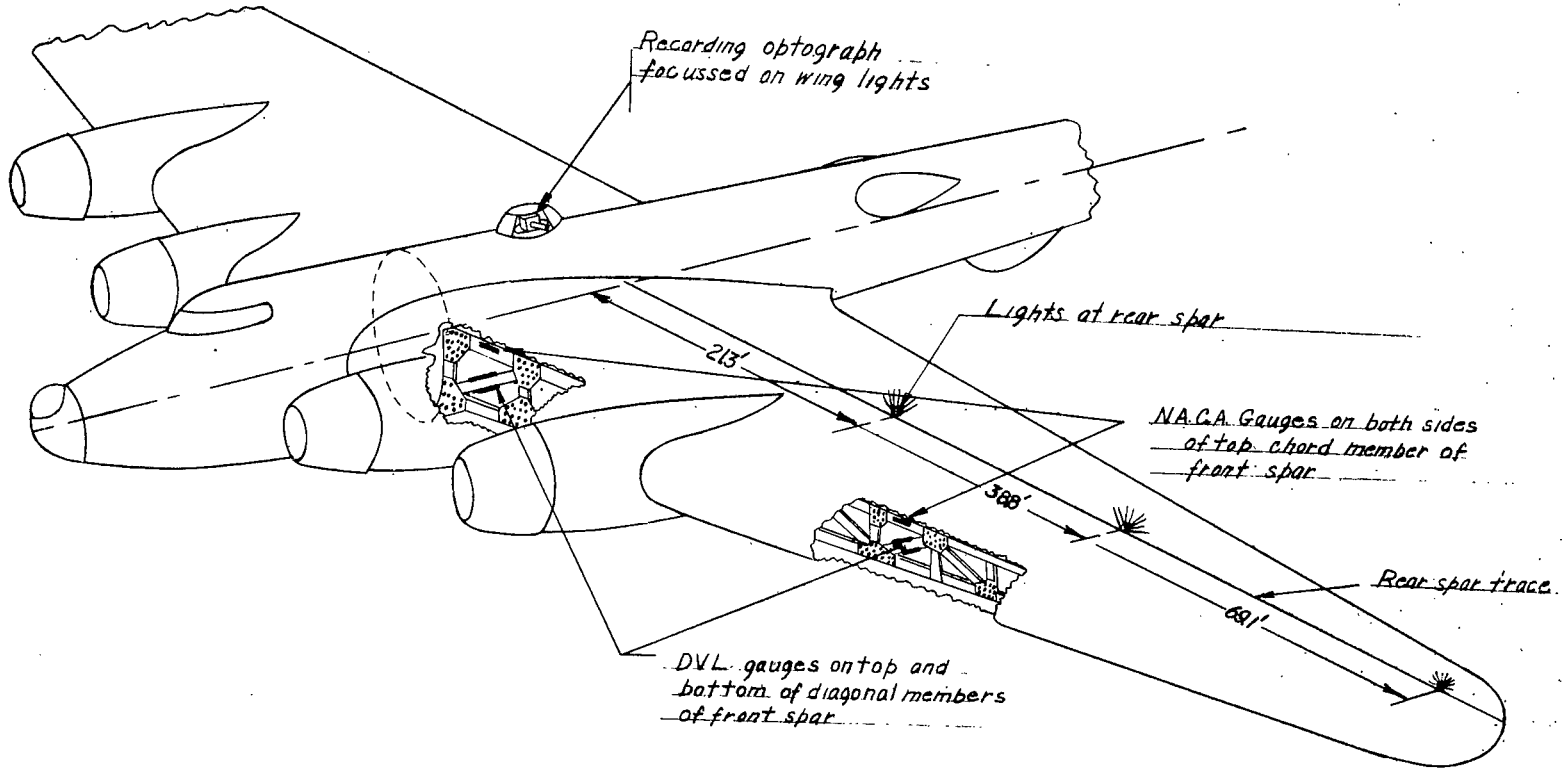

Figure 3- Sketch of Strain Gauge and Wing Optograph installation on the XB-15

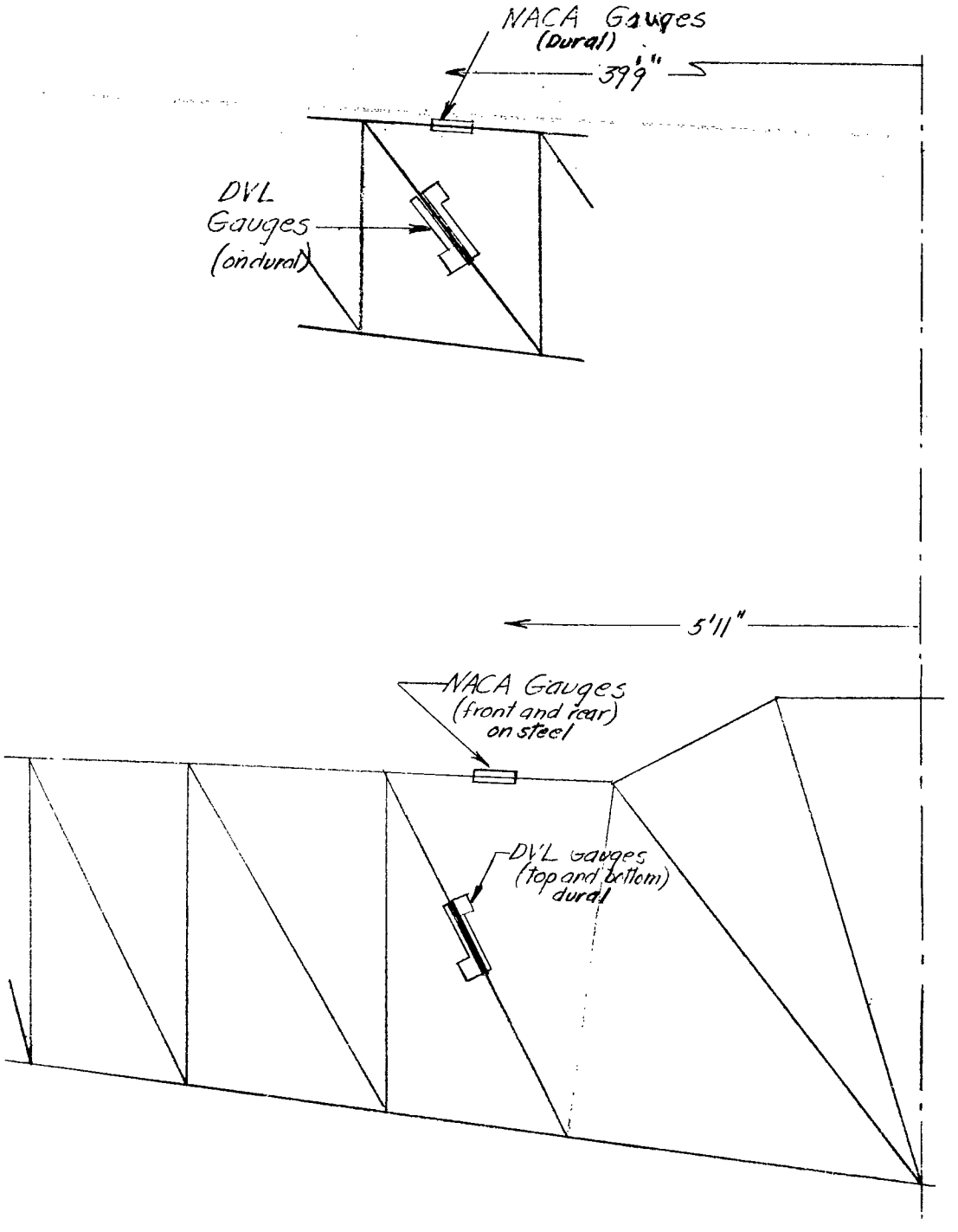

