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TECHNICAL NOTE

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MEASUREMENTS OF LANDING-GEAR FORCES AND HORIZONTAL-TAIL LOADS IN LANDING TESTS OF A LARGE BOMBER-TYPE AIRPLANE

By John R. Westfall

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

A series of landings has been made with a large bomber-type airplane equipped with twin vertical tails to determine the time history of the impact forces on the landing gear and the resulting response of the airplane structure, particularly that of the horizontal tail, to the landing loads. About 50 landings were made, including normal, braked, and prerotation landings, but complete time histories were obtained for only 23 landings. The quantities measured included the vertical and drag components of the landing-gear loads, landing-gear deflection, stabilizer bending moments, structural accelerations, and airplane velocity and attitude. The tests were undertaken to investigate the specific causes of stabilizer failures on early models of the airplane, and it was found that the maximum stabilizer loads occurred in normal landings as a result of resonance with fore-and-aft landing-gear vibration. The data presented are adaptable to use in the analytical solution of the problem of structural response during landing impacts.

INTRODUCTION

The occurrence of structural failures on large airplanes, which cannot be explained on the basis of rigid-body phenomena, has served to emphasize the importance of structural elasticity in producing critical loading conditions during landing impacts. Typical of such failures are those of the horizontal stabilizer of early models of a large bomber-type airplane.

In order to investigate the specific cause of these failures, the Langley Memorial Aeronautical Laboratory of the NACA conducted a series of landing tests with a large bomber-type airplane equipped with twin vertical tails. In these tests, simultaneous measurements were made of the impact forces on the landing gear and of the resulting response of the airplane structure, particularly that of the horizontal tail. The test landings were made over a fairly wide range of vertical and horizontal velocity and attitude angle and included normal-, braked-, and prerotation-landing conditions. The maximum tail response was found to occur in normal landings as a result of resonance with fore-and-aft vibration of the landing gear when both main wheels touched simultaneously and vibrated in phase.

Although no attempt was made during the investigation to correlate experimental results with mathematically derived values, the measurements are suitable for use in the analytical solution of the problem of structural response during landing impacts in the manner proposed by Biot and Bisplinghoff (reference 1). Such a solution requires that the time histories of the external forcing function (that is, the impact loads on the landing gear) be obtained for various types of airplane in actual landings covering a sufficient number of landing conditions to constitute an adequate statistical sample.

APPARATUS AND METHOD

Airplane

The airplane used in the tests was a large four-motored bomber-type airplane equipped with tricycle landing gear and twin vertical tails mounted on the outboard ends of the stabilizer. The characteristics of the airplane are given in table I, and the natural frequencies of vibration are given in table II. The airplane was equipped with a 25g stabilizer, that is, one designed for an ultimate static load of 25 times the weight of the tail assembly. A number of stabilizer failures, apparently caused by loads imposed as a result of landing impacts, had been reported for earlier models of the airplane that were equipped with 15g stabilizers.

Tests

The tests consisted of a series of about 50 landings, all made on the concrete runways of Langley Field, Va., during which records were taken of the impact forces on the landing gear and of the resulting structural response. Normal, braked, and prerotation landings were included in the investigation. The landings were intended to cover as wide a range of velocity, attitude, and severity as practicable. The landings, however, were probably not so severe, at least on the average, as might be encountered under training or combat conditions and most could be classed as average landings by an experienced pilot. All the landings were made by one NACA test pilot.

Conditions at Contact

About a year and a half prior to the tests, the runways were coated with a camouflage material consisting of sawdust spread on an asphalt binder. At the time that the tests were begun, about one-third to one-half the surface of the runways was still covered with the camouflage coating in patches of varying size, shape, and thickness. This coating plus tire streaks, frost (encountered during some of the landings), and other foreign material contributed to the possibility that the coefficients of friction encountered would be lower on the coated concrete than on the bare dry concrete.

The vertical velocity and attitude of the airplane at contact were determined by means of two NACA recording phototheodolites. Ground speed was determined from the rotational velocity attained by the main wheels just after the impact recorded by two 35 millimeter motion-picture cameras operating at speeds of about 60 frames per second. The values of ground speed thus obtained were checked against values computed from readings of the airspeed indicator (which had been calibrated against true airspeed) and the surface wind velocity.

Measurement of Landing Gear and Stabilizer Loads

The vertical and the drag components of the impact force on the landing gear were measured by wire strain gages attached to the straight part of the landing-gear strut below the oleo cylinder. The strain gages, connected to form a conventional Wheatstone bridge, were supplied from a 2000-cycle oscillator. The bridge output was amplified and recorded on a Miller oscillograph, model E, the elements of which had a natural frequency of about 60 cycles per second. No side component of load was measured during the tests.

The inertia drag load on the main gear was also computed from the angular acceleration of the main landing wheels as determined from motion pictures of the wheels taken by the two 35-millimeter cameras. In order to facilitate these computations, an average value of tire deflection was assumed to exist throughout each landing. This assumption, of course, introduced an error in drag-load computations amounting to as much as 6 or 7 percent for the maximum values of the hardest landings, which was of about the same order as the error in the strain-gage readings.

Accelerations in the airplane were measured by standard NACA air-damped accelerometers installed near the center of gravity of the airplane, at the center of the fuselage near the rear spar of the stabilizer, and at the outboard end of the rear spar of the left stabilizer. The natural frequency of all the accelerometers was about 20 cycles per second. The locations of these accelerometers are indicated in figure 1.

The stabilizer loads were measured by means of wire strain gages located near the top and bottom of the front and rear spars of the stabilizer, one set being located near the root of the spars and another near the outboard end. These loads were computed as bending moments.

Brake Preloading

For some landings a predetermined amount of braking force was applied to the main wheels prior to contact by means of a device that permitted an adjustable pressure to be put on the hydraulic brake lines. A release lever was incorporated into the device to make possible instantaneous release of the brakes at any time and it was the practice of the pilot to release them immediately after the impact. Two pressure gages were connected into the hydraulic brake lines and gave readings of the brake pressures on both wheels. The maximum brake-preloading pressure used during the tests was about 25 pounds per square inch. This value was chosen as an upper limit because observations of the pressure gages during the decelerating runs after the impact was over showed that about 20 pounds per square inch was the maximum braking pressure used in slowing the airplane.

Prerotation

Special fittings with anemometer-cup-type wind vanes were attached to the main wheels in an effort to produce prerotation; however, they functioned erratically and were discarded. Prerotation was then achieved by touching the wheels to the runway to bring them up to speed, lifting the airplane off the runway by speeding up the engines, and again making contact while the wheels were revolving at high speed. The amount of prerotation obtained by this method was, of course, not controllable.

PRECISION OF DATA

The measurements of the following quantities are estimated to be correct within the limits shown:

Gross weight of airplane at contact, pounds	±100
Ground speed at contact, miles per hour	±3
Vertical velocity at contact, foot per second	±1.0
Attitude angle at contact, degree	±0.7
Main-landing-gear vertical loads, from strain gages, pounds	±2000
Main-landing-gear drag loads, from strain gages, pounds	±1000
Nose-gear vertical loads, from strain gages, pounds	±1500
Nose-gear drag loads, from strain gages, pounds	±1000
Main-landing-gear drag loads, computed from wheel-acceleration data, pounds	±1000
Tail bending moments from strain gages, percent	±5
Strut deflection, from camera records, inch	±0.1
Normal component of acceleration from accelerometer records, g	
Center of gravity	±0.2
Center of horizontal tail	±0.3
Left tail tip	±0.3
Time interval, second	±0.01

PRESENTATION AND DISCUSSION OF DATA

The test results are presented in tables III to VI and in figures 2 to 51. Certain of these figures show curves that represent the probability that given values of the variables selected for treatment will be equaled or exceeded. Probability may be interpreted herein as the ratio of the number of events that satisfy a given condition to the total number of events. The curves in all cases are Pearson type III probability curves (reference 2).

Tabulation of Landings

Table III summarizes the conditions at contact for the various landings. Table IV lists the landings in approximately decreasing order of severity in the three general types of landing (normal, braked, and prerotation) and presents maximum values of accelerations and of total landing-gear loads.

Velocity at Contact

The ground speeds at the time of contact are listed in tables III and IV. The ground speed covered the range from 80 to 128 miles per hour with an average value of 95 miles per hour. The vertical velocity at the time of impact (table IV) ranged from about 1 foot per second to about 7 feet per second, and in approximately 50 percent of the landings the vertical velocity was 2 feet per second or less. This result is in agreement with results of previous tests on large airplanes (reference 3).

Figure 2 is a curve of probability of vertical velocity at contact. This curve is based on the data from the normal and the braked landings; the prerotation landings were on the whole rather gentle because of the technique employed in making them and, hence, are not considered representative landings from the standpoint of vertical velocity. An inspection of the curve shows that, on the average, for this airplane about 1.3 landings out of 100 may be expected to equal or exceed the maximum vertical velocity recorded during the tests (6.9 fps) and about 1 out of 200 would equal or exceed 8 feet per second.

Landing-Gear Loads

Complete time histories of the impact parameters were obtained in 23 of the landings. In some additional landings, time histories were obtained for only one of the main-landing-gear units. Time histories of the landing-gear loads are presented for convenience at the end of the paper. (Data are presented for the normal landings in figs. 20 to 36, for the braked landings in figs. 37 to 44, and for the prerotation landings in figs. 45 to 51.) The maximum vertical load measured on one landing gear (40,900 lb) was about 41 percent of the design ultimate load whereas the maximum drag load measured (18,500 lb) was 73 percent of the design ultimate load.

Figure 3 presents probability curves of maximum values of the vertical load on the two main wheels for the normal and the braked landings. The probability of experiencing a given value of vertical load was appreciably greater for the left wheel than for the right wheel in both the normal and the braked landings. The vertical loads measured during braked landings tended to be higher than those measured during normal landings, although a scarcity of data on the braked landings made the significance of this phenomenon uncertain.

Figure 4 presents probability curves for maximum drag loads on the main wheels for normal and braked landings. No significant difference was noted between the probabilities for the two wheels, nor between the probabilities for normal and braked landings.

Table V lists the time intervals between contact of the two main landing wheels and notes which wheel contacted first. A curve of probability of time between contact of the two wheels is presented in figure 5. The probability that the time between contact will fall within a given interval may be determined by the difference between the probabilities for the time values involved. Thus, the probability that a landing would be made in the interval between 0.14 and 0.16 second after contact is 0.425 minus 0.360, which gives a value of 0.065.

The time to reach the maximum value of the vertical loads on each main wheel (fig. 6) varied from 0.09 second to 0.33 second for all landings, the average being about 0.17 second. It was not evident that any relationship existed between the magnitude of the maximum vertical load and the time to reach the maximum values of the vertical load.

Figure 7 presents the time for each main wheel to reach maximum drag load plotted against the magnitude of the drag load for normal landings. The average time from contact to maximum load was about 0.17 second. Despite considerable scatter, there was some indication that the time elapsed from contact to the maximum values of the drag load was less for the larger values of the drag load.

Table VI lists maximum values of main-wheel drag loads as computed from strain-gage reading and from wheel-acceleration data. Figures 8 to 10 compare time histories of main-landing-gear drag loads computed by the two methods.

A study of the time histories of the landing-gear loads disclosed no clear-cut relation between the order of development of the vertical load and the order of development of the drag load. This result is ascribable in part, at least, to random variation of the coefficient of friction during the impact.

Effect of Braking on Landing-Gear Loads

The tendency of braked landings to produce higher vertical loads than are produced by normal landings has already been pointed out. Another effect was to reduce the ratio of maximum drag load to maximum vertical load, as compared with the ratios for normal landings (fig. 11). This effect would be expected since braking tends to delay the wheel "spin-up" time past the point at which the vertical load is a maximum, and the coefficient of friction is usually less when the tire is sliding than when wheel slippage is small.

Effect of Prerotation on Landing-Gear Loads

The data from the prerotation landings were not subjected to a statistical analysis since the piloting technique involved was felt to be such as to prohibit direct comparison with the normal and the braked landings. Furthermore, the degree of prerotation was not the same for all landings. Certain qualitative results can, however, be discerned. As would be expected, prerotation had a marked effect in reducing the wheel drag load. The average ratio of maximum drag load to maximum vertical load for all prerotation landings was 0.11, compared with 0.41 for normal landings and 0.36 for braked landings. All these values are the average of those for the two main wheels.

Structural Response to Impact Loads

Figure 12 shows the tail-assembly weight distribution over the semispan of the stabilizer, computed from data furnished by the manufacturer, and the computed design yield and the design ultimate bending moments over the semispan. The measured stabilizer bending moments were converted into percentages of design yield bending moment and the maximum values for each landing are listed in table IV.

The maximum bending moment measured during the tests (50 percent of the design yield value) occurred during a normal landing (landing 10) in which the two main wheels contacted simultaneously and vibrated in phase in a fore-and-aft direction immediately following wheel spin-up (fig. 13). The frequency of the landing-gear oscillations was about the same as that of the stabilizer in symmetrical bending as may be seen by comparing the data of figure 14 and table II. Two other landings of about equal severity (figs. 14 and 15), in which the landing-gear vibrations were out of phase, did not produce such high bending moments; moreover, the pattern of the curve of bending moments of the two landings did not show the resonance effect that was present in landing 10. On the other hand, another landing of much less severity (landing 8 in fig. 16), in which the landing-gear vibrations were in phase, showed the same resonant tendencies as landing 10 and large stabilizer bending moments.

Figure 17 is a plot of probability of occurrence of values of stabilizer bending moments in normal landings. The curve shows that about one landing in 100 would develop the maximum stabilizer load measured during the tests (50 percent of the design yield bending moment). It might be pointed out that 50 percent of the design yield bending moment for the 25g stabilizer would be about 83 percent of the design yield bending moment for the 15g stabilizer, with which early models of the airplane were equipped and on which several stabilizer failures were experienced in service.

Further inspection of table IV indicates that high tail-tip accelerations are not necessarily associated with high stabilizer loads. Braked landings, in general, seemed to produce somewhat smaller tail loads than did normal landings. The effect of prerotation on tail loads was obscured by lack of data; however, prerotation did reduce landing-gear oscillations to a marked degree, as can be seen from the time histories of the landing-gear deflections for a prerotation and a normal landing in which the values of the impact parameters were about equal (figs. 18 and 19). If, as indicated previously, the stabilizer loads were increased by a coupling effect with the fore-and-aft landing-gear vibrations, prerotation should reduce tail loads.

Analysis of Separate Effects of Impact Parameters

An attempt was made to isolate the effects of some of the parameters that constitute the over-all forcing function. The results were in the main negative; that is, determining specific relationships was difficult. For example, no apparent relationship was noted between the ratio of maximum vertical loads on the left and right wheels and the time interval between contacts; furthermore, there seemed to be about as much likelihood that the higher vertical and drag loads would occur on the second wheel to contact as on the first. No relationship was apparent between the ratio of the maximum vertical loads on the two main wheels and the ratio of the maximum drag loads on the two main wheels. In most of the landings the left wheel contacted first. This result is attributed in part, at least, to an admitted tendency of the pilot to land with the left wing low for better visibility.

SUMMARY OF RESULTS

Measurements of landing-gear forces and horizontal-tail loads in landing tests of a large bomber-type airplane equipped with twin vertical tails indicated the following results:

1. The maximum vertical velocity measured in 50 landings was about 7 feet per second, and in about 50 percent of the landings the vertical velocity was 2 feet per second or less. Ground speeds at contact varied from 80 to 128 miles per hour, the average being about 95 miles per hour.

2. A statistical analysis of the vertical-velocity data indicated that about 1.3 landings out of 100 could be expected to equal or exceed the maximum value measured during the tests and that about 1 out of every 200 would equal or exceed 8 feet per second.

3. The maximum value of vertical load on the main landing gear was about 41 percent of the design ultimate load, whereas the maximum value of drag load was about 73 percent of the design ultimate load.

4. The ratio of maximum drag load to maximum vertical load was 0.41 for normal landings, compared with 0.36 for braked landings and 0.11 for prerotation landings.

5. The probability of equaling or exceeding given values of vertical loads on the main landing gear was higher for braked than for normal landings, although a paucity of data on the braked landings made the significance of this phenomenon uncertain.

6. In most of the landings the left wheel contacted first, although this characteristic might be attributed largely to piloting technique.

7. No relationship was discernible between the ratio of vertical loads on the left and right wheels and the time interval between contacts.

8. There appeared to be a higher probability for the left wheel to equal or exceed a given value of vertical load than the right wheel.

9. No relationship appeared to exist between the order of development of maximum vertical load and the order of development of maximum drag load.

10. The largest stabilizer load measured was about 50 percent of the design yield bending moment for the 25g stabilizer with which the airplane was equipped. This value of stabilizer load was measured in a normal landing in which the main wheels contacted simultaneously and vibrated in phase in a fore-and-aft direction subsequent to wheel spin-up. Evidence was that this coupling effect between the in-phase vibrations of the main landing gear units and the vibrations of the stabilizer in symmetrical bending could result in the development of large stabilizer bending moments.

11. Brake preloading tended to reduce tail loads.

12. Prerotation of the main wheels reduced drag loads and landing-gear vibration to a great extent although data were insufficient to predict its effect upon stabilizer loads.

13. A statistical analysis of the stabilizer-load data indicated that in about one landing out of 100, values of stabilizer bending load equal to the maximum measured during the tests could be expected.

14. Large values of stabilizer tip acceleration were not necessarily associated with large values of stabilizer bending moment.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., June 27, 1946

REFERENCES

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2. Elderton, W. Palin: Frequency Curves and Correlation. Cambridge Univ. Press, 1938.

3. Hootman, J. A., and Jones, A. R.: Results of Landing Tests of Various Airplanes. NACA TN No. 863, 1942.

TABLE I

AIRPLANE CHARACTERISTICS

Gross weight at landing, lb	48,900 to 50,100
Wing span, ft	110
Wing area, sq ft	1048
Horizontal tail area, total, sq ft	192.0
Stabilizer area, sq ft	140.5
Weight of tail assembly, lb	869.6
Normal rated horsepower	4400
Center-of-gravity position, as flown, percent M.A.C.	27.9 to 28.2
Height of center of gravity above ground, static position of airplane, ft	8.2
Approximate moment of inertia in pitch, as flown, slug-ft^2	150,000
Moment of inertia of main wheel, slug-ft^2	33.5
Wheel tread, ft	25.62
Wheel base, ft	16.00
Wing incidence, deg	3.0

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TABLE II

NATURAL VIBRATION FREQUENCIES OF AIRPLANE

[From vibration tests conducted by the Air Material Command, Army Air Forces]

Part	Type of vibration	Frequency (cpm)	Location of vibrator	Remarks
Wing (approx. 400 gal gas in each wing)	Symmetrical bending	215	Outboard end of aileron	Nodal line just outboard of inboard engine; large fuselage vertical motion
	Symmetrical inner-panel torsion combined with symmetrical bending	315	Outboard end of aileron	Nodal line runs diagonally from just outboard of outboard engine at leading edge to wing root at trailing edge; outboard engine pitching considerably
	Inner-panel torsion	520	Between cylinders 7 and 9 on engine 2	Small response outboard engines; larger response inboard engines; amplitude too small to check phase; rear of fuselage moving vertically
		515	Floor of fuselage just forward of tail turret	
	Higher-order bending	590	Outboard end of aileron	Phase symmetrical by pickups
		990	Outboard end of aileron	Phase unsymmetrical by pickups
		1360	Outboard end of aileron	Phase symmetrical by pickups
Fuselage	Side bending	340	Inspection door on bottom of fuselage, 2 feet forward of tail light; lateral impulses	Very small amplitude
		520	Thrustwise impulses at bottom rudder hinge	Large amplitude mode; node at waist gun cut-out
	Vertical bending	980	Floor of fuselage just forward of tail turret	Amplitude too small to determine node line
Stabilizer	Symmetrical bending combined with wing symmetrical bending; pitching of airplane also excited	400	Vertical impulses at second rudder hinge from bottom	Stabilizer nodes $4\frac{1}{2}$ feet from center line of airplane Wing tip and stabilizer tip in phase
	Torsion	640	Thrustwise impulses at bottom rudder hinge	Phase symmetrical by pickups; nodal line near rear spar

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TABLE III

CONDITIONS AT CONTACT

Landing (a)	Type of landing	Gross weight of airplane at contact (lb)	Attitude angle (deg) (b)	Vertical velocity (fps)	Ground speed (mph)	Wind direction	Airplane course (deg)	Wind velocity (mph)	Brake preloading (lb/sq in.)
1	Normal	50,000	4.1	1.8	111	ESE	270	5	--
2	Normal	49,700	1.0	1.9	116	ESE	270	5	--
3	Normal	49,300	.6	1.7	126	ESE	270	5	--
4	Normal	49,900	5.1	1.3	96	NNW	350	10	--
5	Normal	49,600	-.1	1.7	113	NNW	350	10	--
6	Normal	49,200	5.3	1.8	97	NNW	350	10	--
7	Normal	49,000	5.7	1.8	88	NNW	350	10	--
8	Normal	49,900	1.2	2.5	106	E	70	7	--
9	Normal	49,700	6.1	.7	91	E	70	7	--
10	Normal	49,300	-.9	6.5	102	E	70	7	--
11	Braked	48,900	3.7	4.1	98	E	70	7	5
12	Normal	49,900	1.7	2.2	102	NNW	350	11	--
13	Normal	49,700	.9	4.0	107	NNW	350	12	--
14	Braked	49,300	.4	3.6	87	NNW	350	13	5
15	Braked	48,900	2.4	3.0	89	NNW	350	14	10
16	Normal	49,700	5.2	2.9	103	ENE	350	4	--
17	Normal	49,500	4.5	---	96	ENE	350	4	--
18	Braked	49,200	3.2	2.2	105	ENE	350	4	10
19	Normal	50,100	3.9	4.2	118	N	250	19	--
20	Normal	49,400	---	2.4	84	N	350	20	--
21	Braked	49,200	---	2.8	90	N	350	21	15
22	Braked	48,900	5.1	1.2	84	N	350	22	22
23	Normal	50,100	3.6	2.3	100	NNW	350	12	--
24	Normal	49,900	3.9	.9	94	NNW	350	12	--
25	Braked	49,600	1.9	4.2	96	NNW	350	12	20
26	Braked	49,200	2.7	.9	94	NNW	350	12	23
27_1	Normal	50,100	---	1.6	82	NNW	350	30	--
27_2	Prerotation	50,100	---	1.8	80	NNW	350	30	--
28_1	Normal	49,700	---	1.5	90	NNW	350	30	--
28_2	Prerotation	49,700	---	1.0	82	NNW	350	30	--
29_1	Normal	49,500	---	1.4	87	NNW	350	30	--
29_2	Prerotation	49,500	---	.9	83	NNW	350	30	--
30_1	Normal	49,200	---	2.6	82	NNW	350	30	--
30_2	Prerotation	49,200	---	2.3	80	NNW	350	30	--
31	Braked	49,000	---	1.0	81	NNW	350	30	24
32_1	Normal	49,800	---	2.9	100	SSW	175	8	--
32_2	Prerotation	49,800	4.8	3.0	97	SSW	175	8	--
33_1	Normal	49,600	3.6	1.9	98	SSW	175	8	--
33_2	Prerotation	49,600	3.7	1.2	96	SSW	175	8	--
34	Braked	49,300	.8	4.9	96	SSW	175	8	19
35	Braked	49,200	4.5	1.8	91	SSW	175	8	24
36_1	Normal	49,800	---	1.3	---	---	---	--	--
36_2	Prerotation	49,800	---	2.2	---	---	---	--	--
37_1	Normal	49,500	---	---	---	---	---	--	--
37_2	Prerotation	49,500	---	---	---	---	---	--	--
$36a_1$	Normal	50,000	1.1	1.4	98	SW	250	7	--
$36a_2$	Prerotation	50,000	2.4	1.0	94	SW	250	7	--
$37a_1$	Normal	49,800	.8	1.6	98	SW	250	7	--
$37a_2$	Prerotation	49,800	4.9	1.3	90	SW	250	7	--
38_1	Normal	49,500	.5	3.1	100	SW	250	7	--
38_2	Prerotation	49,500	2.5	2.9	94	SW	250	7	--
39_1	Normal	49,300	---	2.6	102	SW	250	7	--
39_2	Prerotation	49,300	3.8	2.1	100	SW	250	7	--
40	Normal	50,100	3.0	1.4	87	SSW	170	20	--
41	Normal	49,900	4.4	1.3	89	SSW	170	20	--
42	Normal	49,600	-1.4	6.9	128	SSW	170	20	--
43	Normal	49,400	.2	1.1	112	SSW	170	20	--
44	Braked	49,100	1.0	5.8	91	SSW	170	20	23

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Angle between longitudinal axis of airplane and the horizontal, positive in nose-up direction.