Figure 4.– Front spar truss center lines and strain gage locations

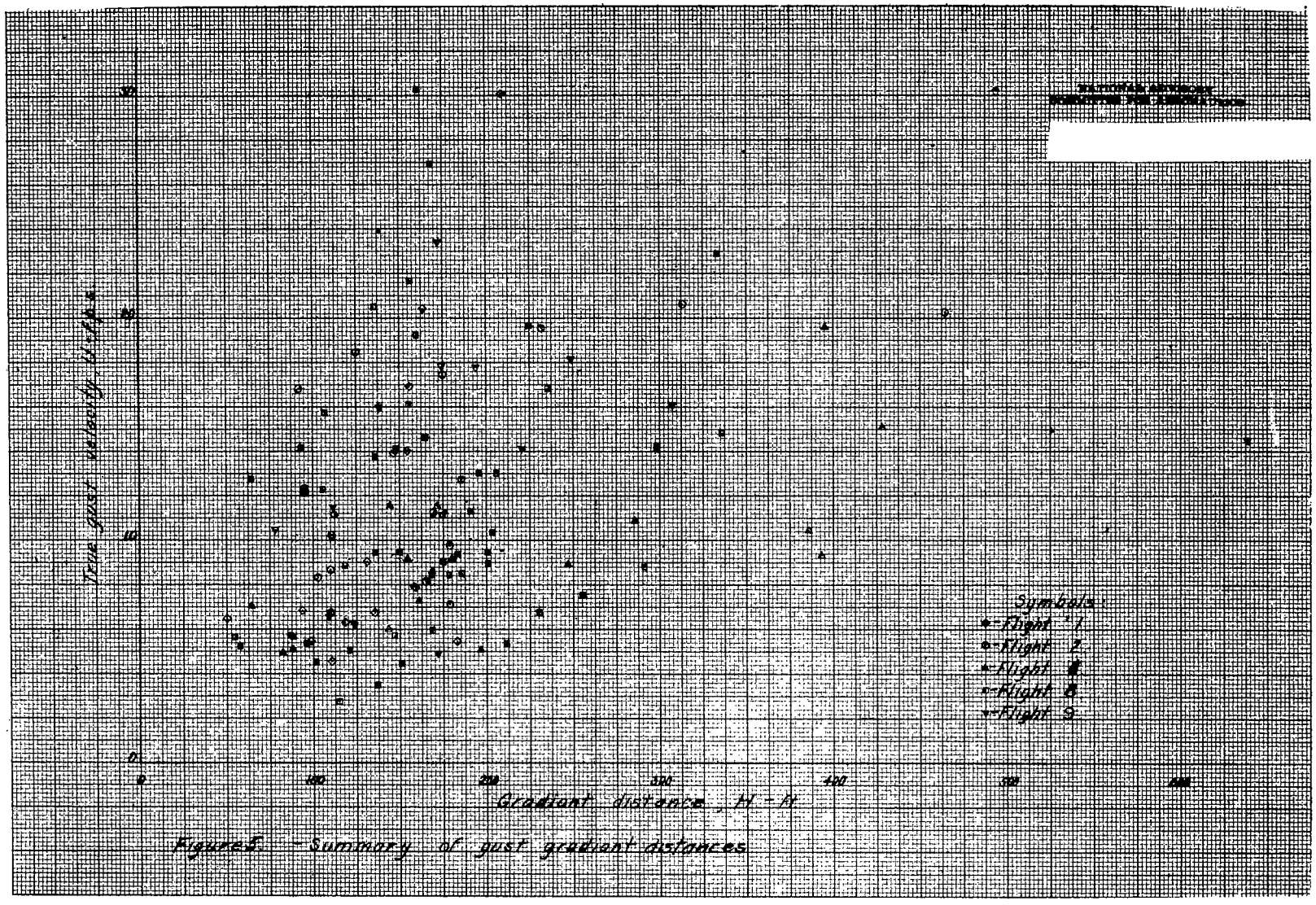

Figure 5. - Summary of gust gradient distances

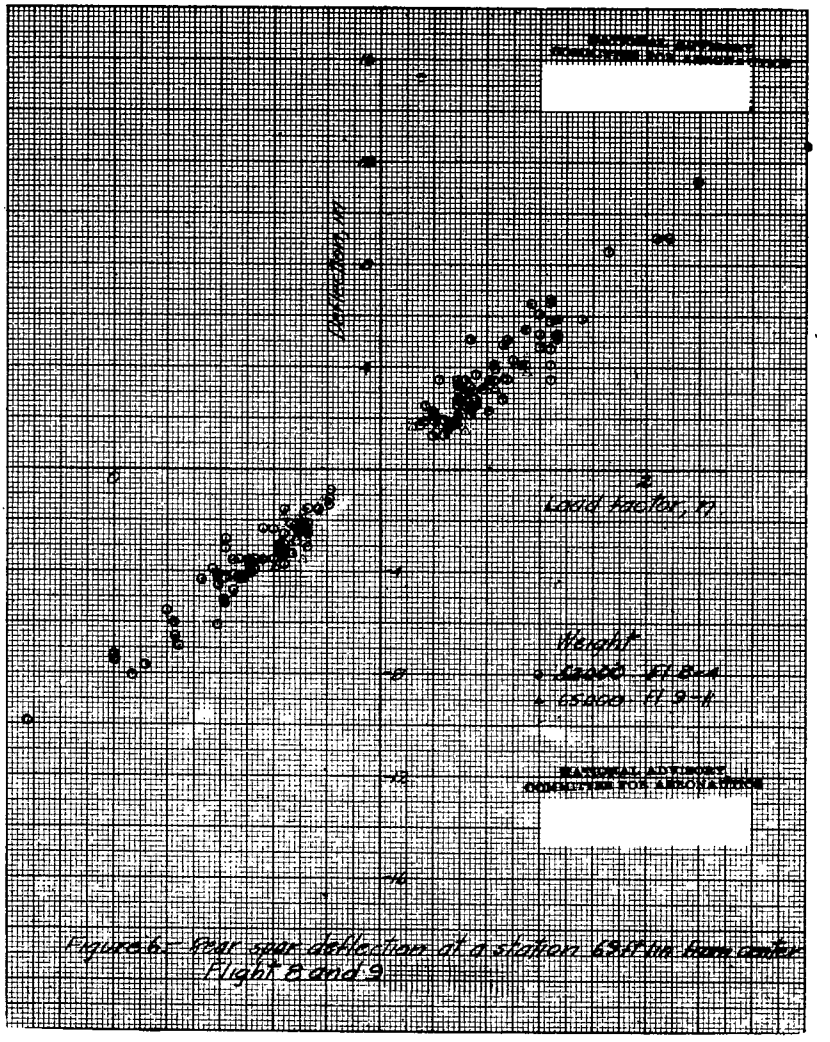