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TABLE IV

LANDINGS CLASSIFIED ACCORDING TO TYPE AND SEVERITY OF IMPACT

Landing (a)	Increment of maximum acceleration (g) At c.g.	At center of tail	At left tail tip	Vertical velocity (fps)	Ground speed (mph)	Maximum total main-gear vertical load (lb)	Maximum total main-gear drag load (lb)	Maximum nose-wheel vertical load (lb) (b)	Maximum stabilizer design yield bending moment (percent)
				Normal					
10	1.55	3.55	7.20	6.5	102	70,100	25,400	15,400	50.3
42	1.35	3.10	6.20	6.9	128	58,400	21,500	3,500	36.9
19	1.40	3.90	6.00	4.2	118	61,800	20,700	------	37.3
39_1	1.00	1.55	5.60	2.6	102	43,600	------	------	29.0
16	.70	1.60	2.30	2.9	103	50,200	12,000	------	23.5
20	.60	1.45	5.80	2.4	84	36,000	15,100	------	21.4
13	.80	1.10	3.10	4.0	107	31,700	7,600	------	37.5
8	.60	1.70	6.10	2.5	106	34,200	12,500	3,200	37.8
12	----	1.10	1.40	2.2	102	29,400	14,500	------	24.4
38_1	.65	2.20	2.70	3.1	100	27,100	14,800	------	28.5
2	.65	1.45	2.90	1.9	116	33,300	13,400	------	27.6
30_1	----	----	----	2.6	82	40,000	------	------	----
6	----	1.00	2.90	1.8	97	34,100	10,100	------	24.5
7	----	1.10	1.60	1.8	88	33,000	11,700	------	23.9
5	----	1.15	2.50	1.7	113	33,300	13,400	------	30.6
4	----	1.40	2.90	1.3	96	31,600	12,500	------	30.1
32_1	.60	1.10	2.70	2.9	100	32,200	8,400	------	17.0
43	.60	1.20	2.70	1.1	112	29,000	15,400	------	----
33_1	.60	1.15	3.30	1.9	98	28,100	9.700	------	----
23	.55	1.25	2.00	2.3	100	25,100	9,700	------	14.2
27_1	----	1.70	3.70	1.6	82	26,600	6,000	------	----
28_1	----	1.05	1.70	1.5	90	25,500	10,100	------	14.4
29_1	.35	.80	2.30	1.4	87	23,400	------	------	----
$36a_1$	.60	1.20	1.90	1.4	98	17,800	------	------	----
40	.30	.90	1.30	1.4	87	26,000	10,200	------	12.5
41	.35	.90	1.40	1.3	89	16,000	9,400	------	----
9	.30	.55	----	.7	91	21,900	5,600	------	21.3
17	.30	.30	1.00	---	96	------	------	------	----
37_1	.30	.75	1.15	---	---	------	------	------	----
24	.10	.60	1.25	.9	94	9,500	7,600	------	6.6
$37a_1$	.20	.40	.80	1.6	98	11,200	------	------	----
				Braked					
44	1.10	2.60	4.00	5.8	91	67,700	15,300	3,600	----
34	1.20	2.25	3.90	4.9	96	54,200	19,300	------	24.7
14	.80	1.35	4.80	3.6	87	48,800	18,500	------	25.5
21	.75	1.35	2.70	2.8	90	53,000	10,500	------	10.7
11	.90	1.20	3.00	4.1	98	44,100	12,500	------	27.8
25	.65	1.70	2.80	4.2	96	41,100	15,100	------	23.0
15	.50	1.30	2.90	3.0	89	35,100	13,000	------	----
18	.35	.50	2.10	2.2	105	38,700	14,100	------	27.4
35	.30	.75	1.90	1.8	91	35,000	12,600	------	11.1
31	.30	.80	1.90	1.0	81	21,000	7,000	------	11.8
26	.35	.70	1.30	.9	94	23,700	10,200	------	17.0
22	.15	.20	1.60	1.2	84	21,900	5,300	------	6.9
				Prerotation					
30_2	0.80	0.95	2.55	2.3	80	40,700	2,400	------	----
27_2	.80	1.35	3.10	1.8	80	39,400	3,000	------	----
32_2	.65	1.25	3.10	3.0	97	29,800	4,000	------	17.8
38_2	.80	1.20	2.40	2.9	94	24,700	1,600	------	7.4
39_2	.55	.50	1.20	2.1	100	28,600	800	------	6.5
36_2	.40	.75	1.25	2.2	---	29,200	1,700	------	----
33_2	.40	.60	1.50	1.2	96	22,000	1,600	------	----
$36a_2$	.40	.80	.80	1.0	94	17,600	4,300	------	----
28_2	.30	.35	1.00	1.0	82	19,200	1,000	------	8.7
$37a_2$	.35	.45	.40	1.3	90	17,800	1,300	------	----
37_2	.35	.70	1.50	3.1	---	20,100	-----	------	----
29_2	.25	.35	1.70	.9	83	15,200	2,100	------	----

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Nose-wheel loads listed only when nose wheel contacted during primary part of impact.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TABLE V

TIME INTERVALS BETWEEN CONTACT OF LEFT AND

RIGHT MAIN LANDING WHEELS

Landing (a)	First wheel to contact	Time between contacts (sec)	Landing (a)	First wheel to contact	Time between contacts (sec)
1	Right	0.09	28_1	Right	0.04
2	Left	.12	28_2	Left	.15
3	Left	.16	29_1	Right	.21
4	Left	.02	29_2	Left	.12
5	Left	.42	30_1	----	----
6	Right	.15	30_2	Left	.11
7	Left	.10	31	Right	.14
8	Left and right	0	32_1	Left	.12
9	----	----	32_2	Left	.07
[b]10	Left and right	0	33_1	Left	.20
			33_2	Left	.15
11	Left	.04	34	Right	.12
12	Right	.08	35	Left	.10
13	Left	.17	$36a_1$	Left	.34
14	Left	.07	$36a_2$	Left	.17
15	Left	.24	$37a_1$	Left	.33
16	Left	.10	$37a_2$	Left	.19
17	Left	.33	38_1	Right	.02
18	Left	.09	38_2	Left	.26
19	Right	.03	39_1	----	----
20	Left	.04	39_2	Left	.29
21	Right	.14	40	Right	.17
22	Left	.22	41	----	----
23	Right	.14	[c]42	Left	.10
24	----	----			
25	Right	.07	43	Right	.01
26	Left	.46	44	Right	.10
27_1	----	----			
27_2	Left	.05			

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Nose wheel contacted 0.09 second before left and right wheels.

[c] Nose wheel contacted 0.13 second before left wheel.

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TABLE VI

MAXIMUM VALUES OF WHEEL DRAG LOADS FROM STRAIN-

GAGE READINGS AND WHEEL-ANGULAR-ACCELERATION DATA

Landing (a)	Maximum wheel drag load (lb)			
	Left wheel		Right wheel	
	Strain-gage reading	Wheel-acceleration data	Strain-gage reading	Wheel-acceleration data
1	-----	7,140	-----	6,400
2	6,500	8,500	7,700	6,340
3	-----	10,200	-----	8,400
4	6,850	8,970	-----	7,570
5	9,820	9,000	-----	3,400
6	6,705	8,000	-----	11,300
7	6,650	7,260	-----	5,870
8	7,150	7,100	7,020	7,100
9	-----	3,300	5,400	5,500
10	12,700	12,900	12,500	12,700
11	-----	9,800	9,850	10,700
12	7,720	6,850	8,300	6,500
13	7,310	8,900	6,810	5,350
14	11,200	10,500	-----	14,200
15	7,150	8,100	8,400	6,550
16	9,120	9,100	5,410	7,400
17	-----	3,700	-----	4,100
18	4,750	4,700	-----	8,600
19	11,750	11,600	10,300	12,100
20	6,350	6,950	8,900	10,350
21	5,970	-----	10,600	10,000
22	[b]4,600	1,600	[b]4,300	4,910
23	1,110	1,080	[b]9,850	8,200
24	[b]5,670	7,200	[b]7,520	4,550
25	7,030	8,200	10,870	9,500
26	[b]5,330	2,700	[b]8,370	8,500
27_1	6,300	-----	[b]5,800	-----
27_2	2,400	1,390	1,000	-----
28_1	[b]5,890	6,600	[b]6,765	6,400
28_2	500	-----	700	-----

Landing (a)	Maximum wheel drag load (lb)			
	Left wheel		Right wheel	
	Strain-gage reading	Wheel-acceleration data	Strain-gage reading	Wheel-acceleration data
29_1	-----	-----	[b]9,290	11,000
29_2	2,100	5,900	600	900
30_1	-----	-----	-----	-----
30_2	500	-----	2,400	-----
31	4,770	5,110	5,140	5,000
32_1	[b]6,230	-----	6,910	7,670
32_2	1,700	1,850	4,800	3,950
33_1	5,700	-----	8,400	9,900
33_2	900	-----	1,400	1,320
34	5,770	-----	13,680	15,100
35	6,205	6,160	6,980	7,020
36_1	-----	-----	-----	-----
36_2	800	-----	1,600	-----
37_1	-----	-----	-----	-----
37_2	-----	-----	1,300	-----
$36a_1$	[b]8,115	8,500	-----	5,500
$36a_2$	4,300	4,500	2,800	2,800
$37a_1$	4,400	3,900	[b]5,810	4,700
$37a_2$	100	100	1,300	1,250
38_1	6,490	6,800	8,850	9,100
38_2	1,100	1,080	1,600	1,550
39_1	-----	-----	4,750	-----
39_2	200	-----	800	930
40	6,910	6,800	[b]3,450	6,000
41	9,550	9,700	[b]6,620	6,500
42	18,500	18,400	10,560	14,200
43	-----	11,300	8,200	8,800
44	10,000	13,100	14,150	15,000

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Uncorrected for effect of vertical load.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

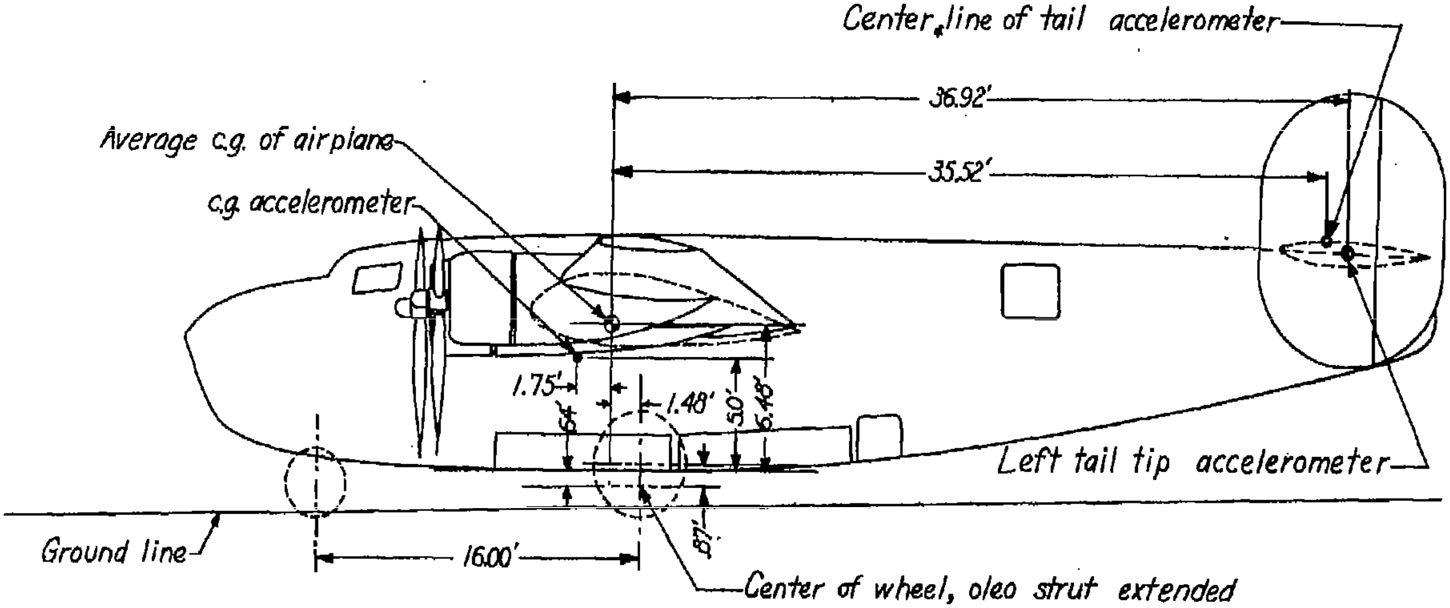

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Figure 1.- Location of accelerometers in the airplane.

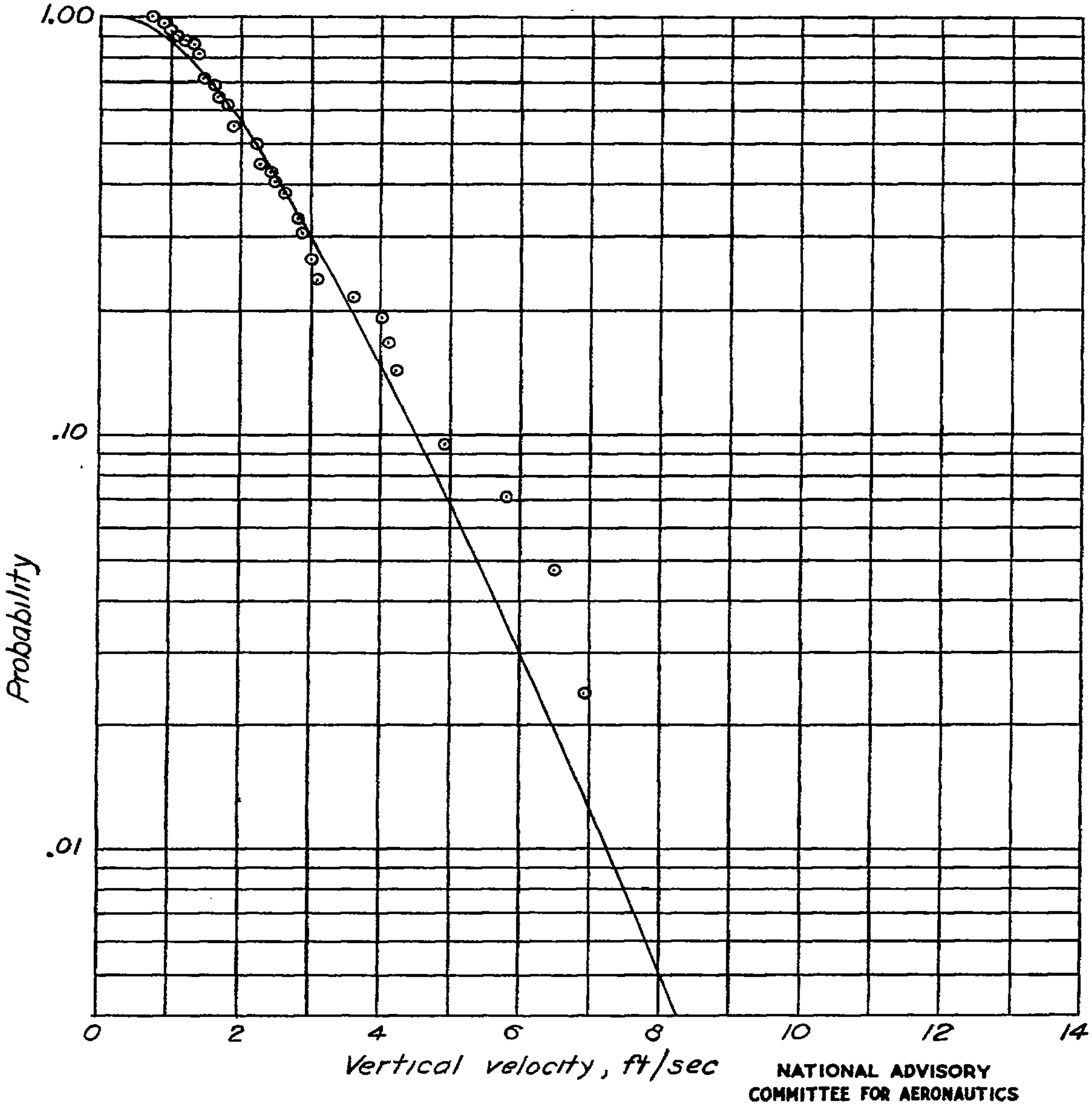

Figure 2.- Probability of equaling or exceeding given values of vertical velocity. Prerotation landings not included.

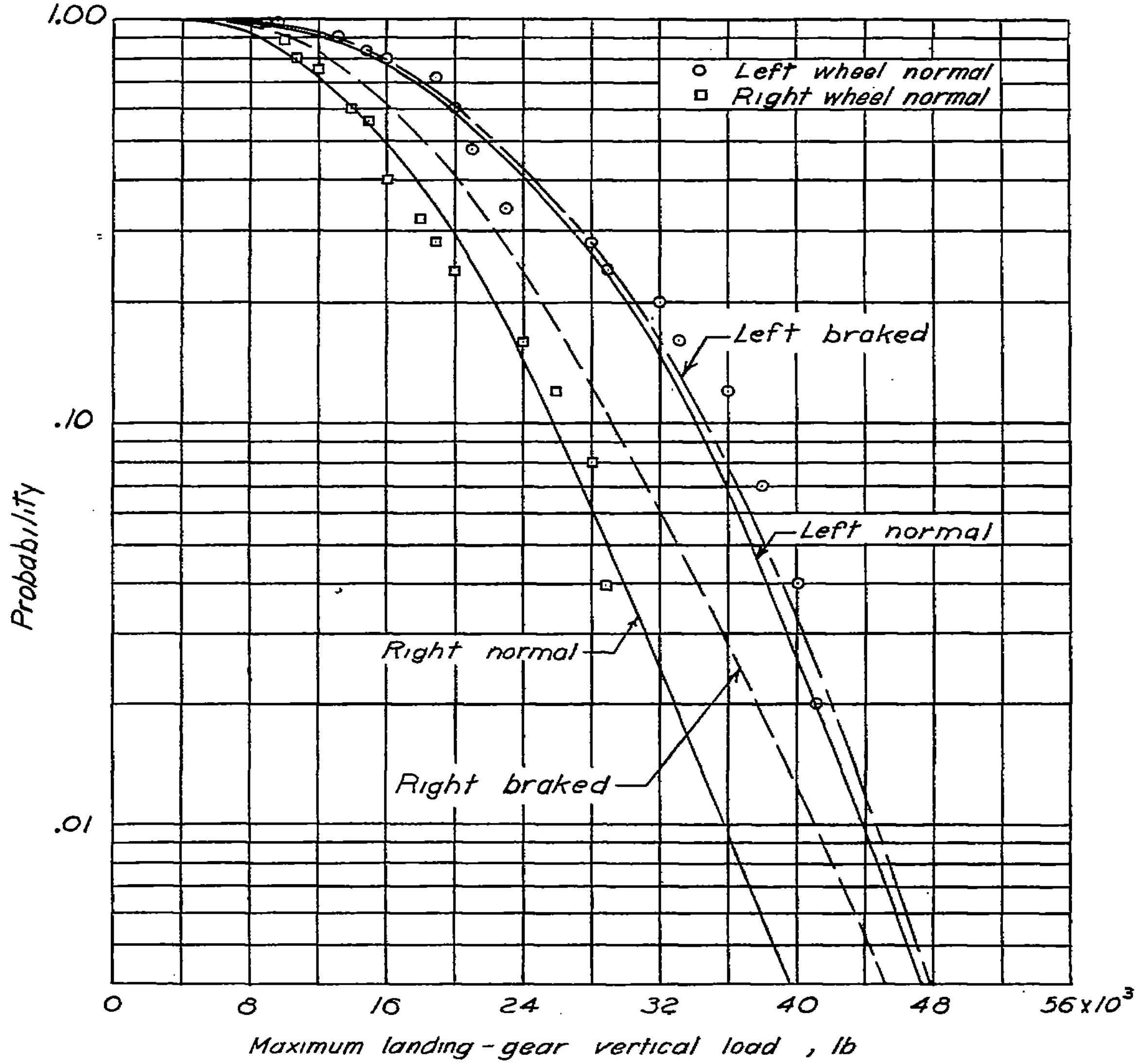

Figure 3.-Probability of equaling or exceeding maximum values of vertical load on main landing gear. Normal and braked landings.

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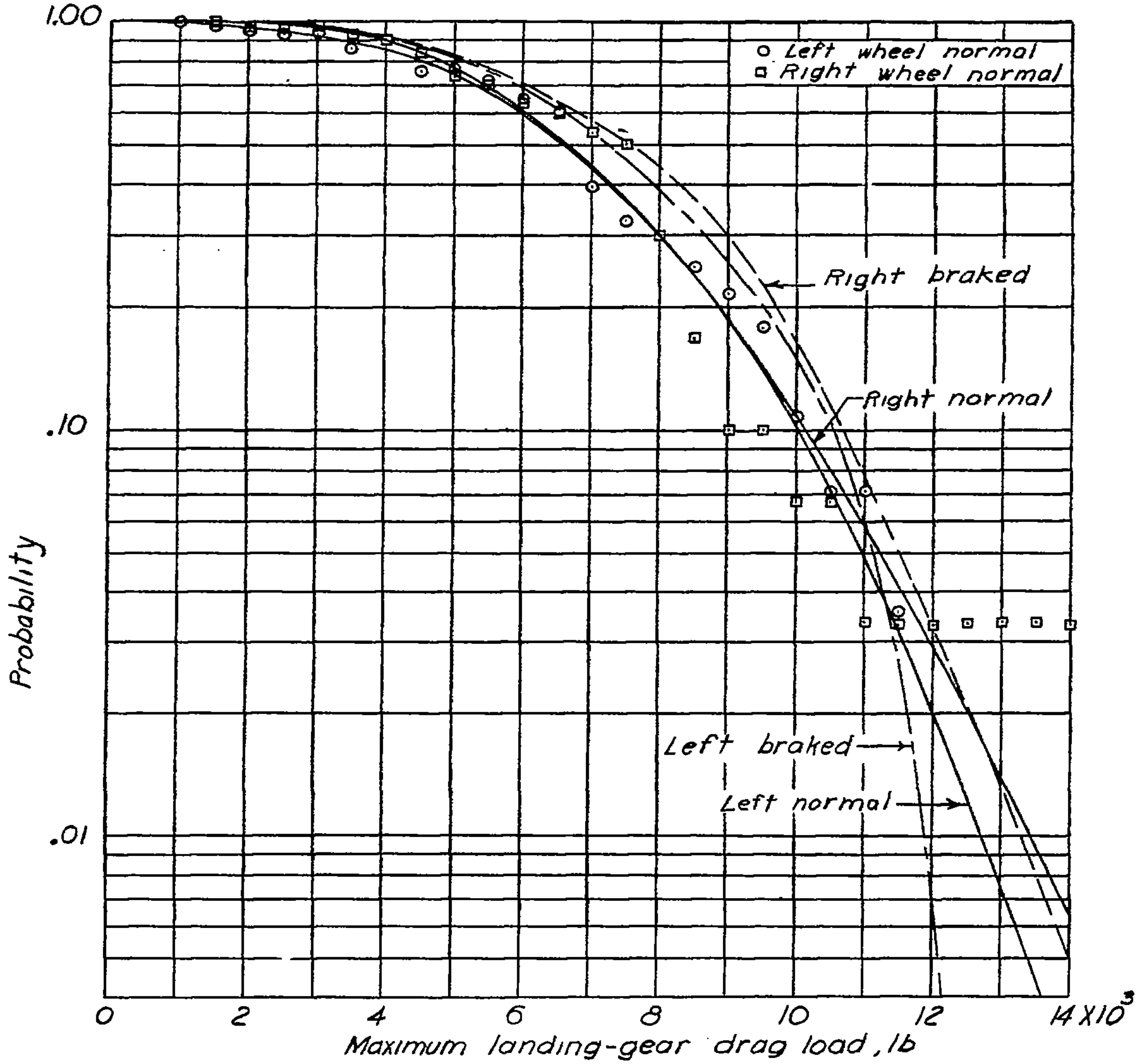

Figure 4.- Probability of equaling or exceeding maximum values of drag load on main landing gear. Normal and braked landings.

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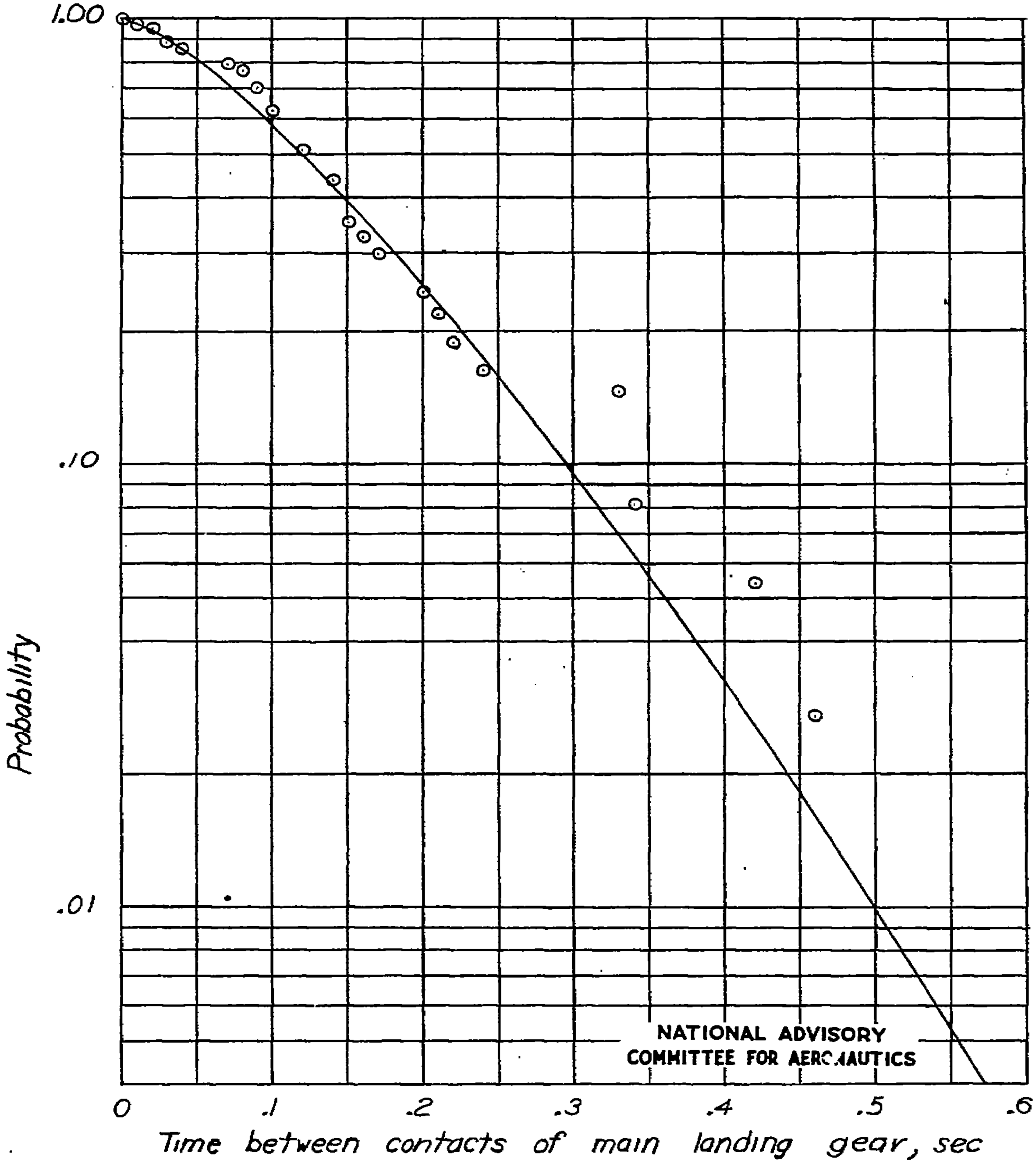


Figure 5.-Probability of equaling or exceeding time between contacts of main landing gear.

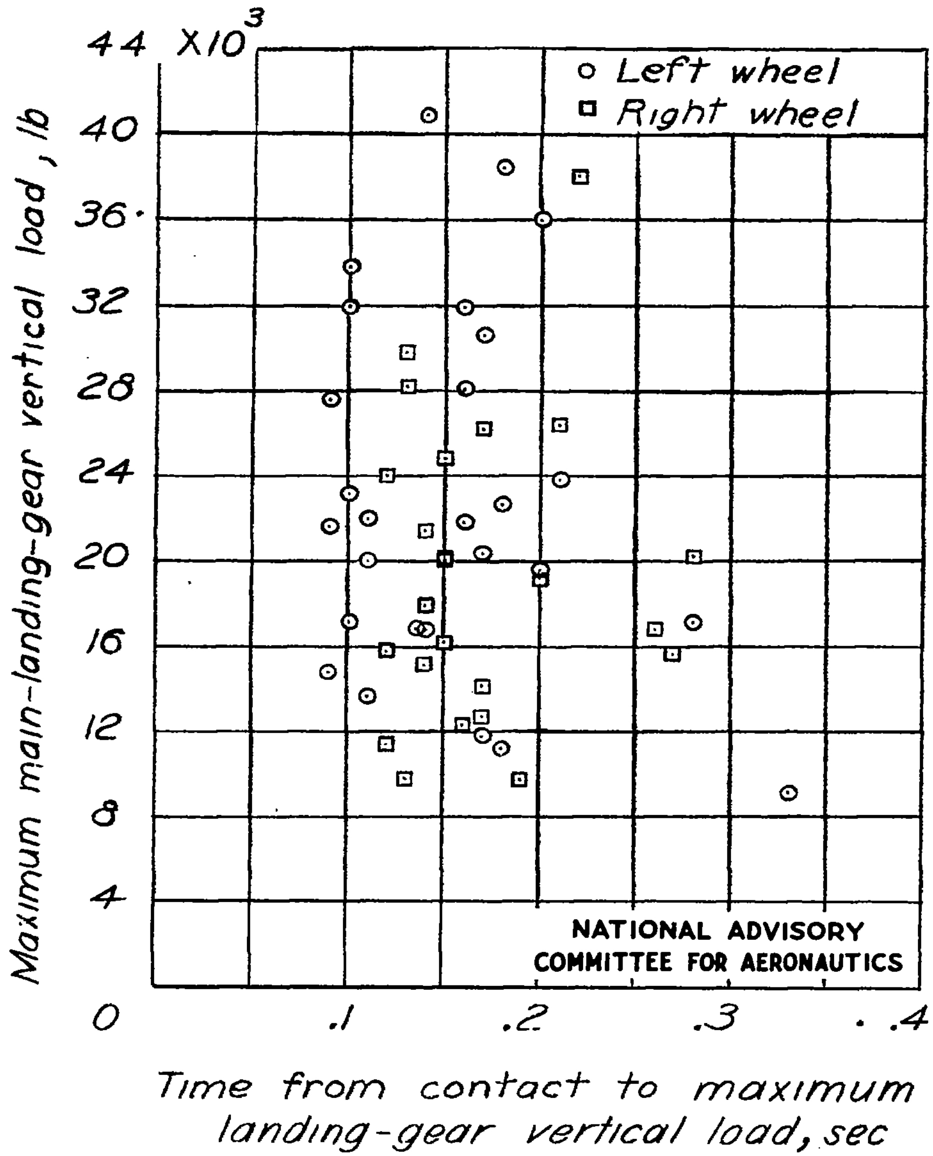


Figure 6.— Magnitude of main-landing-gear vertical load against time to reach maximum values.

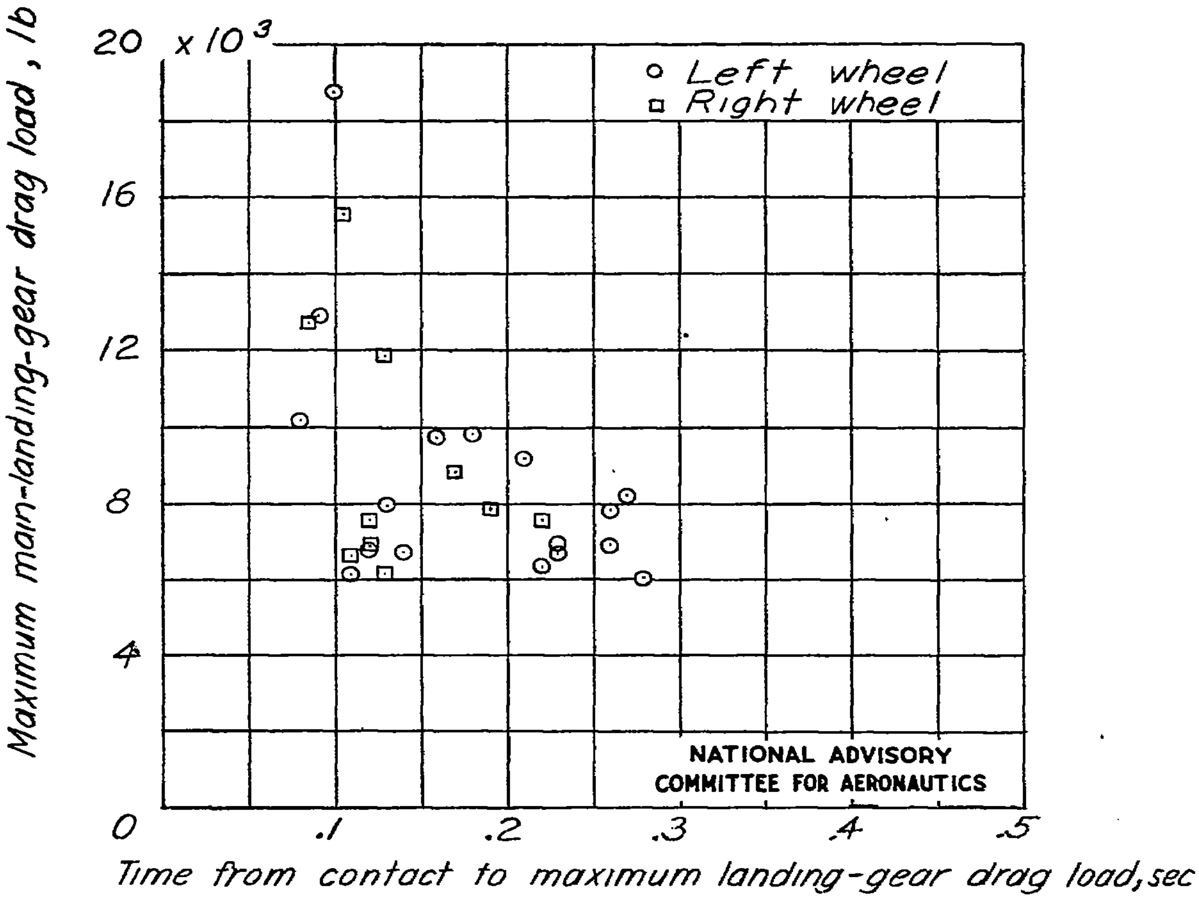


Figure 7.- Magnitude of main-landing-gear drag load against time to reach maximum value. Normal landings.

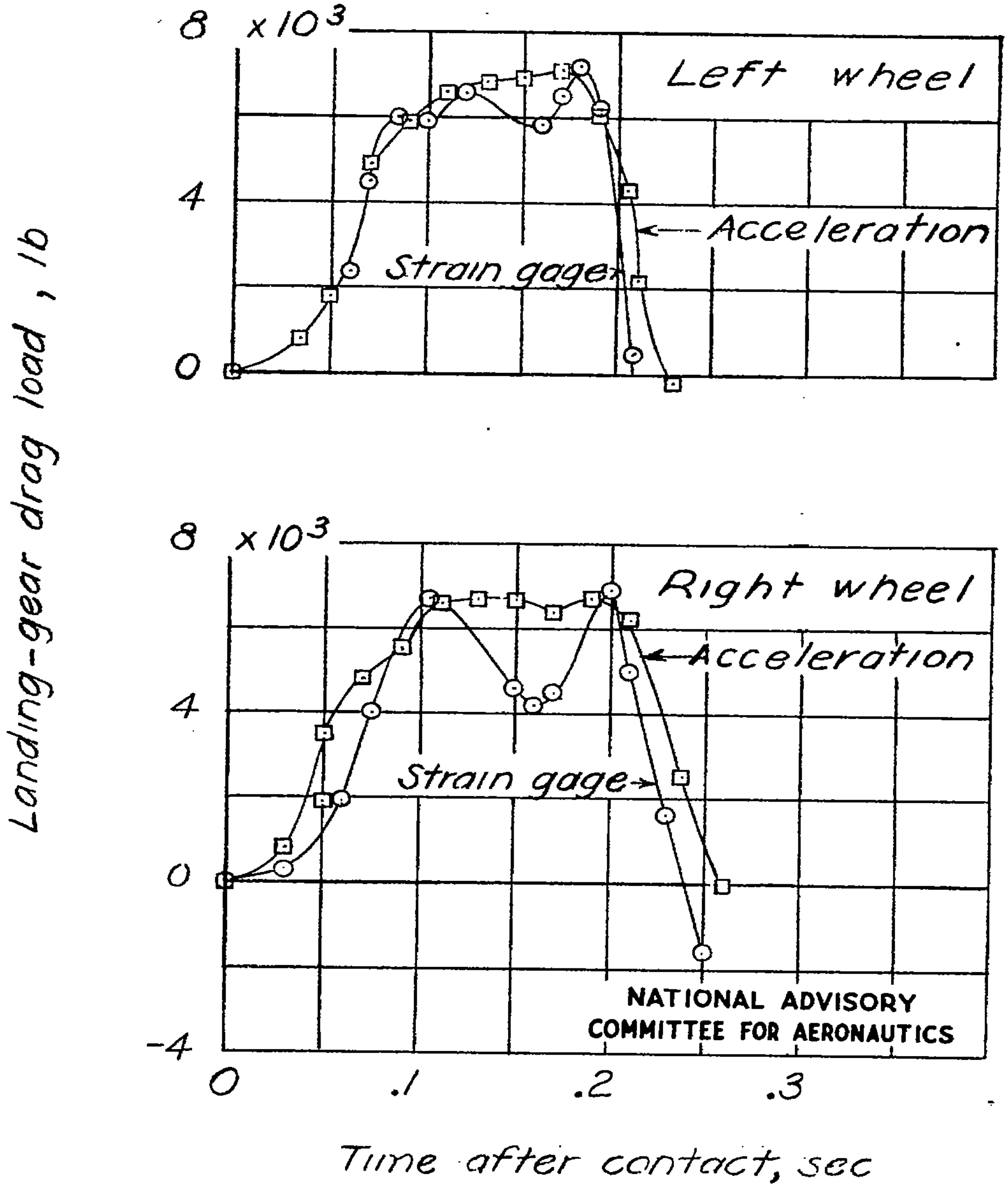


Figure 8.—Comparison of time histories of drag load on main landing gear from strain-gage readings and from wheel-acceleration data during a normal landing. Landing 8.

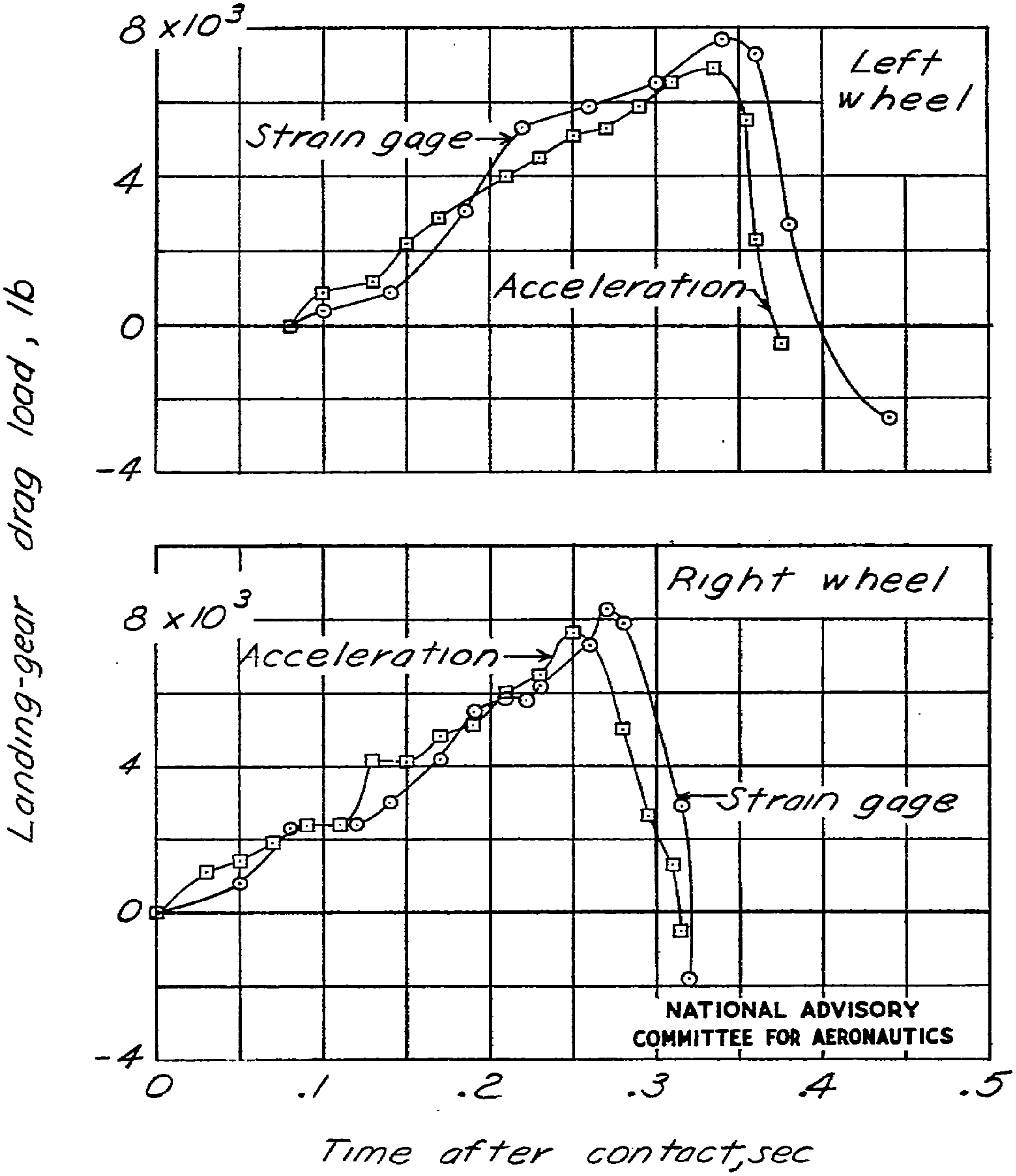


Figure 9.—Comparison of time histories of drag load on main landing gear from strain-gage readings and from wheel-acceleration data during a normal landing. Landing 12.

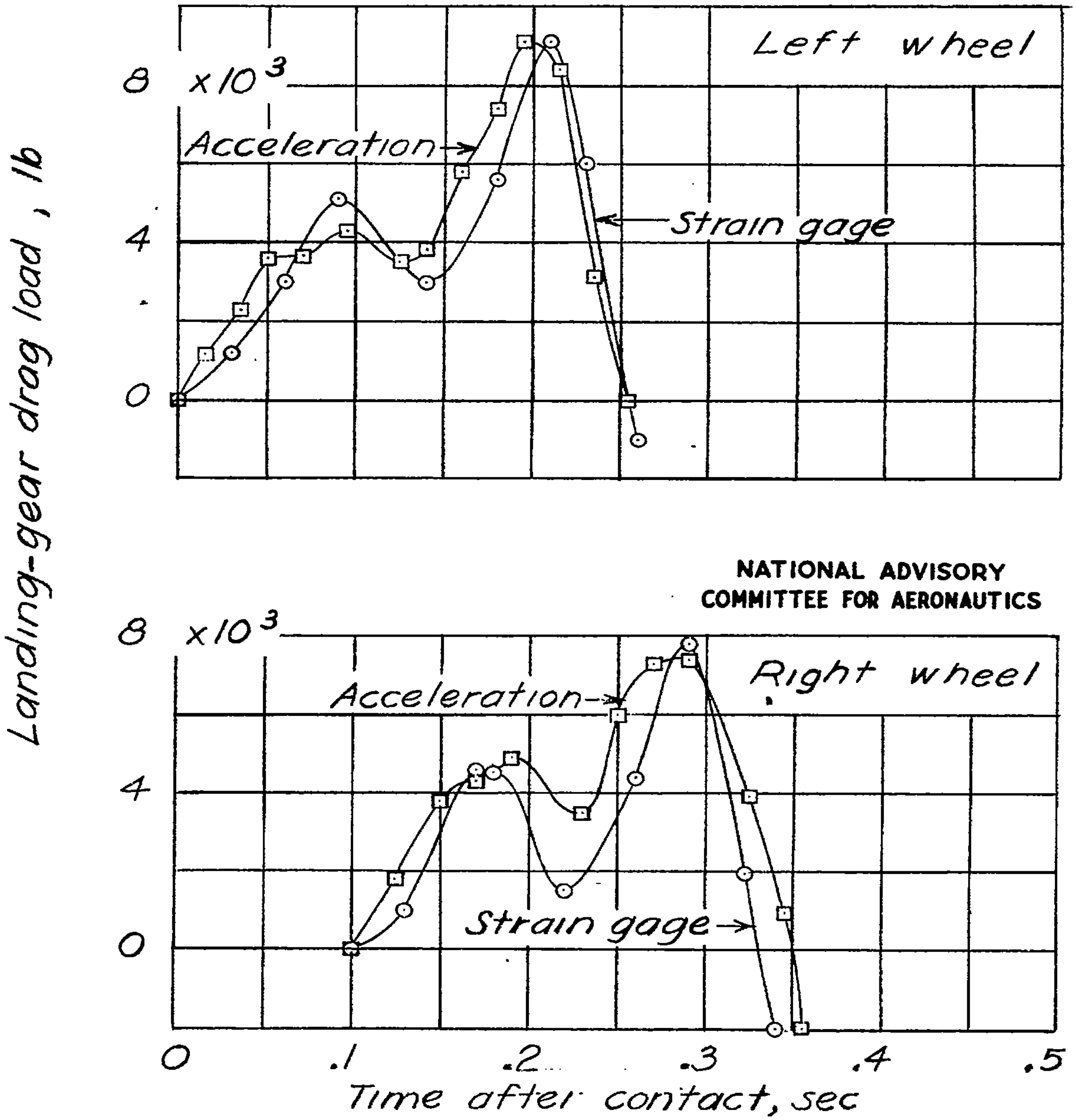


Figure 10.—Comparison of time histories of drag load on main landing gear from strain-gage readings and from wheel-acceleration data during a normal landing. Landing 16.