Figure 6.- Rear spar deflection at a station 63.5 in. from center. Flight 8 and 9.

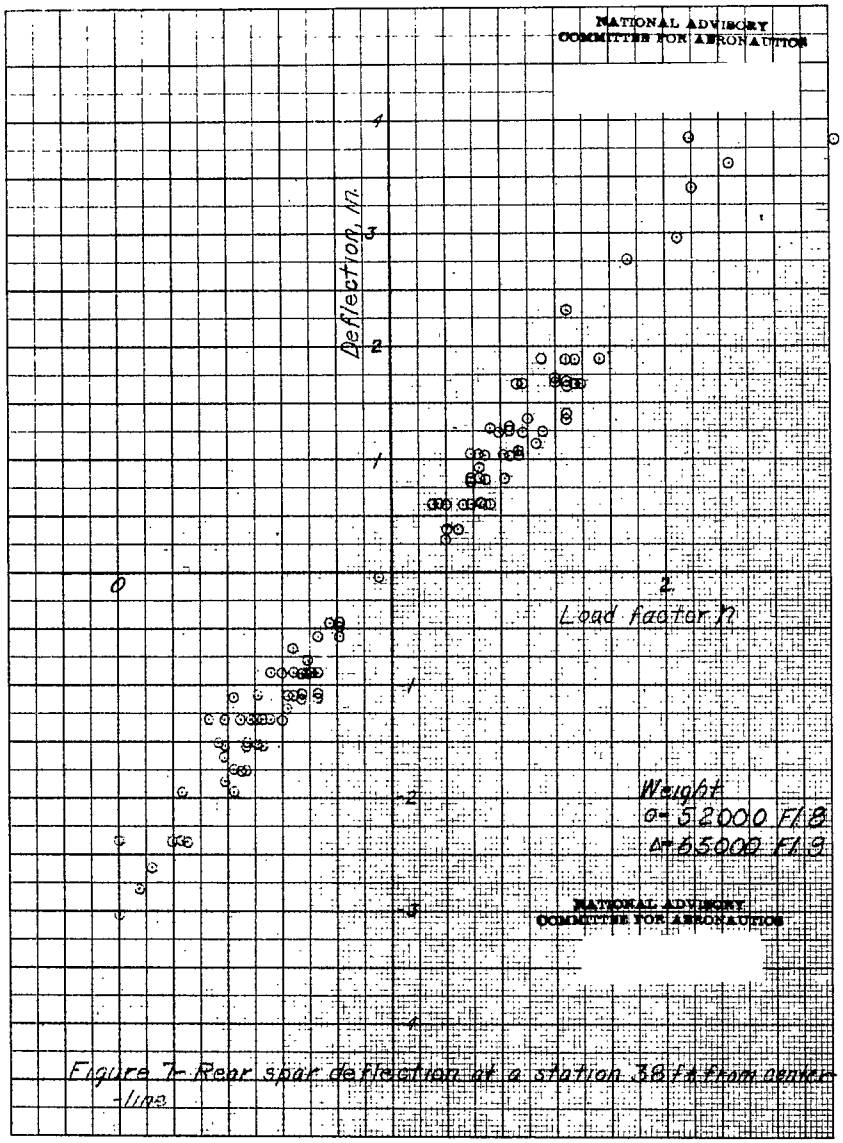

Figure 7- Rear spar deflection at a station 38 ft from center-line.