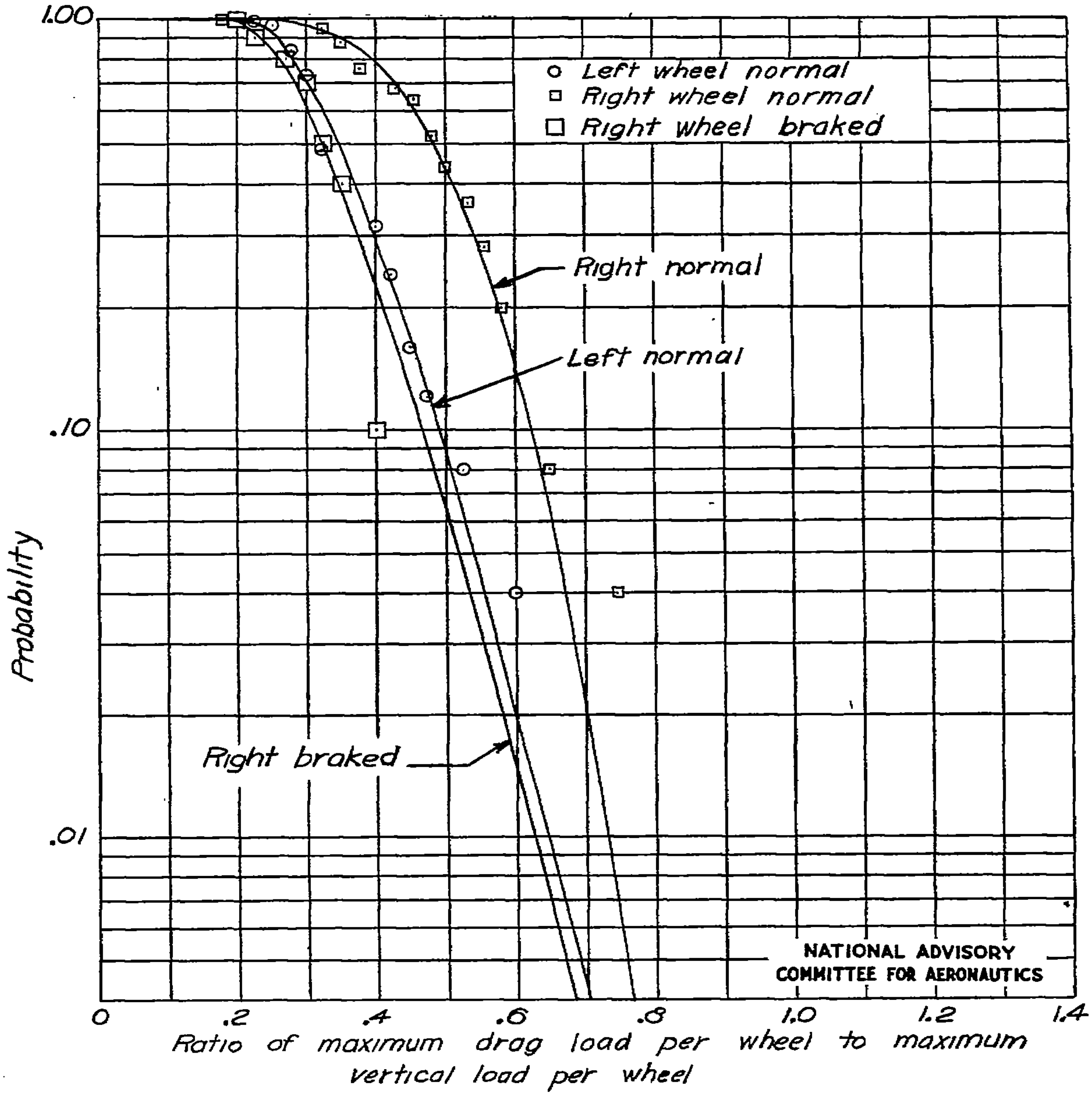
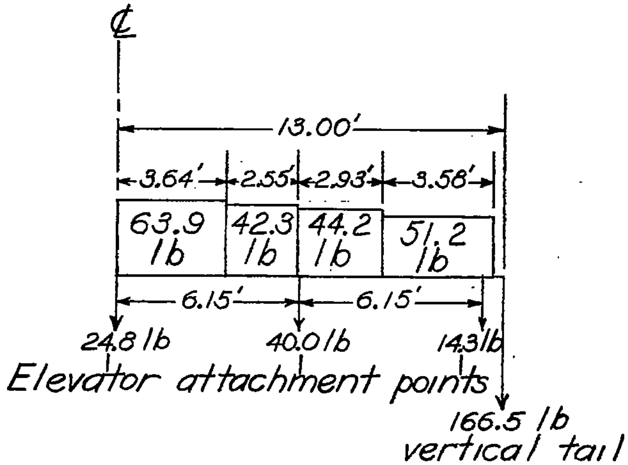
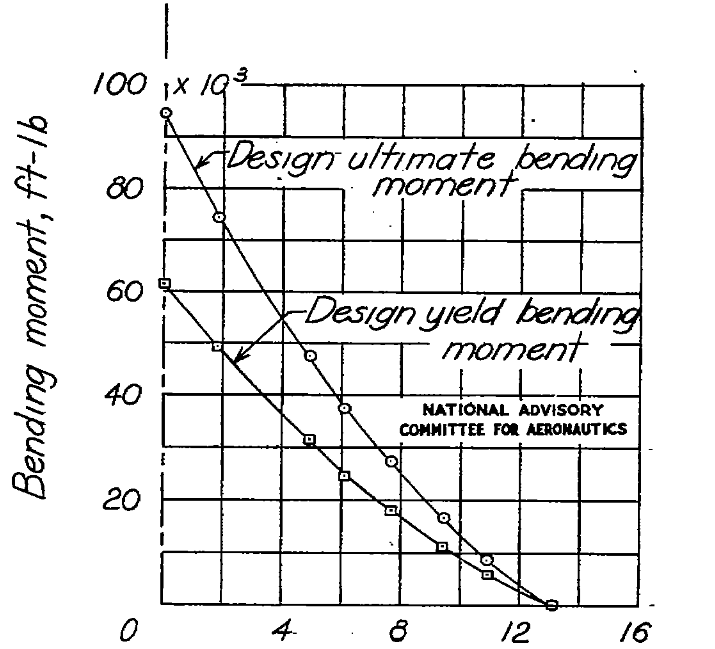


Figure 11.—Probability of equaling or exceeding given values of ratio of maximum drag load per wheel to maximum vertical load per wheel.

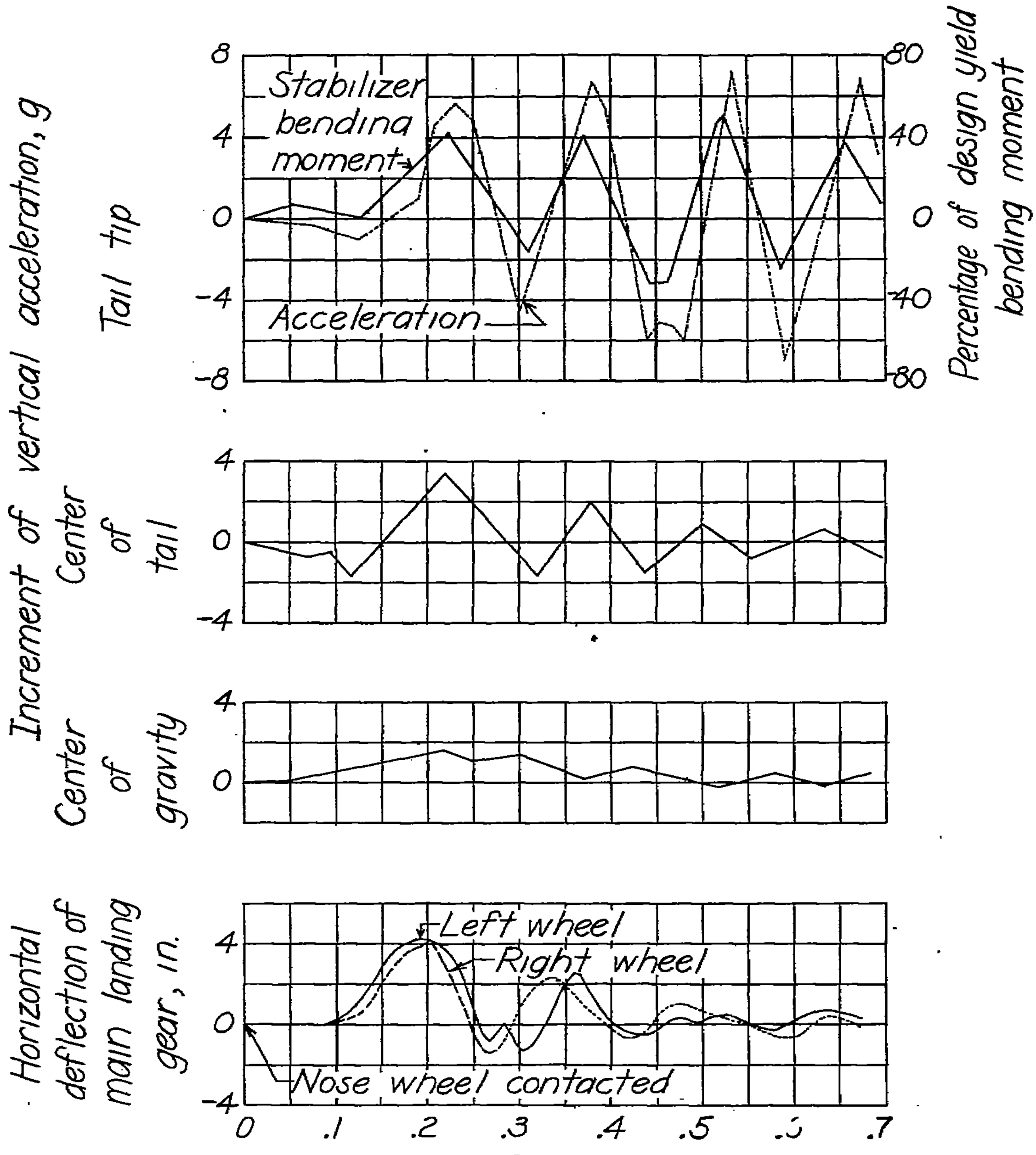


(a) Weight distribution of components of tail assembly.



(b) Stabilizer bending moments.

Figure 12.- Stabilizer loading and bending moments.



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 13.–Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 10.

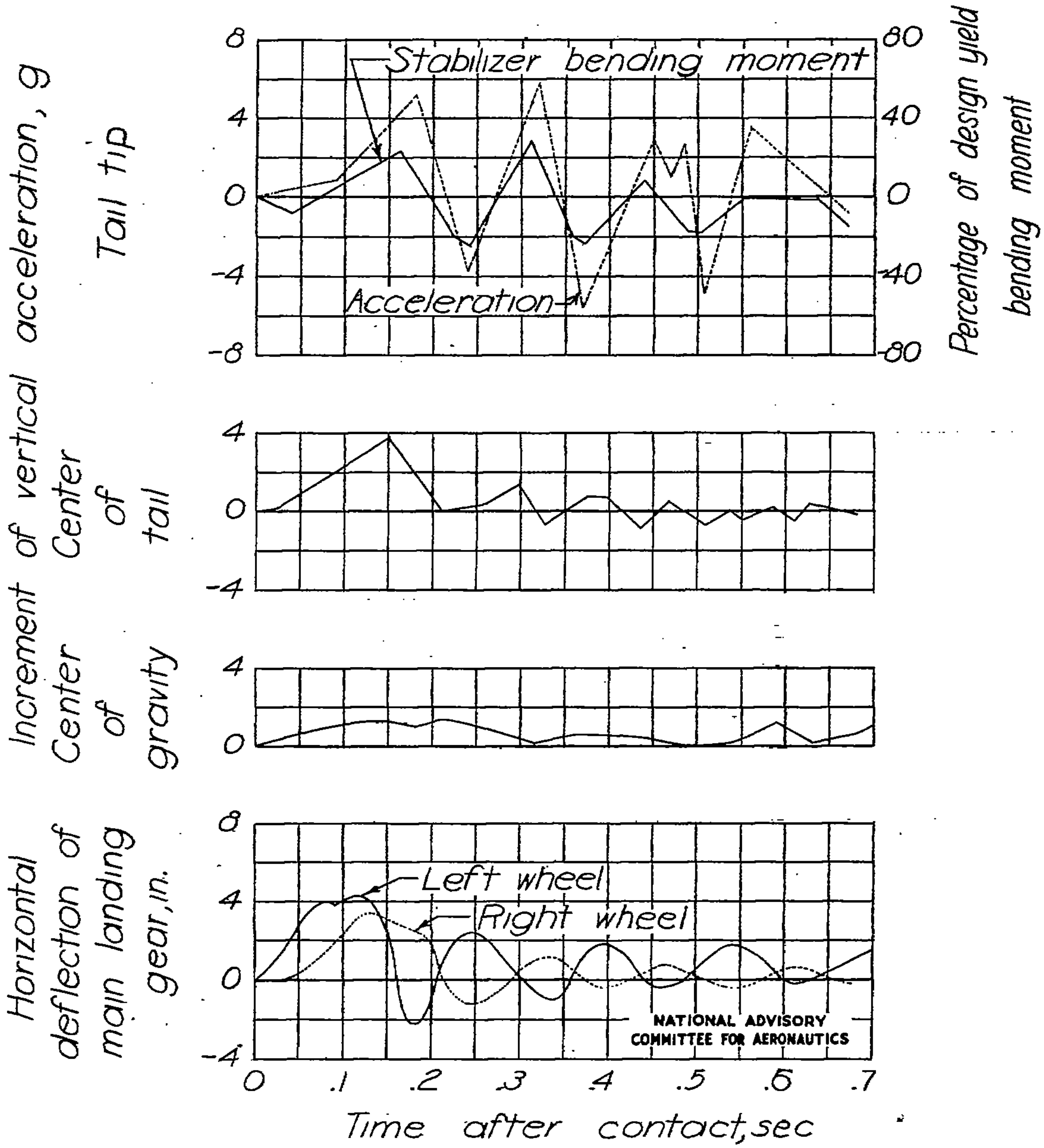


Figure 14.-Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 19.

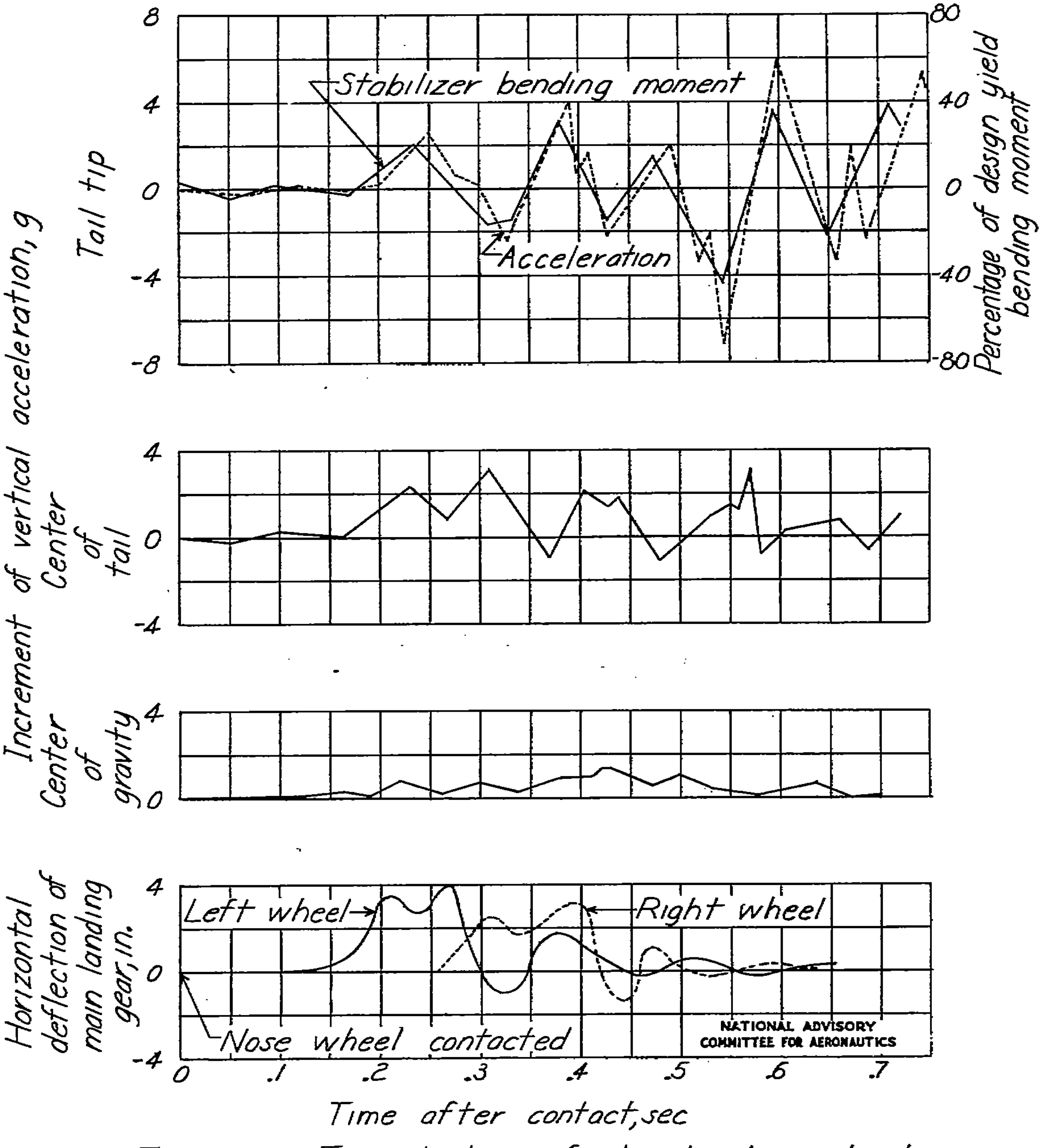


Figure 15.- Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 42.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1140

MEASUREMENTS OF LANDING-GEAR FORCES AND HORIZONTAL-TAIL LOADS IN LANDING TESTS OF A LARGE BOMBER-TYPE AIRPLANE

By John R. Westfall

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

Washington
September 1946

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A series of landings has been made with a large bomber-type airplane equipped with twin vertical tails to determine the time history of the impact forces on the landing gear and the resulting response of the airplane structure, particularly that of the horizontal tail, to the landing loads. About 50 landings were made, including normal, braked, and prerotation landings, but complete time histories were obtained for only 23 landings. The quantities measured included the vertical and drag components of the landing-gear loads, landing-gear deflection, stabilizer bending moments, structural accelerations, and airplane velocity and attitude. The tests were undertaken to investigate the specific causes of stabilizer failures on early models of the airplane, and it was found that the maximum stabilizer loads occurred in normal landings as a result of resonance with fore-and-aft landing-gear vibration. The data presented are adaptable to use in the analytical solution of the problem of structural response during landing impacts.

INTRODUCTION

The occurrence of structural failures on large airplanes, which cannot be explained on the basis of rigid-body phenomena, has served to emphasize the importance of structural elasticity in producing critical loading conditions during landing impacts. Typical of such failures are those of the horizontal stabilizer of early models of a large bomber-type airplane.

In order to investigate the specific cause of these failures, the Langley Memorial Aeronautical Laboratory of the NACA conducted a series of landing tests with a large bomber-type airplane equipped with twin vertical tails. In these tests, simultaneous measurements were made of the impact forces on the landing gear and of the resulting response of the airplane structure, particularly that of the horizontal tail. The test landings were made over a fairly wide range of vertical and horizontal velocity and attitude angle and included normal-, braked-, and prerotation-landing conditions. The maximum tail response was found to occur in normal landings as a result of resonance with fore-and-aft vibration of the landing gear when both main wheels touched simultaneously and vibrated in phase.

Although no attempt was made during the investigation to correlate experimental results with mathematically derived values, the measurements are suitable for use in the analytical solution of the problem of structural response during landing impacts in the manner proposed by Biot and Bisplinghoff (reference 1). Such a solution requires that the time histories of the external forcing function (that is, the impact loads on the landing gear) be obtained for various types of airplane in actual landings covering a sufficient number of landing conditions to constitute an adequate statistical sample.

APPARATUS AND METHOD

Airplane

The airplane used in the tests was a large four-motored bomber-type airplane equipped with tricycle landing gear and twin vertical tails mounted on the outboard ends of the stabilizer. The characteristics of the airplane are given in table I, and the natural frequencies of vibration are given in table II. The airplane was equipped with a 25g stabilizer, that is, one designed for an ultimate static load of 25 times the weight of the tail assembly. A number of stabilizer failures, apparently caused by loads imposed as a result of landing impacts, had been reported for earlier models of the airplane that were equipped with 15g stabilizers.

Tests

The tests consisted of a series of about 50 landings, all made on the concrete runways of Langley Field, Va., during which records were taken of the impact forces on the landing gear and of the resulting structural response. Normal, braked, and prerotation landings were included in the investigation. The landings were intended to cover as wide a range of velocity, attitude, and severity as practicable. The landings, however, were probably not so severe, at least on the average, as might be encountered under training or combat conditions and most could be classed as average landings by an experienced pilot. All the landings were made by one NACA test pilot.

Conditions at Contact

About a year and a half prior to the tests, the runways were coated with a camouflage material consisting of sawdust spread on an asphalt binder. At the time that the tests were begun, about one-third to one-half the surface of the runways was still covered with the camouflage coating in patches of varying size, shape, and thickness. This coating plus tire streaks, frost (encountered during some of the landings), and other foreign material contributed to the possibility that the coefficients of friction encountered would be lower on the coated concrete than on the bare dry concrete.

The vertical velocity and attitude of the airplane at contact were determined by means of two NACA recording phototheodolites. Ground speed was determined from the rotational velocity attained by the main wheels just after the impact recorded by two 35 millimeter motion-picture cameras operating at speeds of about 60 frames per second. The values of ground speed thus obtained were checked against values computed from readings of the airspeed indicator (which had been calibrated against true airspeed) and the surface wind velocity.

Measurement of Landing Gear and Stabilizer Loads

The vertical and the drag components of the impact force on the landing gear were measured by wire strain gages attached to the straight part of the landing-gear strut below the oleo cylinder. The strain gages, connected to form a conventional Wheatstone bridge, were supplied from a 2000-cycle oscillator. The bridge output was amplified and recorded on a Miller oscillograph, model E, the elements of which had a natural frequency of about 60 cycles per second. No side component of load was measured during the tests.

The inertia drag load on the main gear was also computed from the angular acceleration of the main landing wheels as determined from motion pictures of the wheels taken by the two 35-millimeter cameras. In order to facilitate these computations, an average value of tire deflection was assumed to exist throughout each landing. This assumption, of course, introduced an error in drag-load computations amounting to as much as 6 or 7 percent for the maximum values of the hardest landings, which was of about the same order as the error in the strain-gage readings.

Accelerations in the airplane were measured by standard NACA air-damped accelerometers installed near the center of gravity of the airplane, at the center of the fuselage near the rear spar of the stabilizer, and at the outboard end of the rear spar of the left stabilizer. The natural frequency of all the accelerometers was about 20 cycles per second. The locations of these accelerometers are indicated in figure 1.

The stabilizer loads were measured by means of wire strain gages located near the top and bottom of the front and rear spars of the stabilizer, one set being located near the root of the spars and another near the outboard end. These loads were computed as bending moments.

Brake Preloading

For some landings a predetermined amount of braking force was applied to the main wheels prior to contact by means of a device that permitted an adjustable pressure to be put on the hydraulic brake lines. A release lever was incorporated into the device to make possible instantaneous release of the brakes at any time and it was the practice of the pilot to release them immediately after the impact. Two pressure gages were connected into the hydraulic brake lines and gave readings of the brake pressures on both wheels. The maximum brake-preloading pressure used during the tests was about 25 pounds per square inch. This value was chosen as an upper limit because observations of the pressure gages during the decelerating runs after the impact was over showed that about 20 pounds per square inch was the maximum braking pressure used in slowing the airplane.

Prerotation

Special fittings with anemometer-cup-type wind vanes were attached to the main wheels in an effort to produce prerotation; however, they functioned erratically and were discarded. Prerotation was then achieved by touching the wheels to the runway to bring them up to speed, lifting the airplane off the runway by speeding up the engines, and again making contact while the wheels were revolving at high speed. The amount of prerotation obtained by this method was, of course, not controllable.

PRECISION OF DATA

The measurements of the following quantities are estimated to be correct within the limits shown:

Gross weight of airplane at contact, pounds	±100
Ground speed at contact, miles per hour	±3
Vertical velocity at contact, foot per second	±1.0
Attitude angle at contact, degree	±0.7
Main-landing-gear vertical loads, from strain gages, pounds	±2000
Main-landing-gear drag loads, from strain gages, pounds	±1000
Nose-gear vertical loads, from strain gages, pounds	±1500
Nose-gear drag loads, from strain gages, pounds	±1000
Main-landing-gear drag loads, computed from wheel-acceleration data, pounds	±1000
Tail bending moments from strain gages, percent	±5
Strut deflection, from camera records, inch	±0.1
Normal component of acceleration from accelerometer records, g	
Center of gravity	±0.2
Center of horizontal tail	±0.3
Left tail tip	±0.3
Time interval, second	±0.01

PRESENTATION AND DISCUSSION OF DATA

The test results are presented in tables III to VI and in figures 2 to 51. Certain of these figures show curves that represent the probability that given values of the variables selected for treatment will be equaled or exceeded. Probability may be interpreted herein as the ratio of the number of events that satisfy a given condition to the total number of events. The curves in all cases are Pearson type III probability curves (reference 2).

Tabulation of Landings

Table III summarizes the conditions at contact for the various landings. Table IV lists the landings in approximately decreasing order of severity in the three general types of landing (normal, braked, and prerotation) and presents maximum values of accelerations and of total landing-gear loads.

Velocity at Contact

The ground speeds at the time of contact are listed in tables III and IV. The ground speed covered the range from 80 to 128 miles per hour with an average value of 95 miles per hour. The vertical velocity at the time of impact (table IV) ranged from about 1 foot per second to about 7 feet per second, and in approximately 50 percent of the landings the vertical velocity was 2 feet per second or less. This result is in agreement with results of previous tests on large airplanes (reference 3).

Figure 2 is a curve of probability of vertical velocity at contact. This curve is based on the data from the normal and the braked landings; the prerotation landings were on the whole rather gentle because of the technique employed in making them and, hence, are not considered representative landings from the standpoint of vertical velocity. An inspection of the curve shows that, on the average, for this airplane about 1.3 landings out of 100 may be expected to equal or exceed the maximum vertical velocity recorded during the tests (6.9 fps) and about 1 out of 200 would equal or exceed 8 feet per second.

Landing-Gear Loads

Complete time histories of the impact parameters were obtained in 23 of the landings. In some additional landings, time histories were obtained for only one of the main-landing-gear units. Time histories of the landing-gear loads are presented for convenience at the end of the paper. (Data are presented for the normal landings in figs. 20 to 36, for the braked landings in figs. 37 to 44, and for the prerotation landings in figs. 45 to 51.) The maximum vertical load measured on one landing gear (40,900 lb) was about 41 percent of the design ultimate load whereas the maximum drag load measured (18,500 lb) was 73 percent of the design ultimate load.