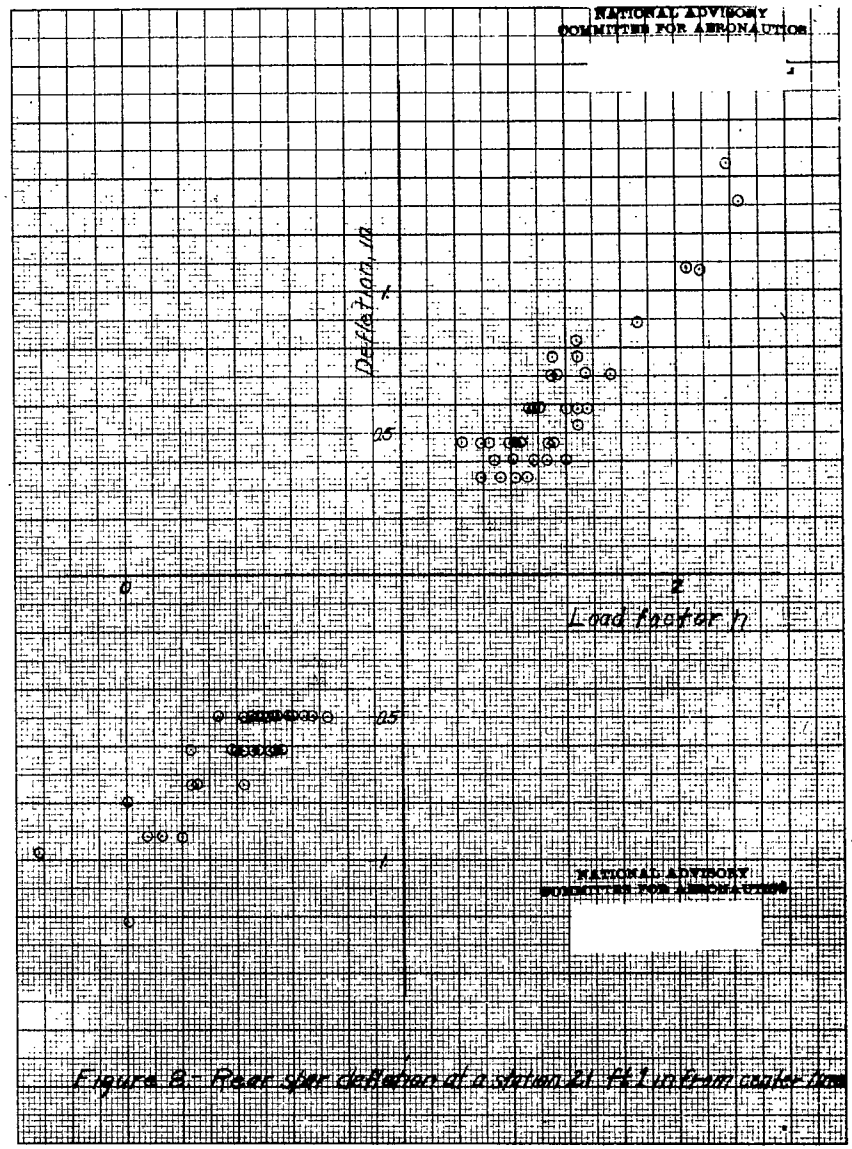

Figure 8- Rear spar deflection at a station 21 ft 1 in from center line

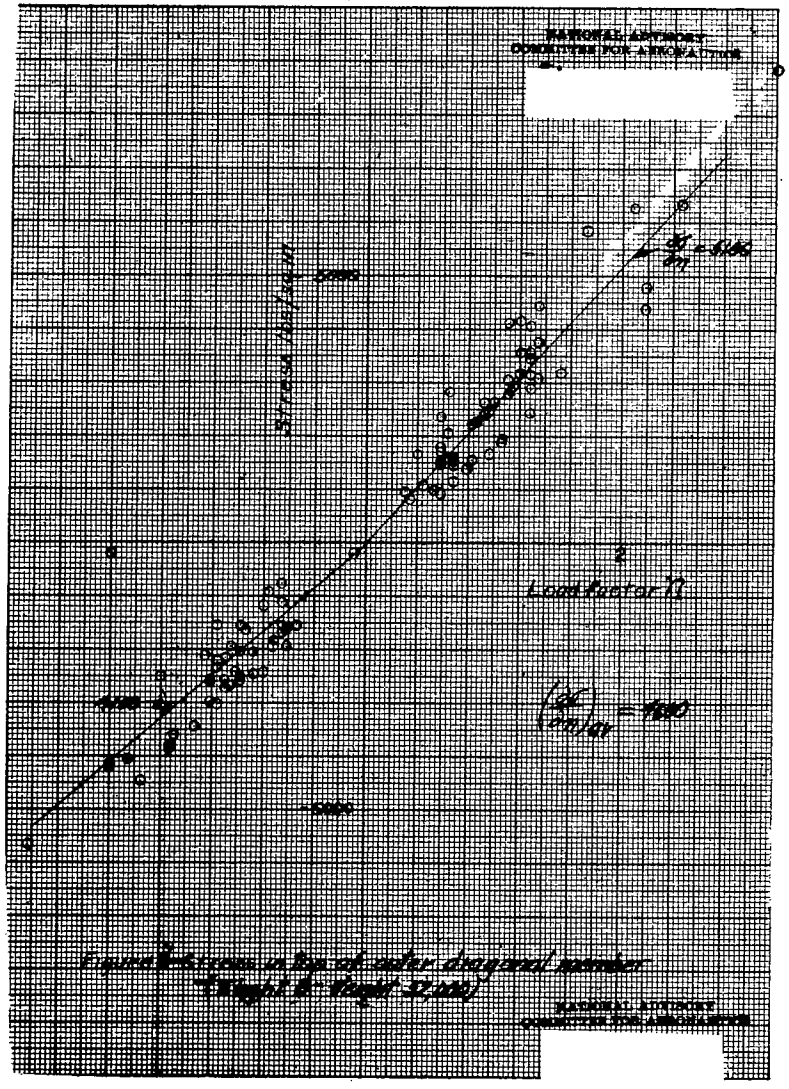

Figure 8 - Stress in top of outer diagonal member (Flight 8 - Weight 32,000)

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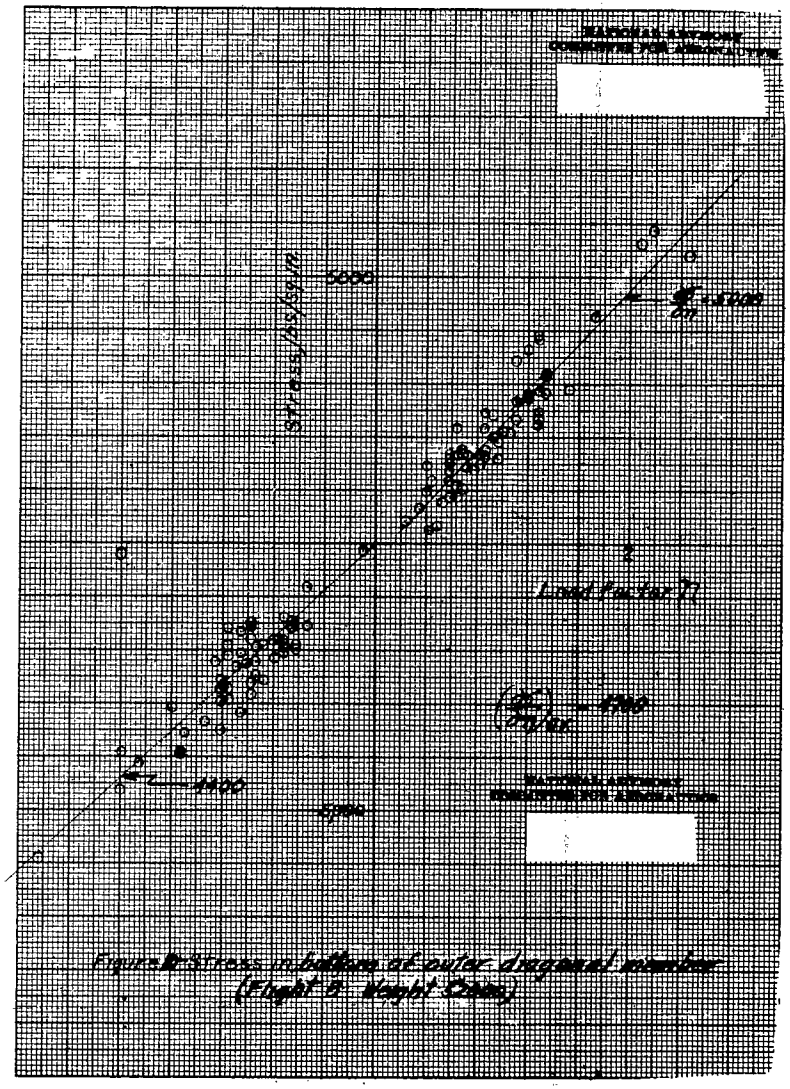

Figure 9 - Stress in bottom of outer diagonal member (Flight 8 - Weight 32,000)

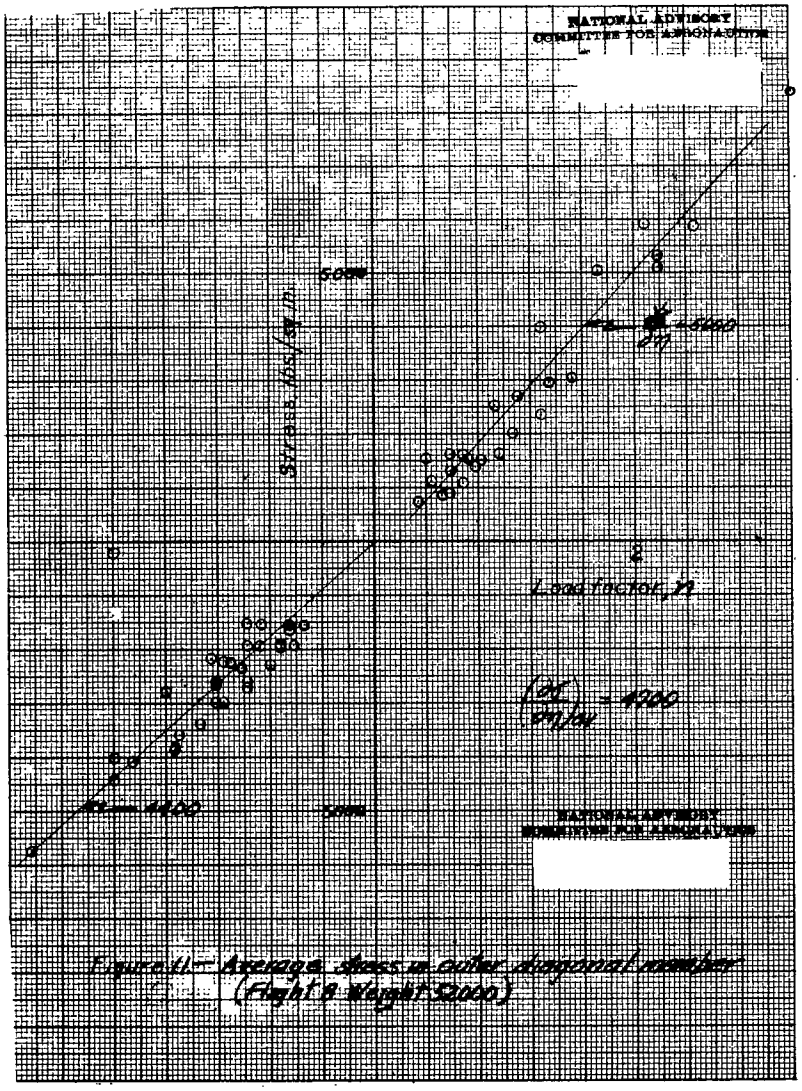

Figure 11.- Average stress in outer diagonal member (Flight B Weight 5000)

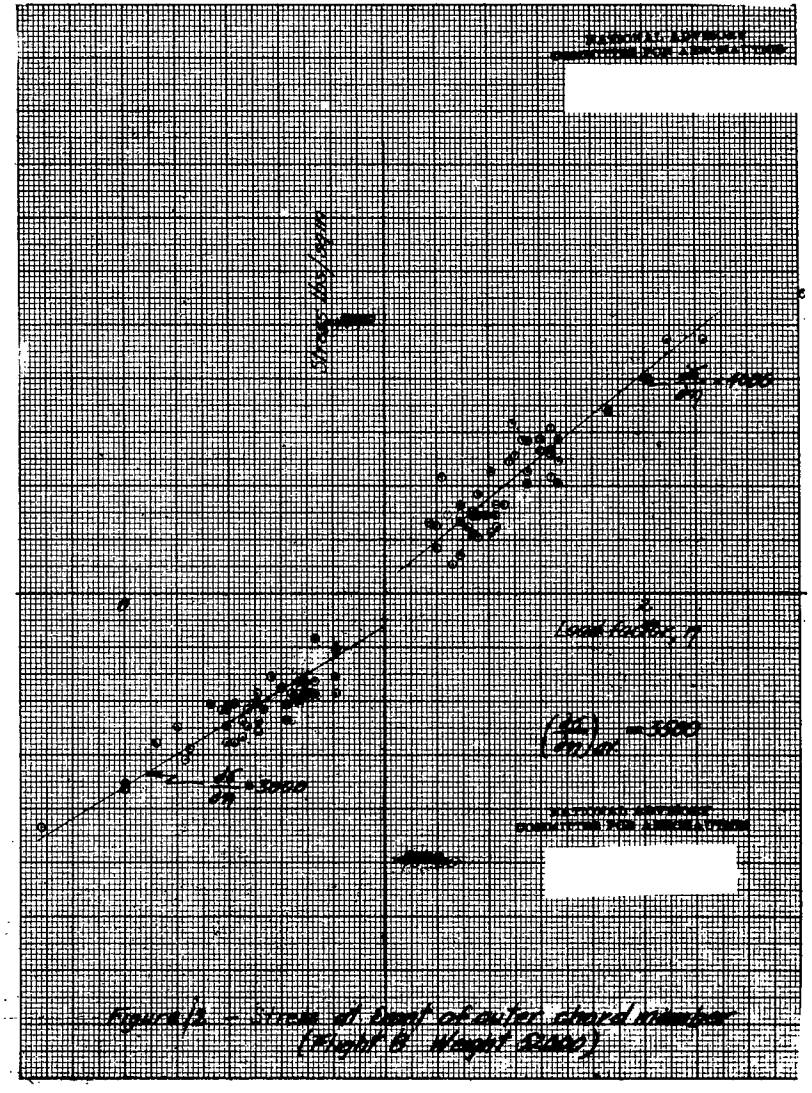

Figure 12.- Stress at root of outer chord member (Flight B Weight 5000)