Figure 3 presents probability curves of maximum values of the vertical load on the two main wheels for the normal and the braked landings. The probability of experiencing a given value of vertical load was appreciably greater for the left wheel than for the right wheel in both the normal and the braked landings. The vertical loads measured during braked landings tended to be higher than those measured during normal landings, although a scarcity of data on the braked landings made the significance of this phenomenon uncertain.

Figure 4 presents probability curves for maximum drag loads on the main wheels for normal and braked landings. No significant difference was noted between the probabilities for the two wheels, nor between the probabilities for normal and braked landings.

Table V lists the time intervals between contact of the two main landing wheels and notes which wheel contacted first. A curve of probability of time between contact of the two wheels is presented in figure 5. The probability that the time between contact will fall within a given interval may be determined by the difference between the probabilities for the time values involved. Thus, the probability that a landing would be made in the interval between 0.14 and 0.16 second after contact is 0.425 minus 0.360, which gives a value of 0.065.

The time to reach the maximum value of the vertical loads on each main wheel (fig. 6) varied from 0.09 second to 0.33 second for all landings, the average being about 0.17 second. It was not evident that any relationship existed between the magnitude of the maximum vertical load and the time to reach the maximum values of the vertical load.

Figure 7 presents the time for each main wheel to reach maximum drag load plotted against the magnitude of the drag load for normal landings. The average time from contact to maximum load was about 0.17 second. Despite considerable scatter, there was some indication that the time elapsed from contact to the maximum values of the drag load was less for the larger values of the drag load.

Table VI lists maximum values of main-wheel drag loads as computed from strain-gage reading and from wheel-acceleration data. Figures 8 to 10 compare time histories of main-landing-gear drag loads computed by the two methods.

A study of the time histories of the landing-gear loads disclosed no clear-cut relation between the order of development of the vertical load and the order of development of the drag load. This result is ascribable in part, at least, to random variation of the coefficient of friction during the impact.

Effect of Braking on Landing-Gear Loads

The tendency of braked landings to produce higher vertical loads than are produced by normal landings has already been pointed out. Another effect was to reduce the ratio of maximum drag load to maximum vertical load, as compared with the ratios for normal landings (fig. 11). This effect would be expected since braking tends to delay the wheel "spin-up" time past the point at which the vertical load is a maximum, and the coefficient of friction is usually less when the tire is sliding than when wheel slippage is small.

Effect of Prerotation on Landing-Gear Loads

The data from the prerotation landings were not subjected to a statistical analysis since the piloting technique involved was felt to be such as to prohibit direct comparison with the normal and the braked landings. Furthermore, the degree of prerotation was not the same for all landings. Certain qualitative results can, however, be discerned. As would be expected, prerotation had a marked effect in reducing the wheel drag load. The average ratio of maximum drag load to maximum vertical load for all prerotation landings was 0.11, compared with 0.41 for normal landings and 0.36 for braked landings. All these values are the average of those for the two main wheels.

Structural Response to Impact Loads

Figure 12 shows the tail-assembly weight distribution over the semispan of the stabilizer, computed from data furnished by the manufacturer, and the computed design yield and the design ultimate bending moments over the semispan. The measured stabilizer bending moments were converted into percentages of design yield bending moment and the maximum values for each landing are listed in table IV.

The maximum bending moment measured during the tests (50 percent of the design yield value) occurred during a normal landing (landing 10) in which the two main wheels contacted simultaneously and vibrated in phase in a fore-and-aft direction immediately following wheel spin-up (fig. 13). The frequency of the landing-gear oscillations was about the same as that of the stabilizer in symmetrical bending as may be seen by comparing the data of figure 14 and table II. Two other landings of about equal severity (figs. 14 and 15), in which the landing-gear vibrations were out of phase, did not produce such high bending moments; moreover, the pattern of the curve of bending moments of the two landings did not show the resonance effect that was present in landing 10. On the other hand, another landing of much less severity (landing 8 in fig. 16), in which the landing-gear vibrations were in phase, showed the same resonant tendencies as landing 10 and large stabilizer bending moments.

Figure 17 is a plot of probability of occurrence of values of stabilizer bending moments in normal landings. The curve shows that about one landing in 100 would develop the maximum stabilizer load measured during the tests (50 percent of the design yield bending moment). It might be pointed out that 50 percent of the design yield bending moment for the 25g stabilizer would be about 83 percent of the design yield bending moment for the 15g stabilizer, with which early models of the airplane were equipped and on which several stabilizer failures were experienced in service.

Further inspection of table IV indicates that high tail-tip accelerations are not necessarily associated with high stabilizer loads. Braked landings, in general, seemed to produce somewhat smaller tail loads than did normal landings. The effect of prerotation on tail loads was obscured by lack of data; however, prerotation did reduce landing-gear oscillations to a marked degree, as can be seen from the time histories of the landing-gear deflections for a prerotation and a normal landing in which the values of the impact parameters were about equal (figs. 18 and 19). If, as indicated previously, the stabilizer loads were increased by a coupling effect with the fore-and-aft landing-gear vibrations, prerotation should reduce tail loads.

Analysis of Separate Effects of Impact Parameters

An attempt was made to isolate the effects of some of the parameters that constitute the over-all forcing function. The results were in the main negative; that is, determining specific relationships was difficult. For example, no apparent relationship was noted between the ratio of maximum vertical loads on the left and right wheels and the time interval between contacts; furthermore, there seemed to be about as much likelihood that the higher vertical and drag loads would occur on the second wheel to contact as on the first. No relationship was apparent between the ratio of the maximum vertical loads on the two main wheels and the ratio of the maximum drag loads on the two main wheels. In most of the landings the left wheel contacted first. This result is attributed in part, at least, to an admitted tendency of the pilot to land with the left wing low for better visibility.

SUMMARY OF RESULTS

Measurements of landing-gear forces and horizontal-tail loads in landing tests of a large bomber-type airplane equipped with twin vertical tails indicated the following results:

1. The maximum vertical velocity measured in 50 landings was about 7 feet per second, and in about 50 percent of the landings the vertical velocity was 2 feet per second or less. Ground speeds at contact varied from 80 to 128 miles per hour, the average being about 95 miles per hour.

2. A statistical analysis of the vertical-velocity data indicated that about 1.3 landings out of 100 could be expected to equal or exceed the maximum value measured during the tests and that about 1 out of every 200 would equal or exceed 8 feet per second.

3. The maximum value of vertical load on the main landing gear was about 41 percent of the design ultimate load, whereas the maximum value of drag load was about 73 percent of the design ultimate load.

4. The ratio of maximum drag load to maximum vertical load was 0.41 for normal landings, compared with 0.36 for braked landings and 0.11 for prerotation landings.

5. The probability of equaling or exceeding given values of vertical loads on the main landing gear was higher for braked than for normal landings, although a paucity of data on the braked landings made the significance of this phenomenon uncertain.

6. In most of the landings the left wheel contacted first, although this characteristic might be attributed largely to piloting technique.

7. No relationship was discernible between the ratio of vertical loads on the left and right wheels and the time interval between contacts.

8. There appeared to be a higher probability for the left wheel to equal or exceed a given value of vertical load than the right wheel.

9. No relationship appeared to exist between the order of development of maximum vertical load and the order of development of maximum drag load.

10. The largest stabilizer load measured was about 50 percent of the design yield bending moment for the 25g stabilizer with which the airplane was equipped. This value of stabilizer load was measured in a normal landing in which the main wheels contacted simultaneously and vibrated in phase in a fore-and-aft direction subsequent to wheel spin-up. Evidence was that this coupling effect between the in-phase vibrations of the main landing gear units and the vibrations of the stabilizer in symmetrical bending could result in the development of large stabilizer bending moments.

11. Brake preloading tended to reduce tail loads.

12. Prerotation of the main wheels reduced drag loads and landing-gear vibration to a great extent although data were insufficient to predict its effect upon stabilizer loads.

13. A statistical analysis of the stabilizer-load data indicated that in about one landing out of 100, values of stabilizer bending load equal to the maximum measured during the tests could be expected.

14. Large values of stabilizer tip acceleration were not necessarily associated with large values of stabilizer bending moment.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., June 27, 1946

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2. Elderton, W. Palin: Frequency Curves and Correlation. Cambridge Univ. Press, 1938.

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TABLE I

AIRPLANE CHARACTERISTICS

Gross weight at landing, lb	48,900 to 50,100
Wing span, ft	110
Wing area, sq ft	1048
Horizontal tail area, total, sq ft	192.0
Stabilizer area, sq ft	140.5
Weight of tail assembly, lb	869.6
Normal rated horsepower	4400
Center-of-gravity position, as flown, percent M.A.C.	27.9 to 28.2
Height of center of gravity above ground, static position of airplane, ft	8.2
Approximate moment of inertia in pitch, as flown, slug-ft^2	150,000
Moment of inertia of main wheel, slug-ft^2	33.5
Wheel tread, ft	25.62
Wheel base, ft	16.00
Wing incidence, deg	3.0

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

TABLE II

NATURAL VIBRATION FREQUENCIES OF AIRPLANE

[From vibration tests conducted by the Air Material Command, Army Air Forces]

Part	Type of vibration	Frequency (cpm)	Location of vibrator	Remarks
Wing (approx. 400 gal gas in each wing)	Symmetrical bending	215	Outboard end of aileron	Nodal line just outboard of inboard engine; large fuselage vertical motion
	Symmetrical inner-panel torsion combined with symmetrical bending	315	Outboard end of aileron	Nodal line runs diagonally from just outboard of outboard engine at leading edge to wing root at trailing edge; outboard engine pitching considerably
	Inner-panel torsion	520	Between cylinders 7 and 9 on engine 2	Small response outboard engines; larger response inboard engines; amplitude too small to check phase; rear of fuselage moving vertically
		515	Floor of fuselage just forward of tail turret	
	Higher-order bending	590	Outboard end of aileron	Phase symmetrical by pickups
		990	Outboard end of aileron	Phase unsymmetrical by pickups
		1360	Outboard end of aileron	Phase symmetrical by pickups
Fuselage	Side bending	340	Inspection door on bottom of fuselage, 2 feet forward of tail light; lateral impulses	Very small amplitude
		520	Thrustwise impulses at bottom rudder hinge	Large amplitude mode; node at waist gun cut-out
	Vertical bending	980	Floor of fuselage just forward of tail turret	Amplitude too small to determine node line
Stabilizer	Symmetrical bending combined with wing symmetrical bending; pitching of airplane also excited	400	Vertical impulses at second rudder hinge from bottom	Stabilizer nodes $4\frac{1}{2}$ feet from center line of airplane Wing tip and stabilizer tip in phase
	Torsion	640	Thrustwise impulses at bottom rudder hinge	Phase symmetrical by pickups; nodal line near rear spar

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

TABLE III

CONDITIONS AT CONTACT

Landing (a)	Type of landing	Gross weight of airplane at contact (lb)	Attitude angle (deg) (b)	Vertical velocity (fps)	Ground speed (mph)	Wind direction	Airplane course (deg)	Wind velocity (mph)	Brake preloading (lb/sq in.)
1	Normal	50,000	4.1	1.8	111	ESE	270	5	--
2	Normal	49,700	1.0	1.9	116	ESE	270	5	--
3	Normal	49,300	.6	1.7	126	ESE	270	5	--
4	Normal	49,900	5.1	1.3	96	NNW	350	10	--
5	Normal	49,600	-.1	1.7	113	NNW	350	10	--
6	Normal	49,200	5.3	1.8	97	NNW	350	10	--
7	Normal	49,000	5.7	1.8	88	NNW	350	10	--
8	Normal	49,900	1.2	2.5	106	E	70	7	--
9	Normal	49,700	6.1	.7	91	E	70	7	--
10	Normal	49,300	-.9	6.5	102	E	70	7	--
11	Braked	48,900	3.7	4.1	98	E	70	7	5
12	Normal	49,900	1.7	2.2	102	NNW	350	11	--
13	Normal	49,700	.9	4.0	107	NNW	350	12	--
14	Braked	49,300	.4	3.6	87	NNW	350	13	5
15	Braked	48,900	2.4	3.0	89	NNW	350	14	10
16	Normal	49,700	5.2	2.9	103	ENE	350	4	--
17	Normal	49,500	4.5	---	96	ENE	350	4	--
18	Braked	49,200	3.2	2.2	105	ENE	350	4	10
19	Normal	50,100	3.9	4.2	118	N	250	19	--
20	Normal	49,400	---	2.4	84	N	350	20	--
21	Braked	49,200	---	2.8	90	N	350	21	15
22	Braked	48,900	5.1	4.2	84	N	350	22	22
23	Normal	50,100	3.6	2.3	100	NNW	350	12	--
24	Normal	49,900	3.9	.9	94	NNW	350	12	--
25	Braked	49,600	1.9	4.2	96	NNW	350	12	20
26	Braked	49,200	2.7	.9	94	NNW	350	12	23
27_1	Normal	50,100	---	1.6	82	NNW	350	30	--
27_2	Prerotation	50,100	---	1.8	80	NNW	350	30	--
28_1	Normal	49,700	---	1.5	90	NNW	350	30	--
28_2	Prerotation	49,700	---	1.0	82	NNW	350	30	--
29_1	Normal	49,500	---	1.4	87	NNW	350	30	--
29_2	Prerotation	49,500	---	.9	83	NNW	350	30	--
30_1	Normal	49,200	---	2.6	82	NNW	350	30	--
30_2	Prerotation	49,200	---	2.3	80	NNW	350	30	--
31	Braked	49,000	---	1.0	81	NNW	350	30	24
32_1	Normal	49,800	---	2.9	100	SSW	175	8	--
32_2	Prerotation	49,800	4.8	3.0	97	SSW	175	8	--
33_1	Normal	49,600	3.6	1.9	98	SSW	175	8	--
33_2	Prerotation	49,600	3.7	1.2	96	SSW	175	8	--
34	Braked	49,300	.8	4.9	96	SSW	175	8	19
35	Braked	49,200	4.5	1.8	91	SSW	175	8	24
36_1	Normal	49,800	---	1.3	---	---	---	--	--
36_2	Prerotation	49,800	---	2.2	---	---	---	--	--
37_1	Normal	49,500	---	---	---	---	---	--	--
37_2	Prerotation	49,500	---	---	---	---	---	--	--
$36a_1$	Normal	50,000	1.1	1.4	98	SW	250	7	--
$36a_2$	Prerotation	50,000	2.4	1.0	94	SW	250	7	--
$37a_1$	Normal	49,800	.8	1.6	98	SW	250	7	--
$37a_2$	Prerotation	49,800	4.9	1.3	90	SW	250	7	--
38_1	Normal	49,500	.5	3.1	100	SW	250	7	--
38_2	Prerotation	49,500	2.5	2.9	94	SW	250	7	--
39_1	Normal	49,300	---	2.6	102	SW	250	7	--
39_2	Prerotation	49,300	3.8	2.1	100	SW	250	7	--
40	Normal	50,100	3.0	1.4	87	SSW	170	20	--
41	Normal	49,900	4.4	1.3	89	SSW	170	20	--
42	Normal	49,600	-1.4	6.9	128	SSW	170	20	--
43	Normal	49,400	.2	1.1	112	SSW	170	20	--
44	Braked	49,100	1.0	5.8	91	SSW	170	20	23

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Angle between longitudinal axis of airplane and the horizontal, positive in nose-up direction.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

TABLE IV

LANDINGS CLASSIFIED ACCORDING TO TYPE AND SEVERITY OF IMPACT

Landing (a)	Increment of maximum acceleration (g) At c.g.	At center of tail	At left tail tip	Vertical velocity (fps)	Ground speed (mph)	Maximum total main-gear vertical load (lb)	Maximum total main-gear drag load (lb)	Maximum nose-wheel vertical load (lb) (b)	Maximum stabilizer design yield bending moment (percent)
Normal									
10	1.55	3.55	7.20	6.5	102	70,100	25,400	15,400	50.3
42	1.35	3.10	6.20	6.9	128	58,400	21,500	3,500	36.9
19	1.40	3.90	6.00	4.2	118	61,800	20,700	------	37.3
39_1	1.00	1.55	5.60	2.6	102	43,600	------	------	29.0
16	.70	1.60	2.30	2.9	103	50,200	12,000	------	23.5
20	.60	1.45	5.80	2.4	84	36,000	15,100	------	21.4
13	.80	1.10	3.10	4.0	107	31,700	7,600	------	37.5
8	.60	1.70	6.10	2.5	106	34,200	12,500	3,200	37.8
12	----	1.10	1.40	2.2	102	29,400	14,500	------	24.4
38_1	.65	2.20	2.70	3.1	100	27,100	14,800	------	28.5
2	.65	1.45	2.90	1.9	116	33,300	13,400	------	27.6
30_1	----	----	----	2.6	82	40,000	------	------	----
6	----	1.00	2.90	1.8	97	34,100	10,100	------	24.5
7	----	1.10	1.60	1.8	88	33,000	11,700	------	23.9
5	----	1.15	2.50	1.7	113	33,300	13,400	------	30.6
4	----	1.40	2.90	1.3	96	31,600	12,500	------	30.1
32_1	.60	1.10	2.70	2.9	100	32,200	8,400	------	17.0
43	.60	1.20	2.70	1.1	112	29,000	15,400	------	----
33_1	.60	1.15	3.30	1.9	98	28,100	9.700	------	----
23	.55	1.25	2.00	2.3	100	25,100	9,700	------	14.2
27_1	----	1.70	3.70	1.6	82	26,600	6,000	------	----
28_1	----	1.05	1.70	1.5	90	25,500	10,100	------	14.4
29_1	.35	.80	2.30	1.4	87	23,400	------	------	----
$36a_1$	.60	1.20	1.90	1.4	98	17,800	------	------	----
40	.30	.90	1.30	1.4	87	26,000	10,200	------	12.5
41	.35	.90	1.40	1.3	89	16,000	9,400	------	----
9	.30	.55	----	.7	91	21,900	5,600	------	21.3
17	.30	.30	1.00	---	96	------	------	------	----
37_1	.30	.75	1.15	---	---	------	------	------	----
24	.10	.60	1.25	.9	94	9,500	7,600	------	6.6
$37a_1$	.20	.40	.80	1.6	98	11,200	------	------	----
Braked									
44	1.10	2.60	4.00	5.8	91	67,700	15,300	3,600	----
34	1.20	2.25	3.90	4.9	96	54,200	19,300	------	24.7
14	.80	1.35	4.80	3.6	87	48,800	18,500	------	25.5
21	.75	1.35	2.70	2.8	90	53,000	10,500	------	10.7
11	.90	1.20	3.00	4.1	98	44,100	12,500	------	27.8
25	.65	1.70	2.80	4.2	96	41,100	15,100	------	23.0
15	.50	1.30	2.90	3.0	89	35,100	13,000	------	----
18	.35	.50	2.10	2.2	105	38,700	14,100	------	27.4
35	.30	.75	1.90	1.8	91	35,000	12,600	------	11.1
31	.30	.80	1.90	1.0	81	21,000	7,000	------	11.8
26	.35	.70	1.30	.9	94	23,700	10,200	------	17.0
22	.15	.20	1.60	1.2	84	21,900	5,300	------	6.9
Prerotation									
30_2	0.80	0.95	2.55	2.3	80	40,700	2,400	------	----
27_2	.80	1.35	3.10	1.8	80	39,400	3,000	------	----
32_2	.65	1.25	3.10	3.0	97	29,800	4,000	------	17.8
38_2	.80	1.20	2.40	2.9	94	24,700	1,600	------	7.4
39_2	.55	.50	1.20	2.1	100	28,600	800	------	6.5
36_2	.40	.75	1.25	2.2	---	29,200	1,700	------	----
33_2	.40	.60	1.50	1.2	96	22,000	1,600	------	----
$36a_2$	.40	.80	.80	1.0	94	17,600	4,300	------	----
28_2	.30	.35	1.00	1.0	82	19,200	1,000	------	8.7
$37a_2$	.35	.45	.40	1.3	90	17,800	1,300	------	----
37_2	.35	.70	1.50	3.1	---	20,100	-----	------	----
29_2	.25	.35	1.70	.9	83	15,200	2,100	------	----

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Nose-wheel loads listed only when nose wheel contacted during primary part of impact.

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TABLE V

TIME INTERVALS BETWEEN CONTACT OF LEFT AND

RIGHT MAIN LANDING WHEELS

Landing (a)	First wheel to contact	Time between contacts (sec)	Landing (a)	First wheel to contact	Time between contacts (sec)
1	Right	0.09	28_1	Right	0.04
2	Left	.12	28_2	Left	.15
3	Left	.16	29_1	Right	.21
4	Left	.02	29_2	Left	.12
5	Left	.42	30_1	----	----
6	Right	.15	30_2	Left	.11
7	Left	.10	31	Right	.14
8	Left and right	0	32_1	Left	.12
9	----	----	32_2	Left	.07
[b]10	Left and right	0	33_1	Left	.20
			33_2	Left	.15
11	Left	.04	34	Right	.12
12	Right	.08	35	Left	.10
13	Left	.17	$36a_1$	Left	.34
14	Left	.07	$36a_2$	Left	.17
15	Left	.24	$37a_1$	Left	.33
16	Left	.10	$37a_2$	Left	.19
17	Left	.33	38_1	Right	.02
18	Left	.09	38_2	Left	.26
19	Right	.03	39_1	----	----
20	Left	.04	39_2	Left	.29
21	Right	.14	40	Right	.17
22	Left	.22	41	----	----
23	Right	.14	[c]42	Left	.10
24	----	----			
25	Right	.07	43	Right	.01
26	Left	.46	44	Right	.10
27_1	----	----			
27_2	Left	.05			

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Nose wheel contacted 0.09 second before left and right wheels.

[c] Nose wheel contacted 0.13 second before left wheel.

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COMMITTEE FOR AERONAUTICS

TABLE VI

MAXIMUM VALUES OF WHEEL DRAG LOADS FROM STRAIN-

GAGE READINGS AND WHEEL-ANGULAR-ACCELERATION DATA

Landing (a)	Maximum wheel drag load (lb)			
	Left wheel		Right wheel	
	Strain-gage reading	Wheel-acceleration data	Strain-gage reading	Wheel-acceleration data
1	-----	7,140	-----	6,400
2	6,500	8,500	7,700	6,340
3	-----	10,200	-----	8,400
4	6,850	8,970	-----	7,570
5	9,820	9,000	-----	3,400
6	6,705	8,000	-----	11,300
7	6,650	7,260	-----	5,870
8	7,150	7,100	7,020	7,100
9	-----	3,300	5,400	5,500
10	12,700	12,900	12,500	12,700
11	-----	9,800	9,850	10,700
12	7,720	6,850	8,300	6,500
13	7,310	8,900	6,810	5,350
14	11,200	10,500	-----	14,200
15	7,150	8,100	8,400	6,550
16	9,120	9,100	5,410	7,400
17	-----	3,700	-----	4,100
18	4,750	4,700	-----	8,600
19	11,750	11,600	10,300	12,100
20	6,350	6,950	8,900	10,350
21	5,970	-----	10,600	10,000
22	[b]4,600	1,600	[b]4,300	4,910
23	1,110	1,080	[b]9,850	8,200
24	[b]5,670	7,200	[b]7,520	4,550
25	7,030	8,200	10,870	9,500
26	[b]5,330	2,700	[b]8,370	8,500
27_1	6,300	-----	[b]5,800	-----
27_2	2,400	1,390	1,000	-----
28_1	[b]5,890	6,600	[b]6,765	6,400
28_2	500	-----	700	-----
29_1	-----	-----	[b]9,290	11,000
29_2	2,100	5,900	600	900
30_1	-----	-----	-----	-----
30_2	500	-----	2,400	-----
31	4,770	5,110	5,140	5,000
32_1	[b]6,230	-----	6,910	7,670
32_2	1,700	1,850	4,800	3,950
33_1	5,700	-----	8,400	9,900
33_2	900	-----	1,400	1,320
34	5,770	-----	13,680	15,100
35	6,205	6,160	6,980	7,020
36_1	-----	-----	-----	-----
36_2	800	-----	1,600	-----
37_1	-----	-----	-----	-----
37_2	-----	-----	1,300	-----
$36a_1$	[b]8,115	8,500	-----	5,500
$36a_2$	4,300	4,500	2,800	2,800
$37a_1$	4,400	3,900	[b]5,810	4,700
$37a_2$	100	100	1,300	1,250
38_1	6,490	6,800	8,850	9,100
38_2	1,100	1,080	1,600	1,550
39_1	-----	-----	4,750	-----
39_2	200	-----	800	930
40	6,910	6,800	[b]3,450	6,000
41	9,550	9,700	[b]6,620	6,500
42	18,500	18,400	10,560	14,200
43	-----	11,300	8,200	8,800
44	10,000	13,100	14,150	15,000

[a] Subscripts 1 and 2 indicate first and second contacts, respectively; affix a on landings 36 and 37 indicates re-run.

[b] Uncorrected for effect of vertical load.

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COMMITTEE FOR AERONAUTICS

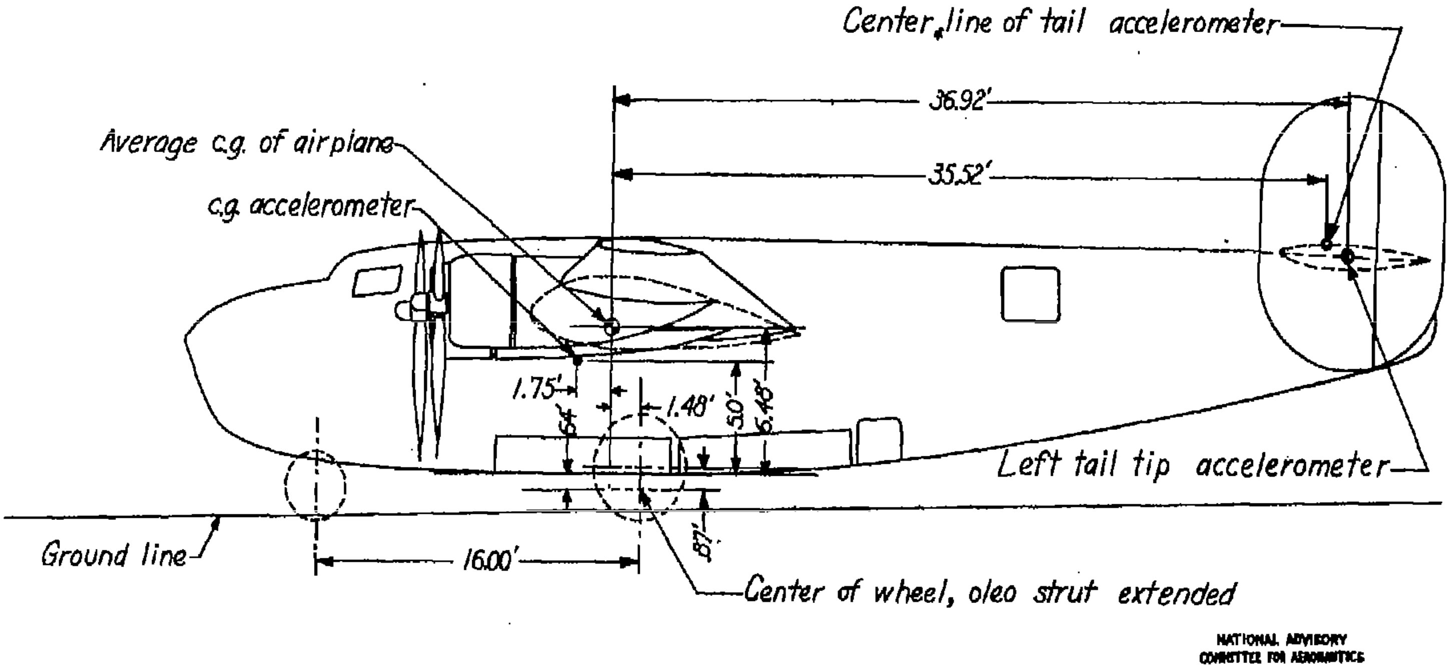

Figure 1. - Location of accelerometers in the airplane.

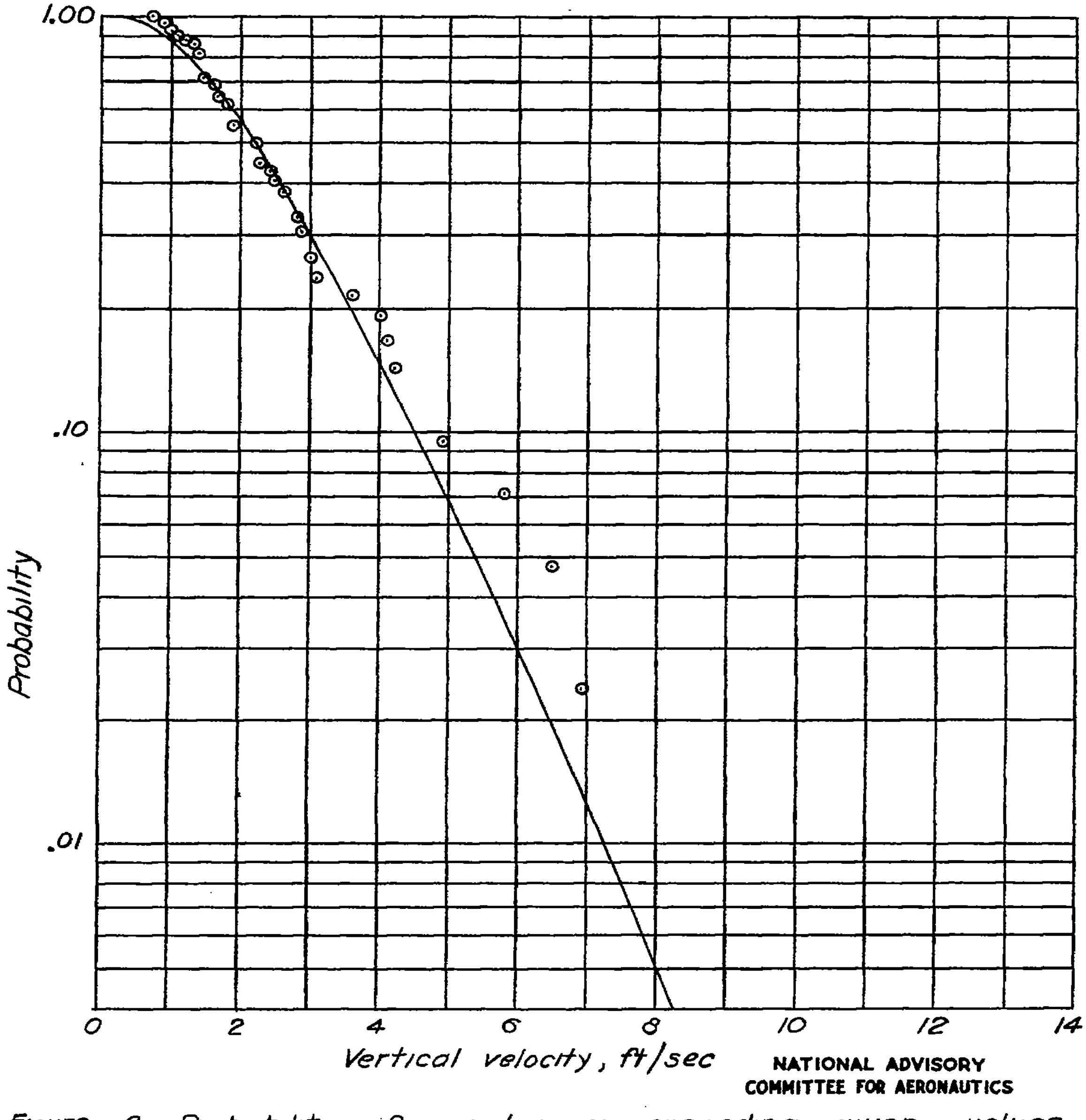

Figure 2.- Probability of equaling or exceeding given values of vertical velocity. Prerotation landings not included.

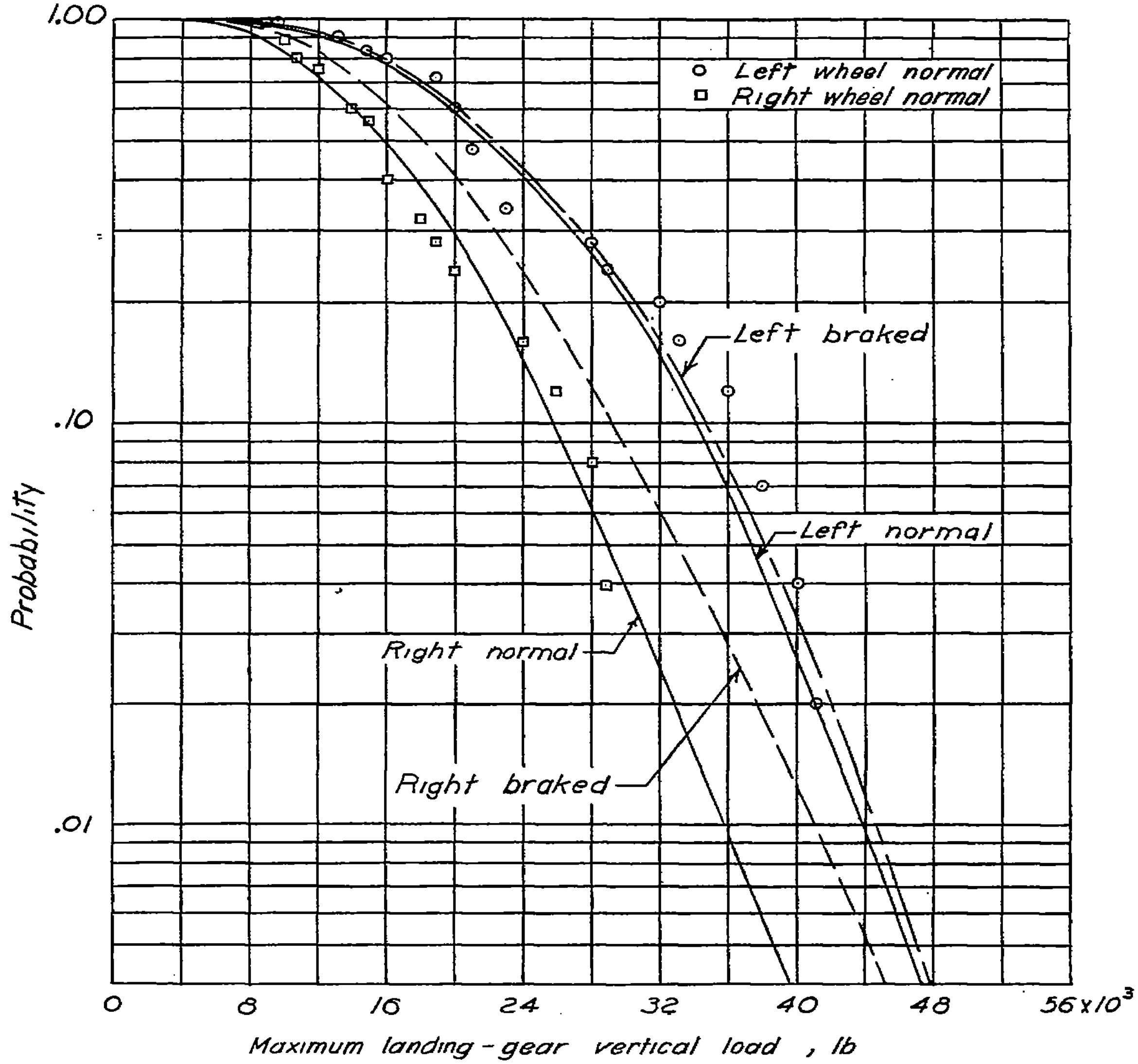

Figure 3.-Probability of equaling or exceeding maximum values of vertical load on main landing gear. Normal and braked landings.

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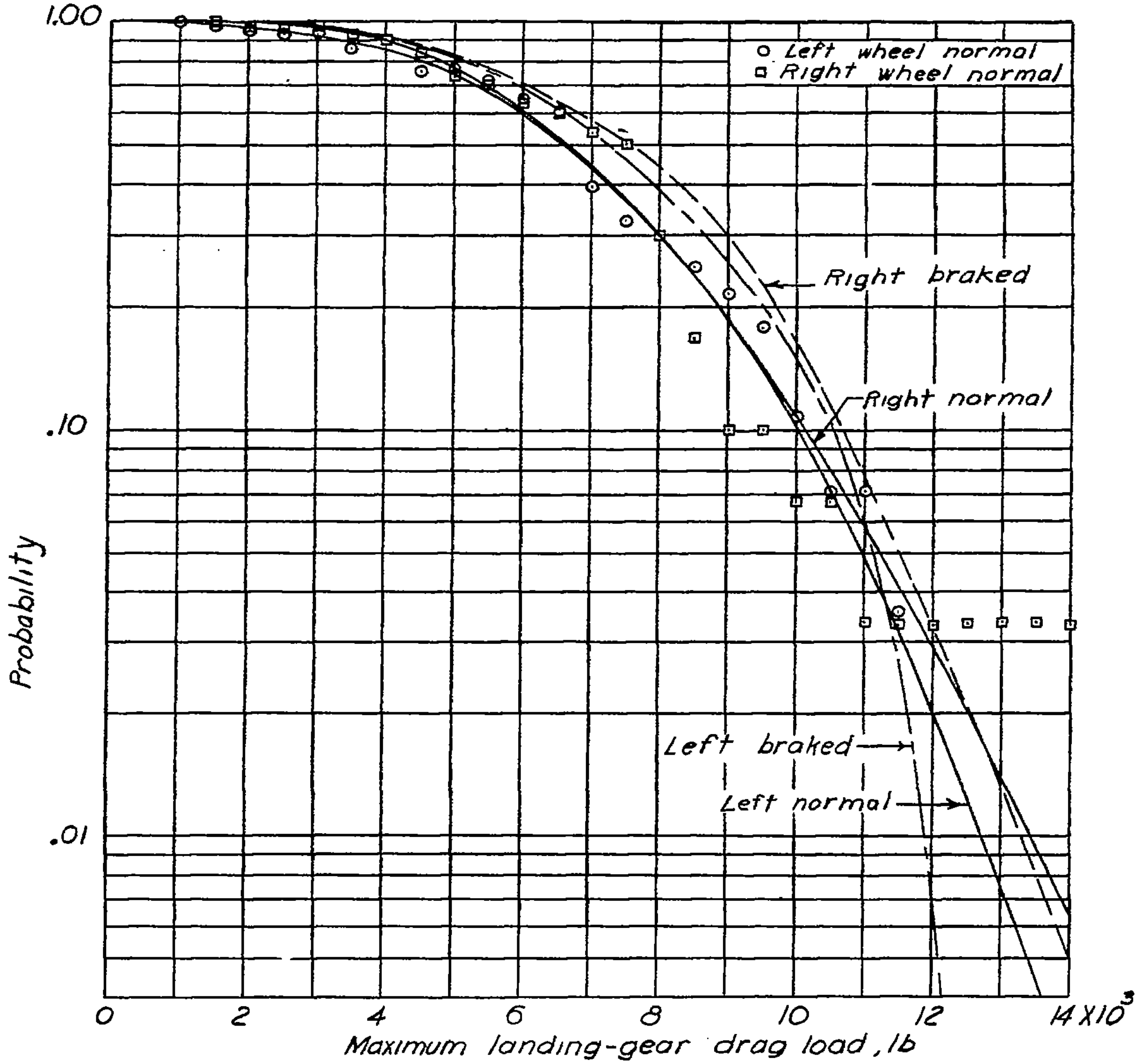

Figure 4.- Probability of equaling or exceeding maximum values of drag load on main landing gear. Normal and braked landings.

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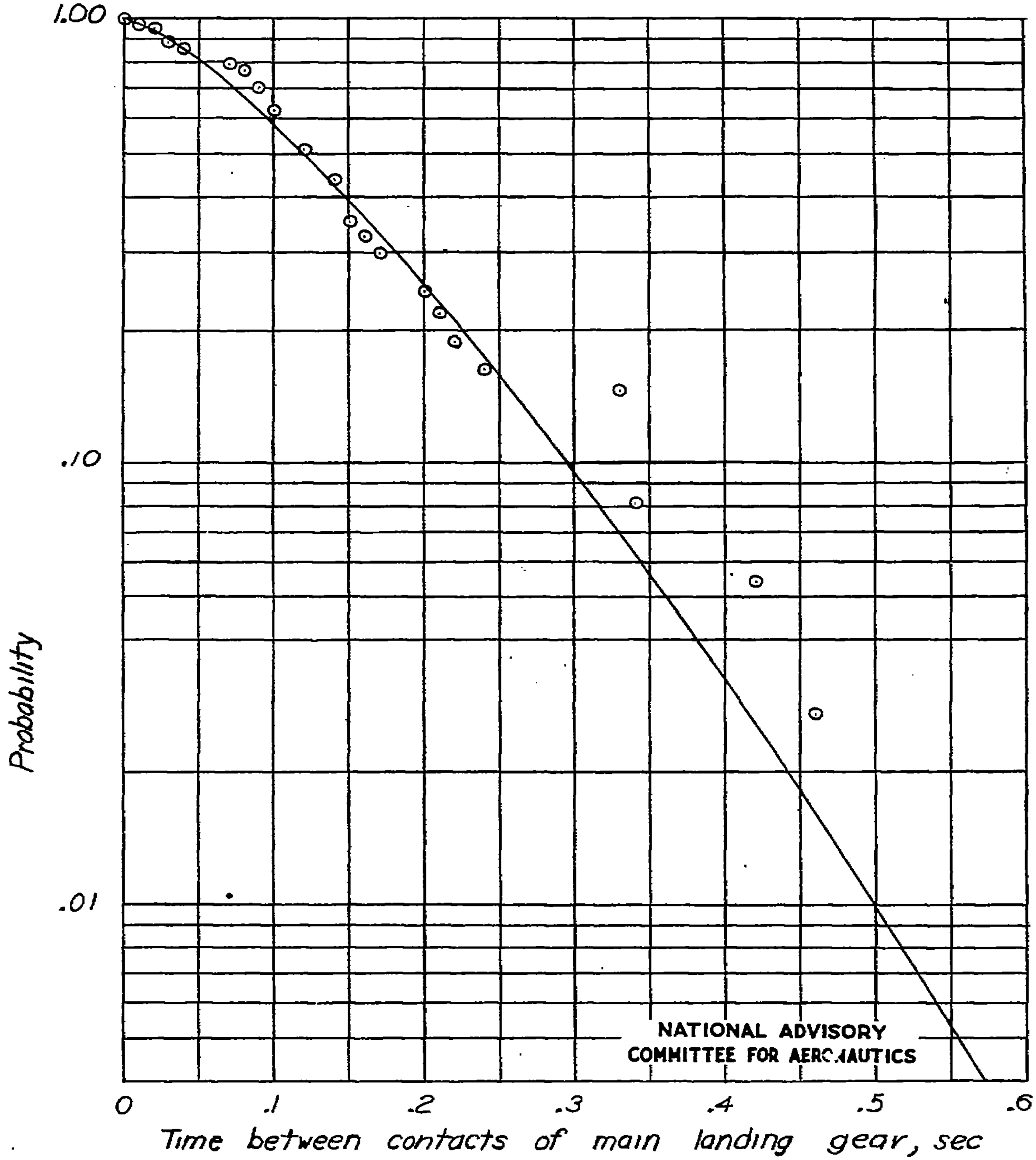


Figure 5.-Probability of equaling or exceeding time between contacts of main landing gear.

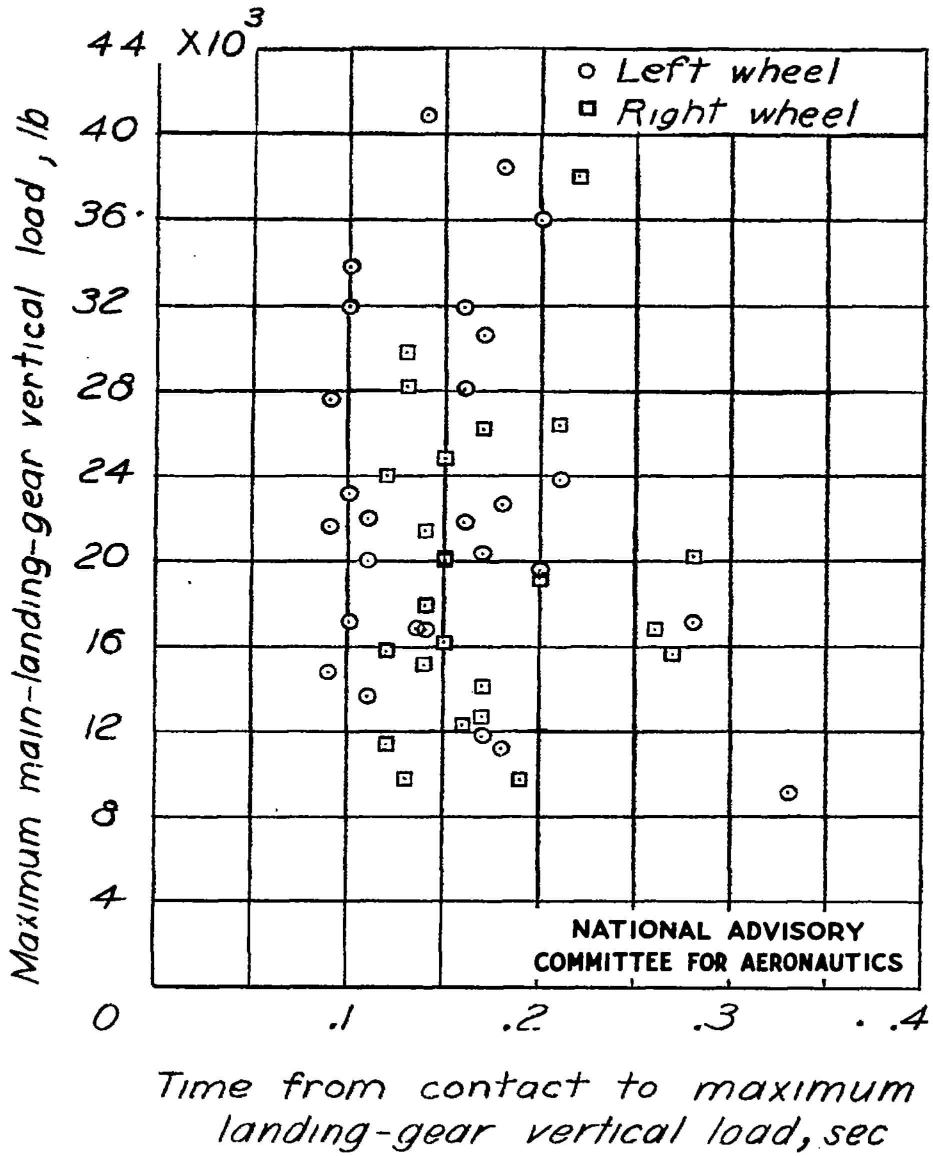


Figure 6.— Magnitude of main-landing-gear vertical load against time to reach maximum values.

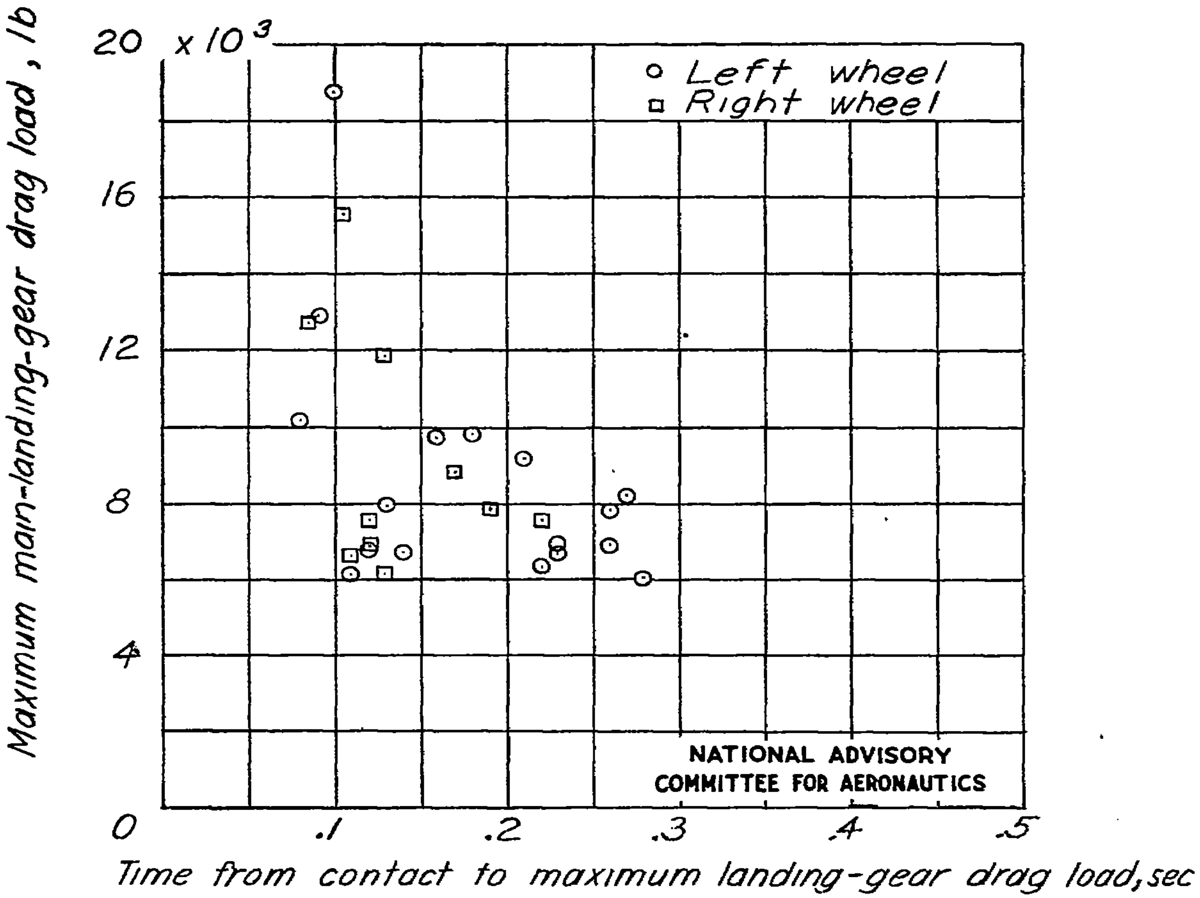


Figure 7.- Magnitude of main-landing-gear drag load against time to reach maximum value. Normal landings.