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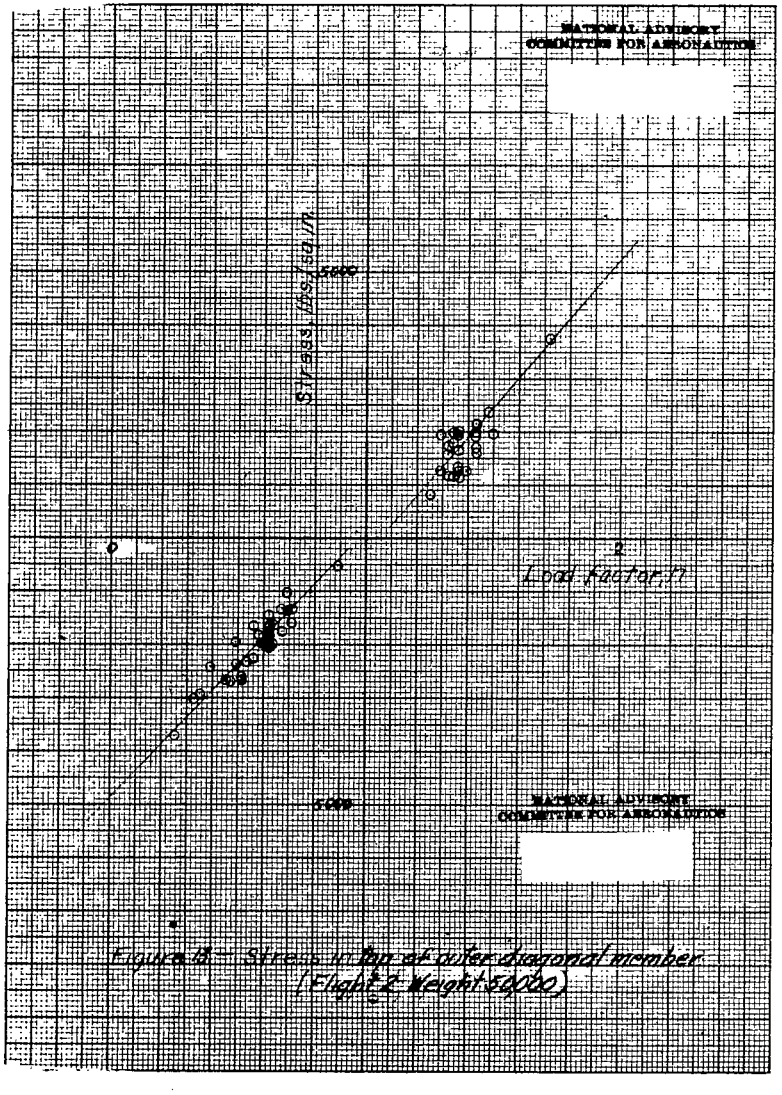

Figure 13 - Stress in top of outer diagonal member
(Flight 2 Weight 50,000)

KEUFFEL & ESSER CO. N.Y.

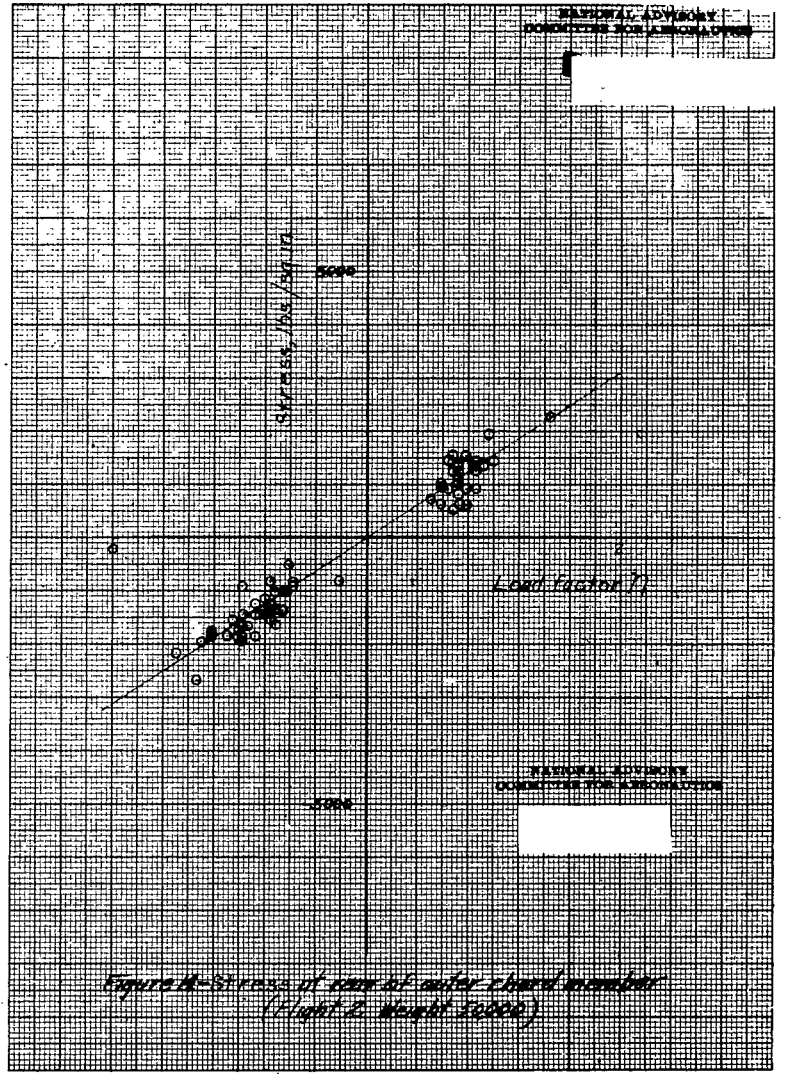

Figure 14 - Stress at rear of outer chord member
(Flight 2 Weight 50,000)