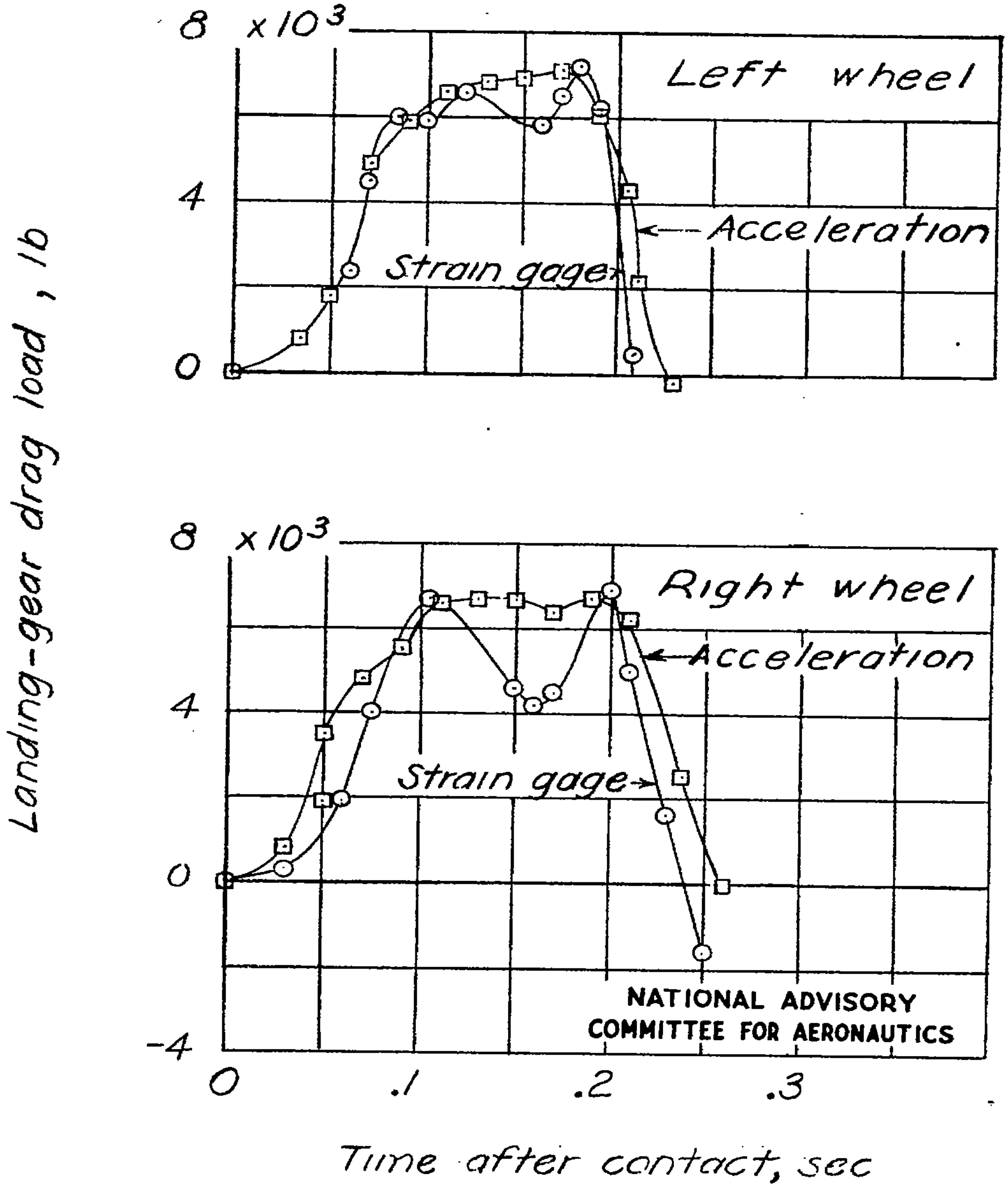


Figure 8.—Comparison of time histories of drag load on main landing gear from strain-gage readings and from wheel-acceleration data during a normal landing. Landing 8.

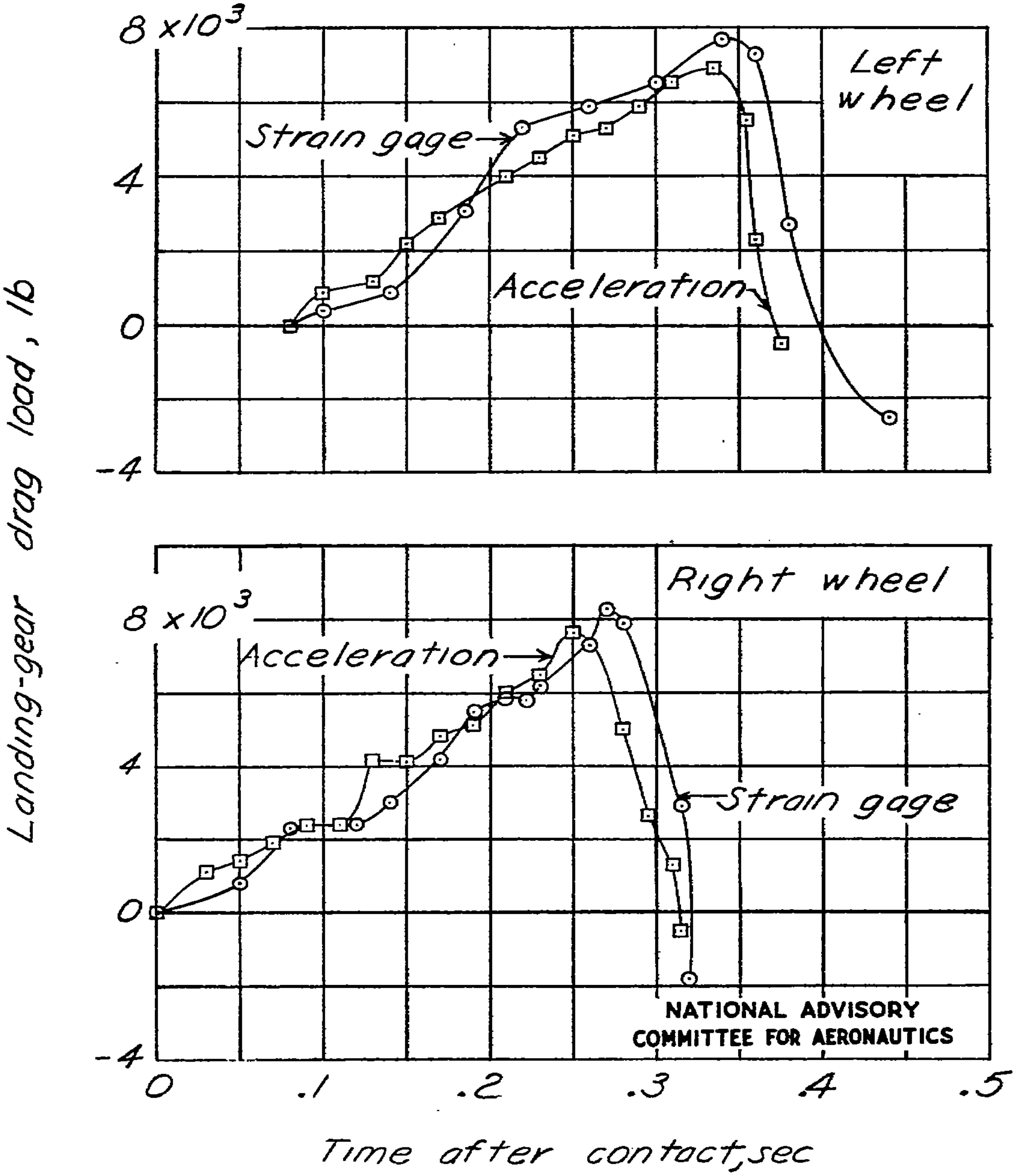


Figure 9.—Comparison of time histories of drag load on main landing gear from strain-gage readings and from wheel-acceleration data during a normal landing. Landing 12.

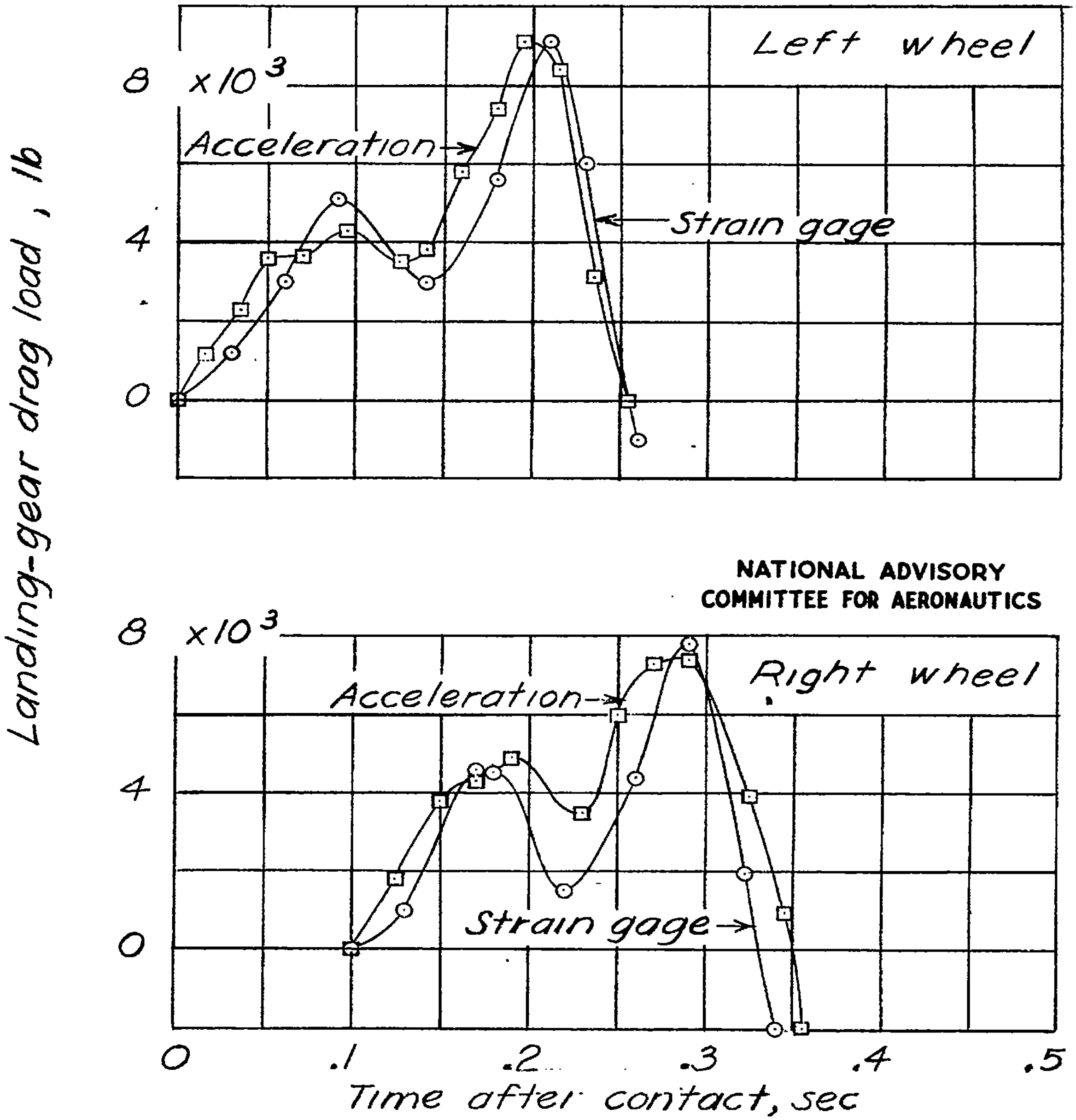


Figure 10.—Comparison of time histories of drag load on main landing gear from strain-gage readings and from wheel-acceleration data during a normal landing. Landing 16.

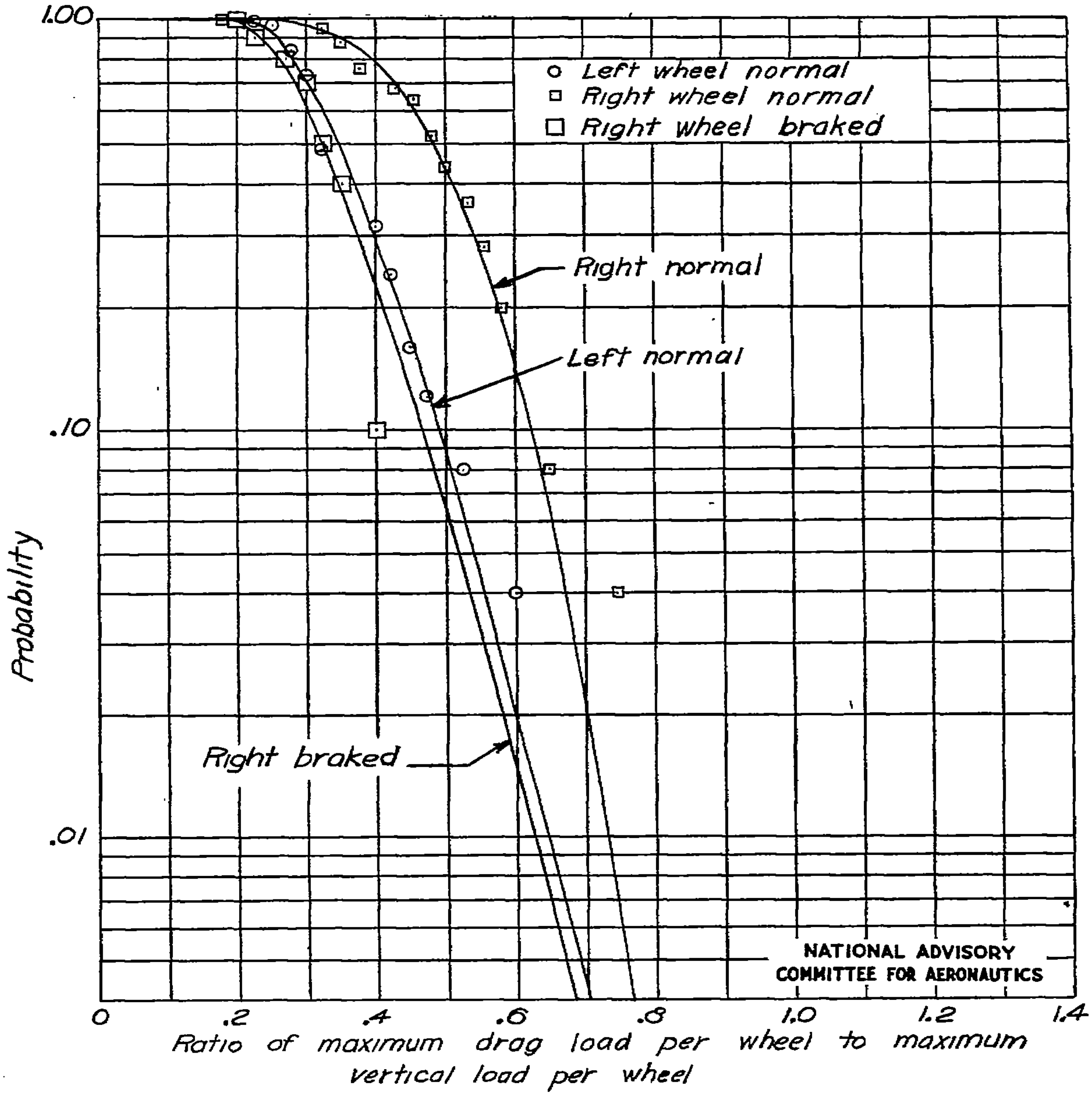
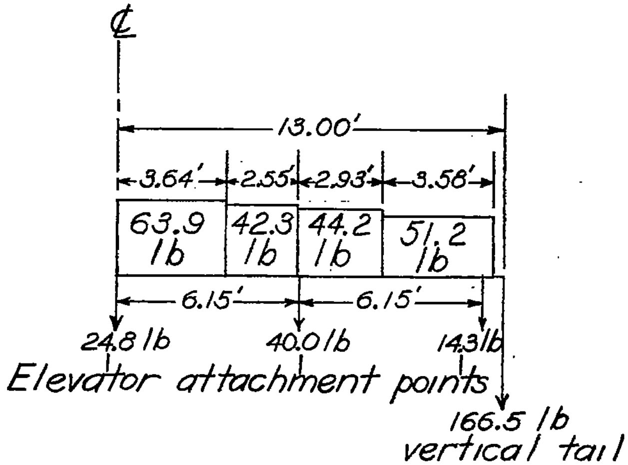
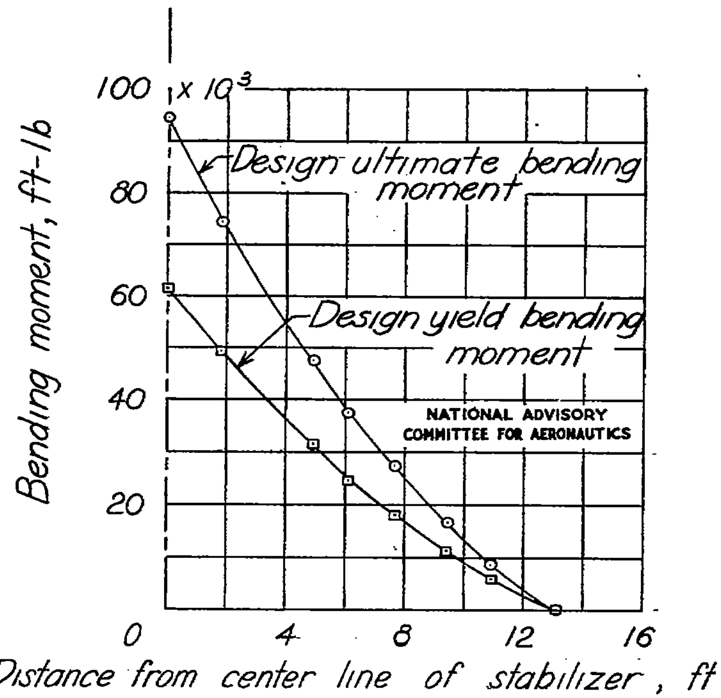


Figure 11.—Probability of equaling or exceeding given values of ratio of maximum drag load per wheel to maximum vertical load per wheel.



(a) Weight distribution of components of tail assembly.



(b) Stabilizer bending moments.

Figure 12.- Stabilizer loading and bending moments.

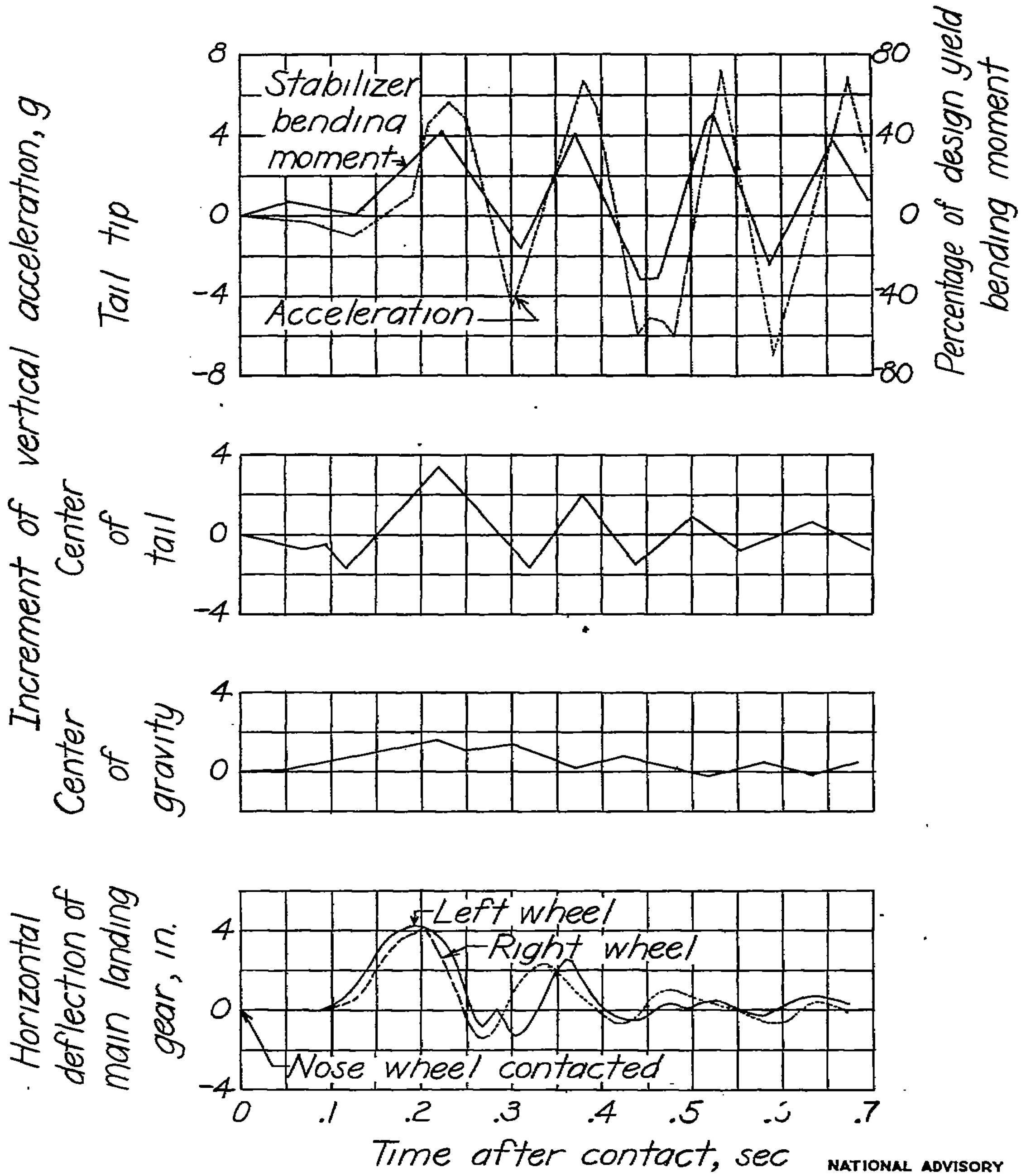


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Figure 13.–Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 10.