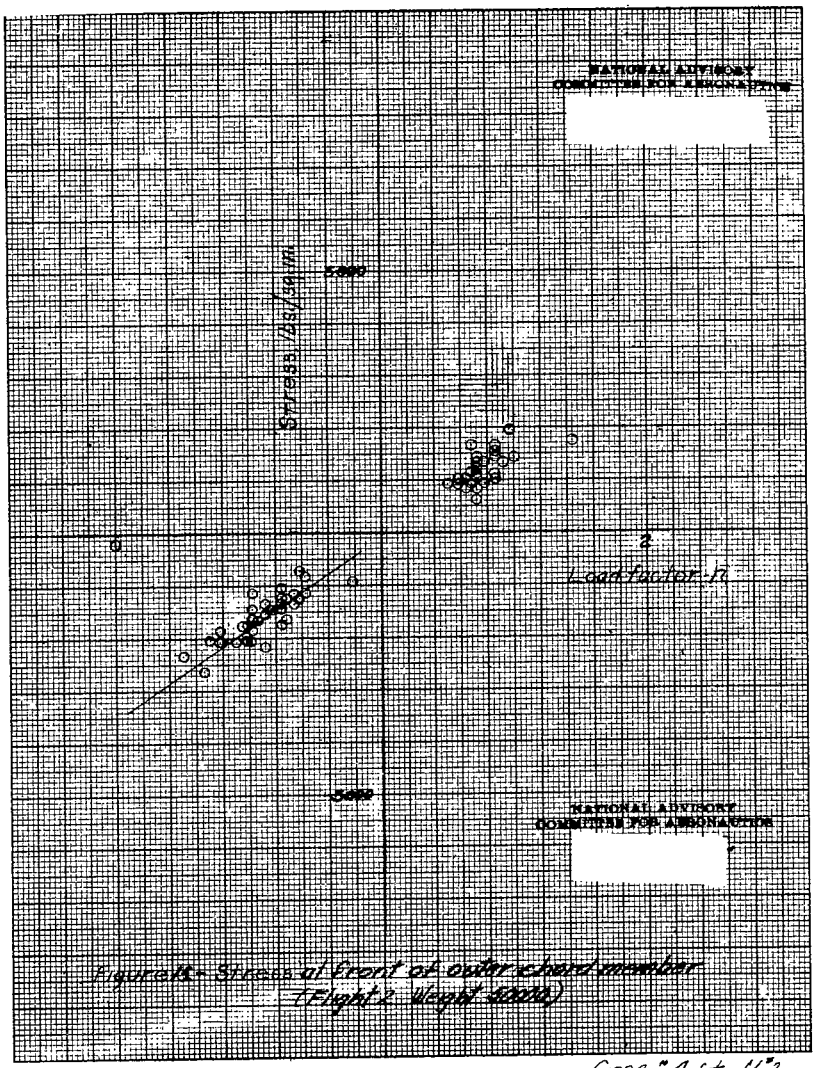

Figure 15 - Stress at front of outer chord member
(Flight 2 Weight 5000)

Gage "4 ft. H."2

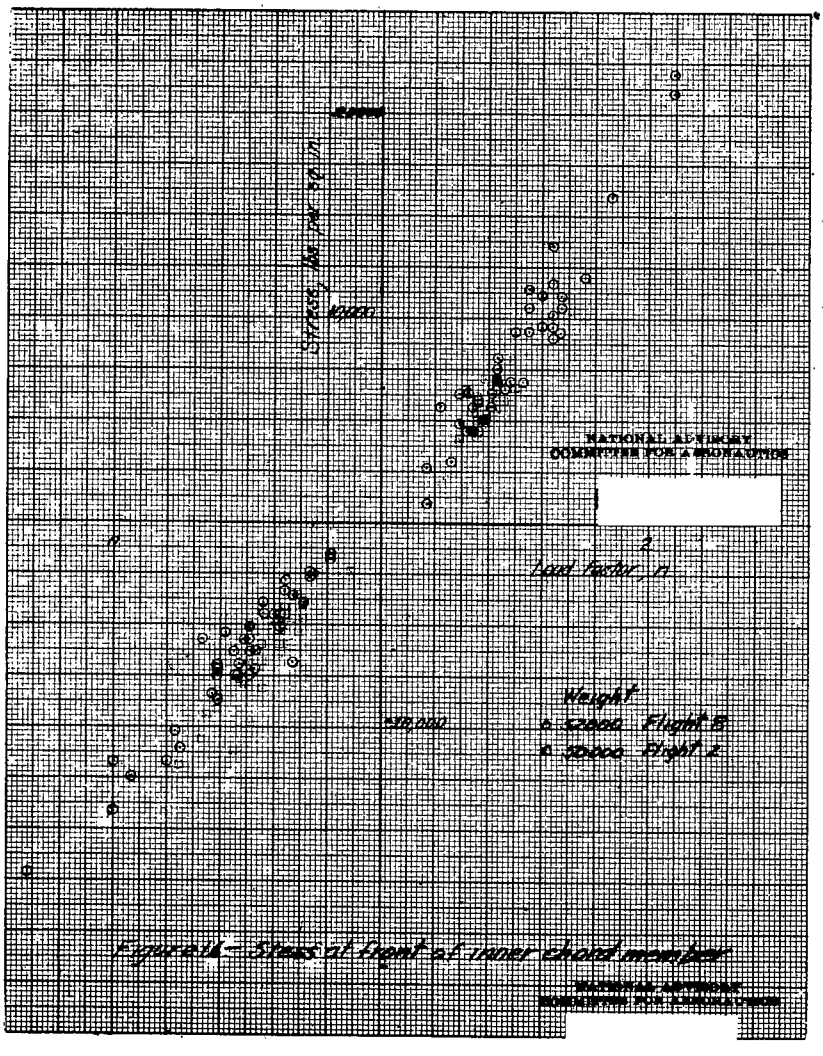

Figure 14.- Stress at front of inner chord member.

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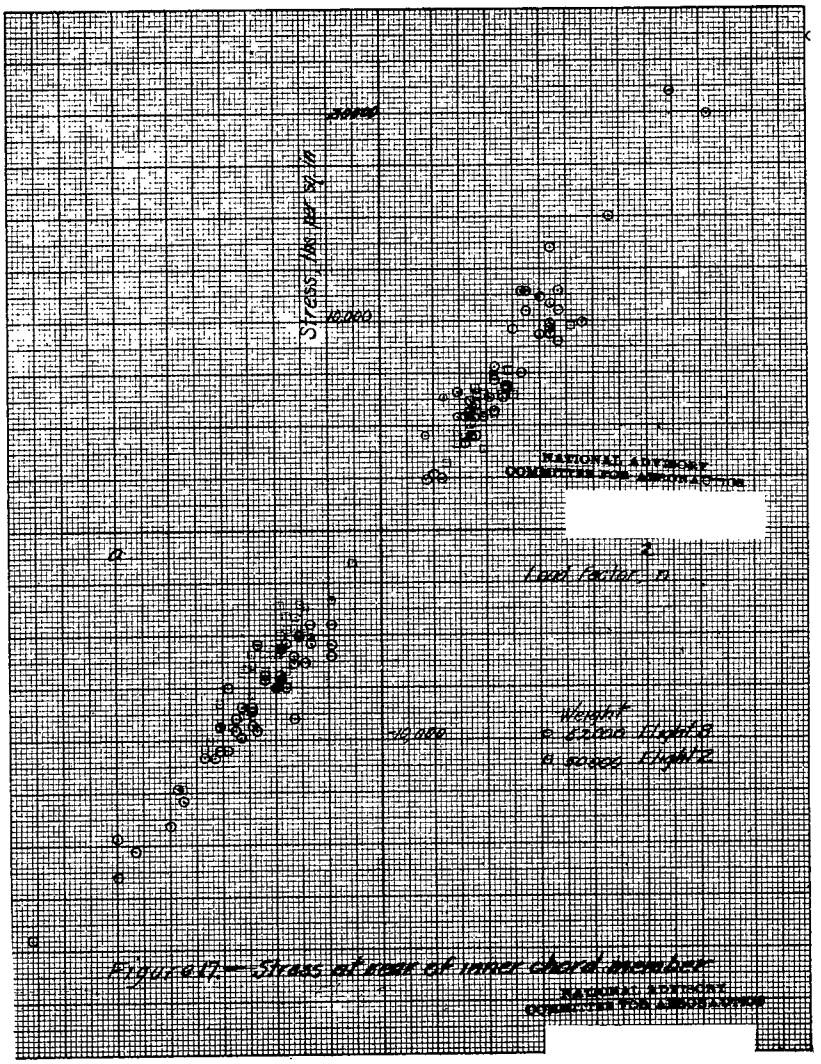

Figure 17.— Stress at rear of inner chord member

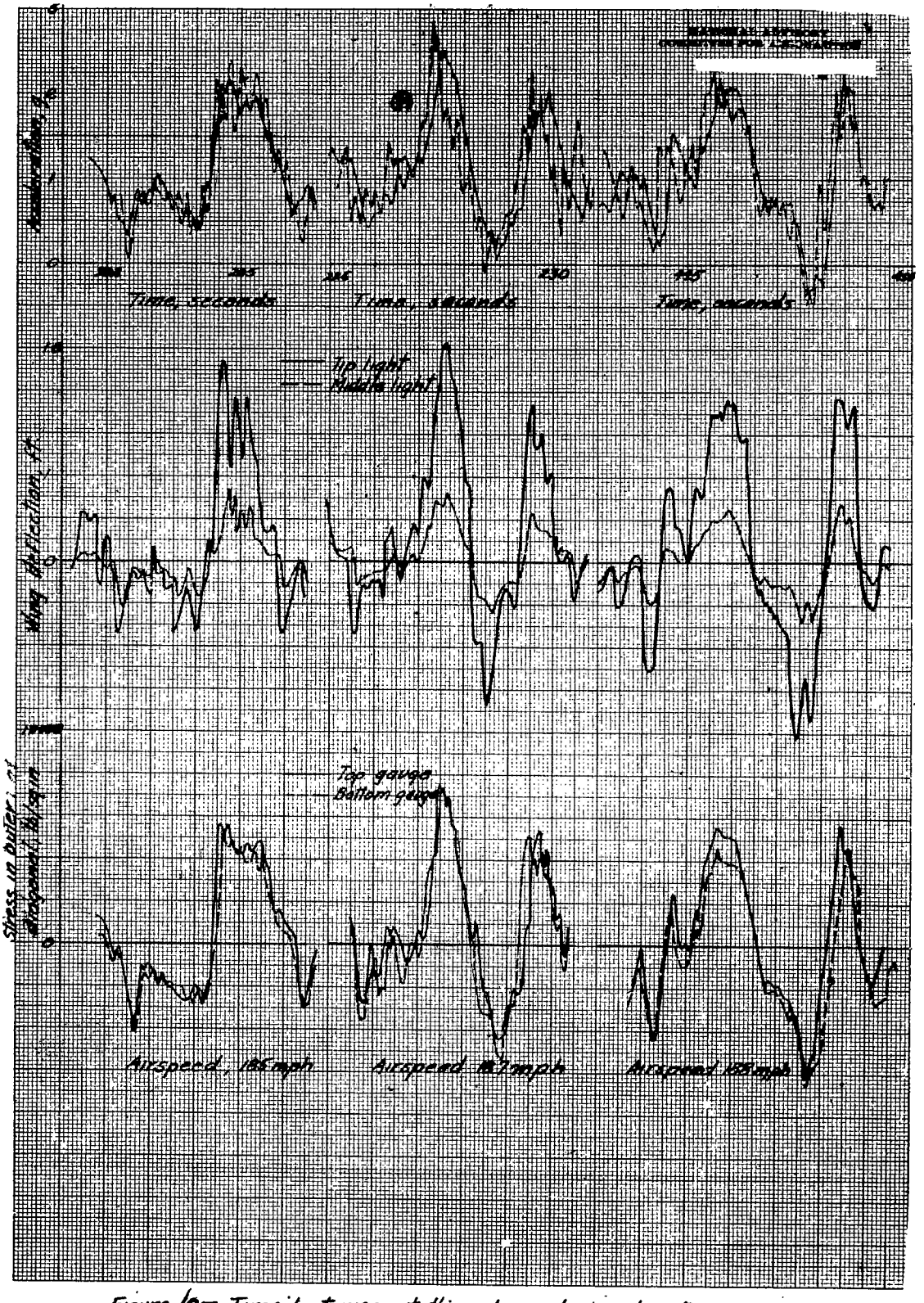

Figure 18 — Time histories at three largest accelerations

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