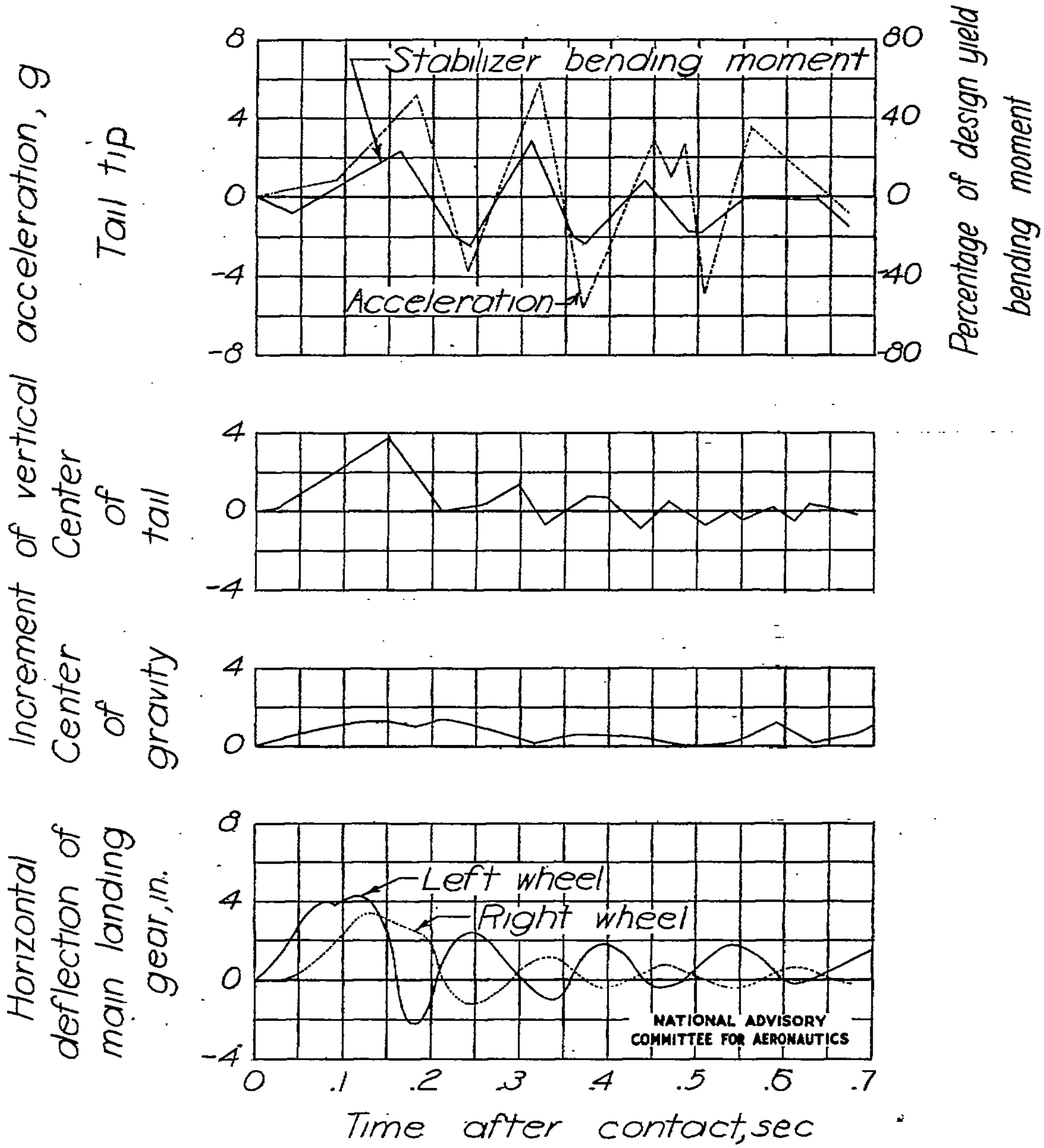

Figure 14.-Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 19.

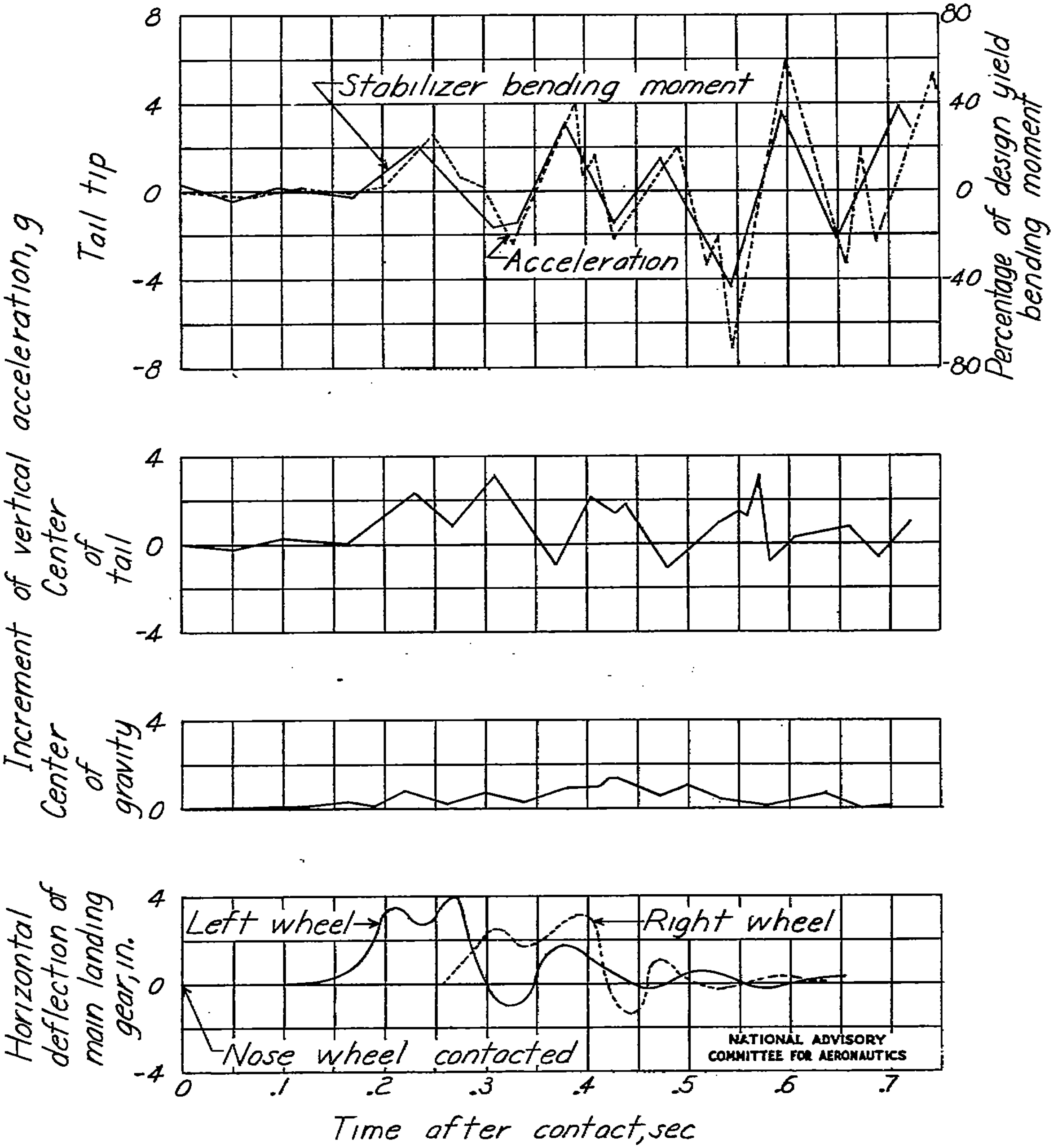

Figure 15.- Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 42.

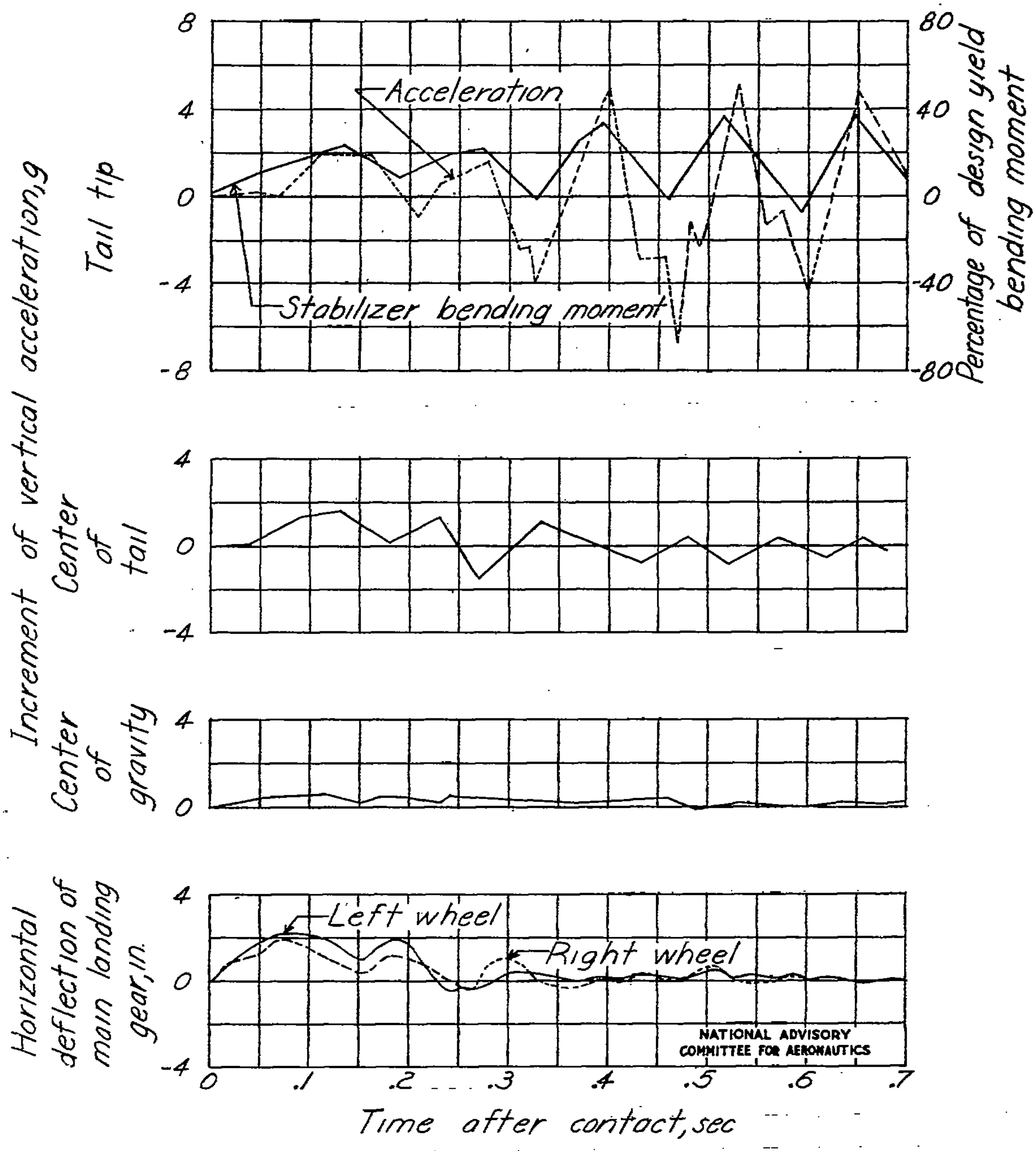

Figure 16.- Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 8.

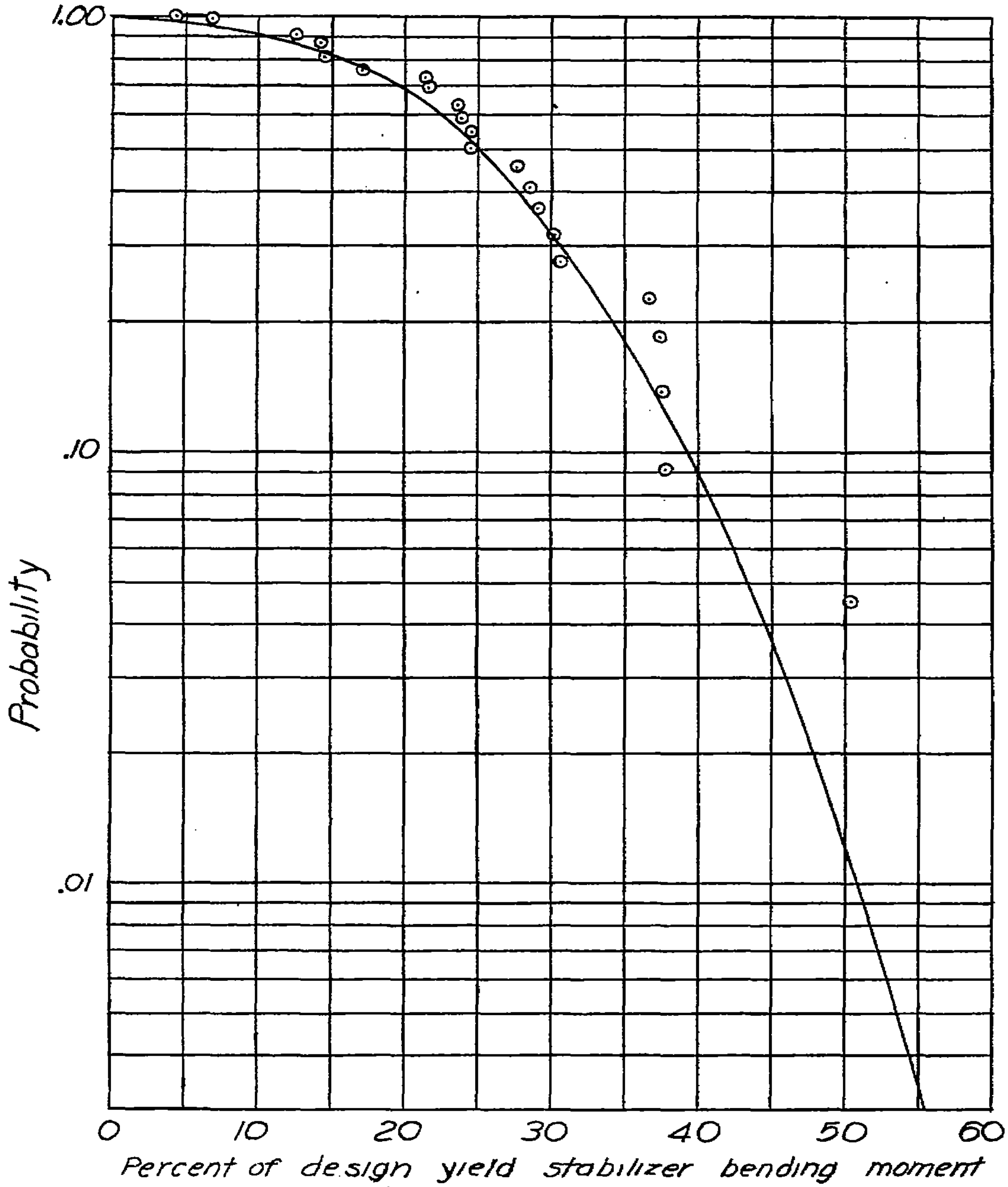

Figure 17.— Probability of equaling or exceeding stabilizer bending moment. Normal landings.

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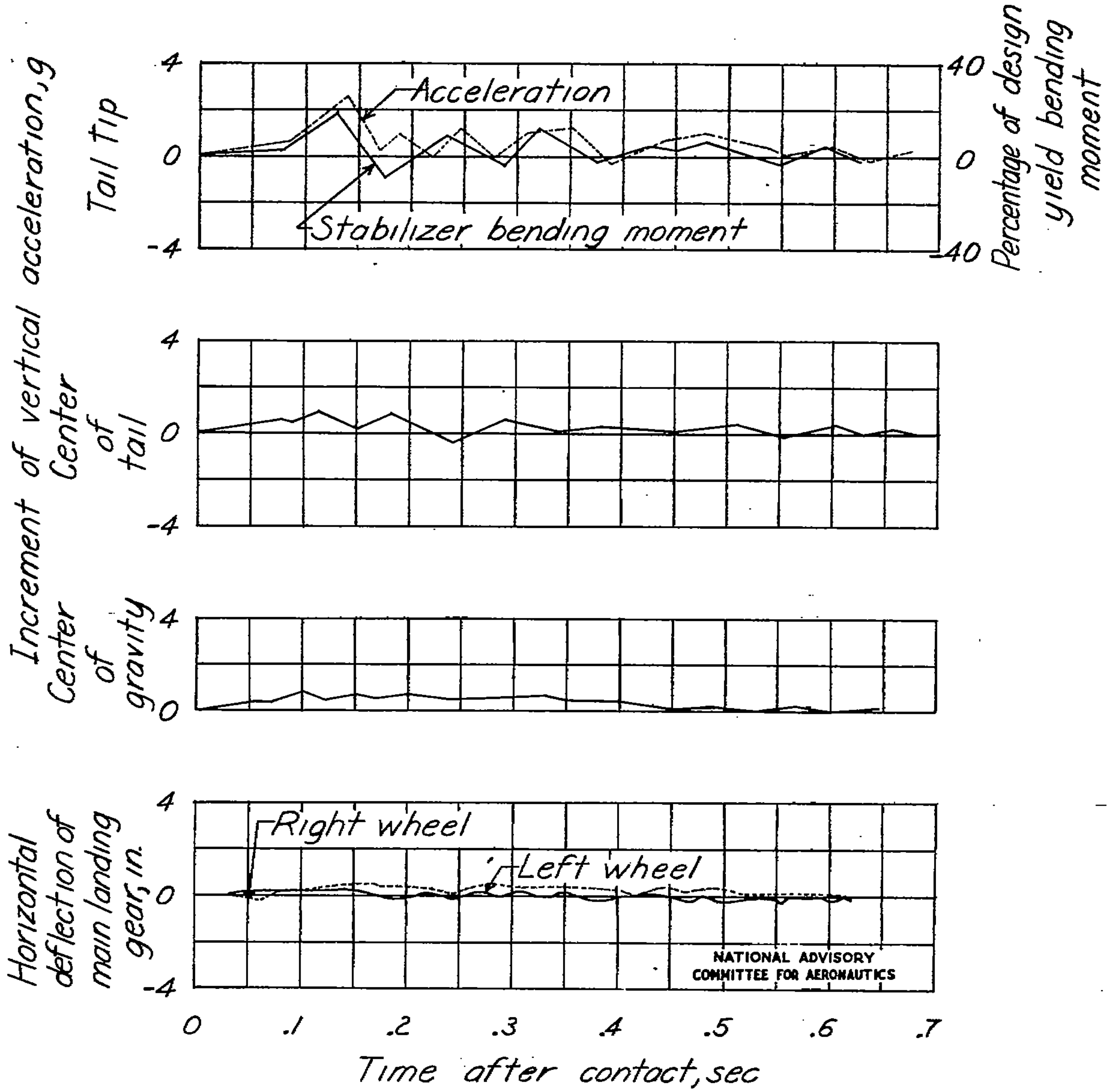

Figure 18.- Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a prerotation landing. Landing 30_2 .

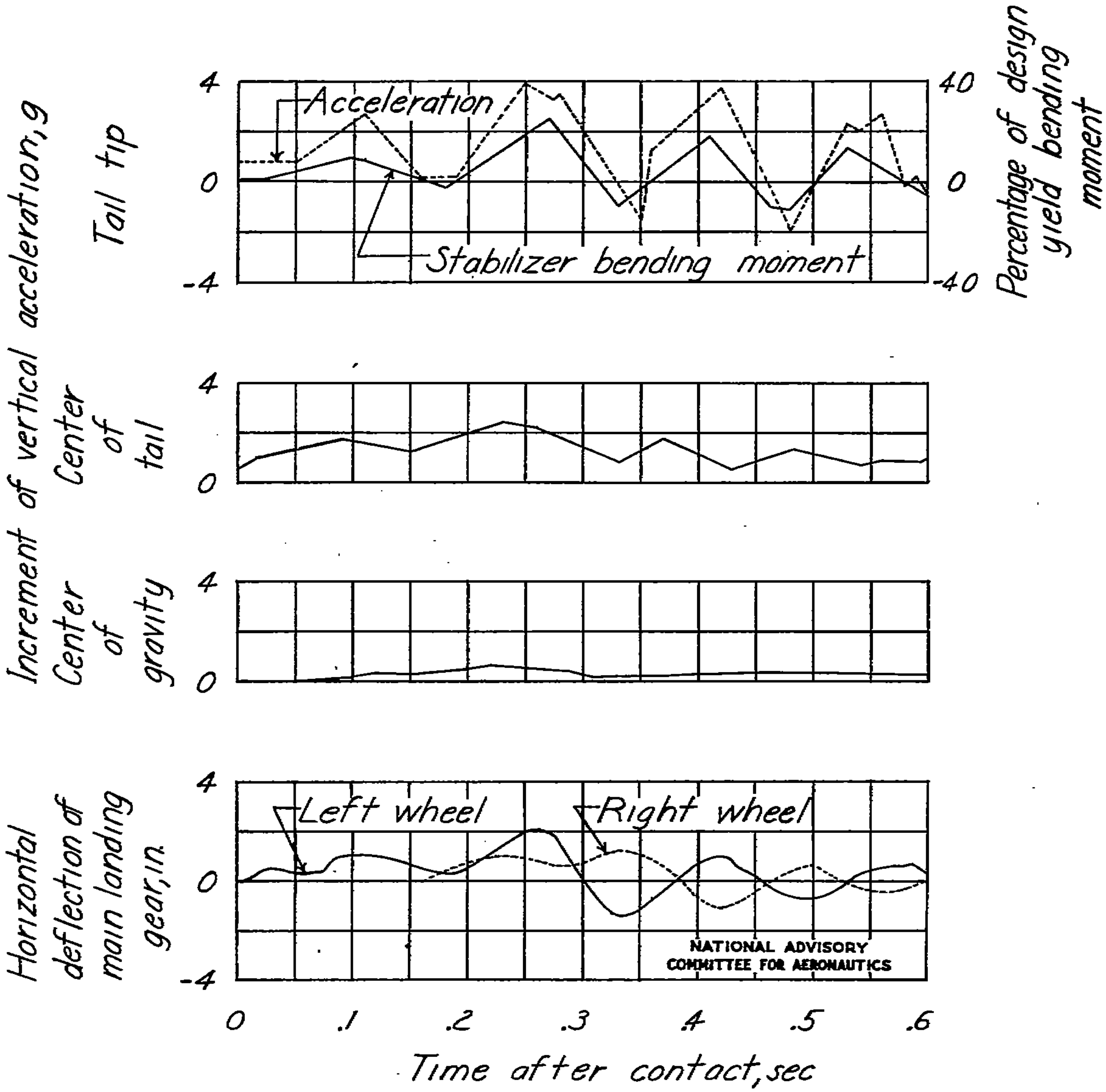

Figure 19.-Time history of structural accelerations, stabilizer bending moment, and landing-gear deflection during a normal landing. Landing 4.

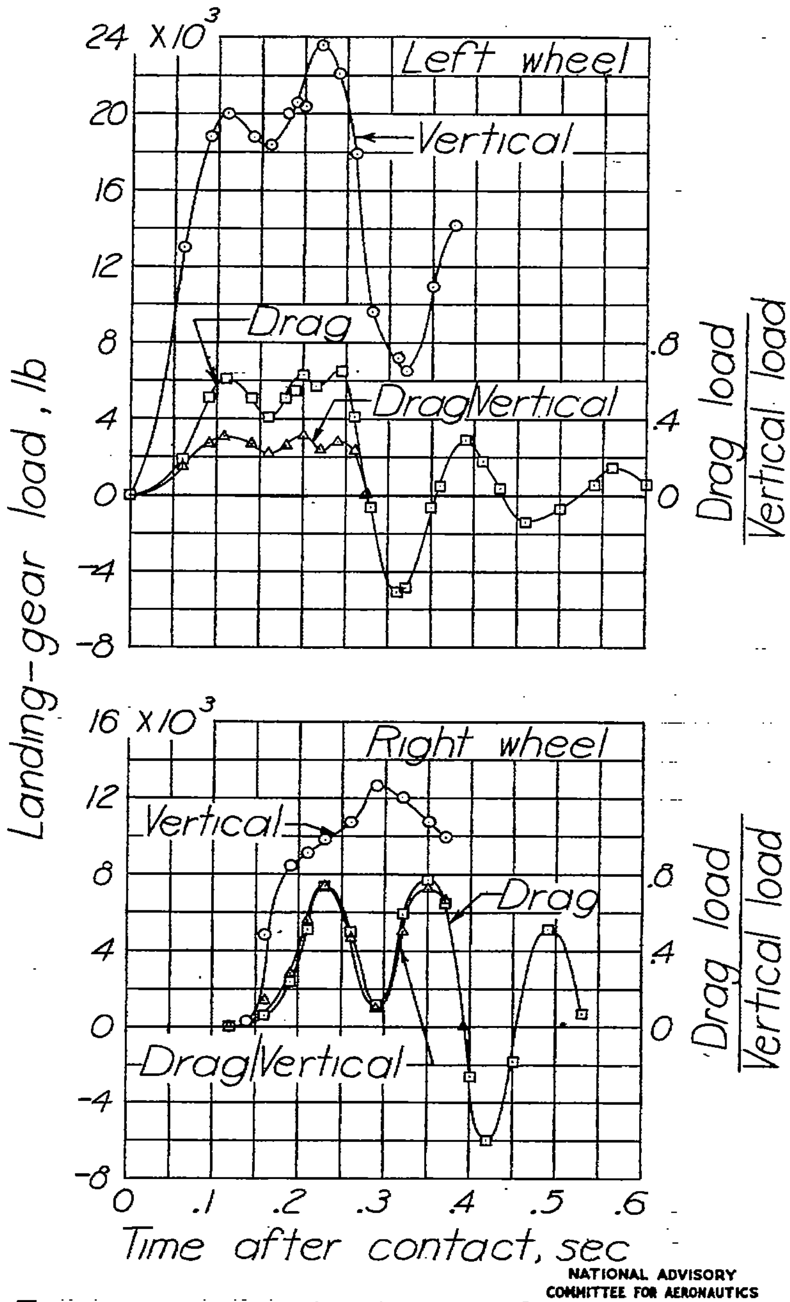

Figure 20.-Time history of loads on main landing gear during a normal landing. Landing 2.

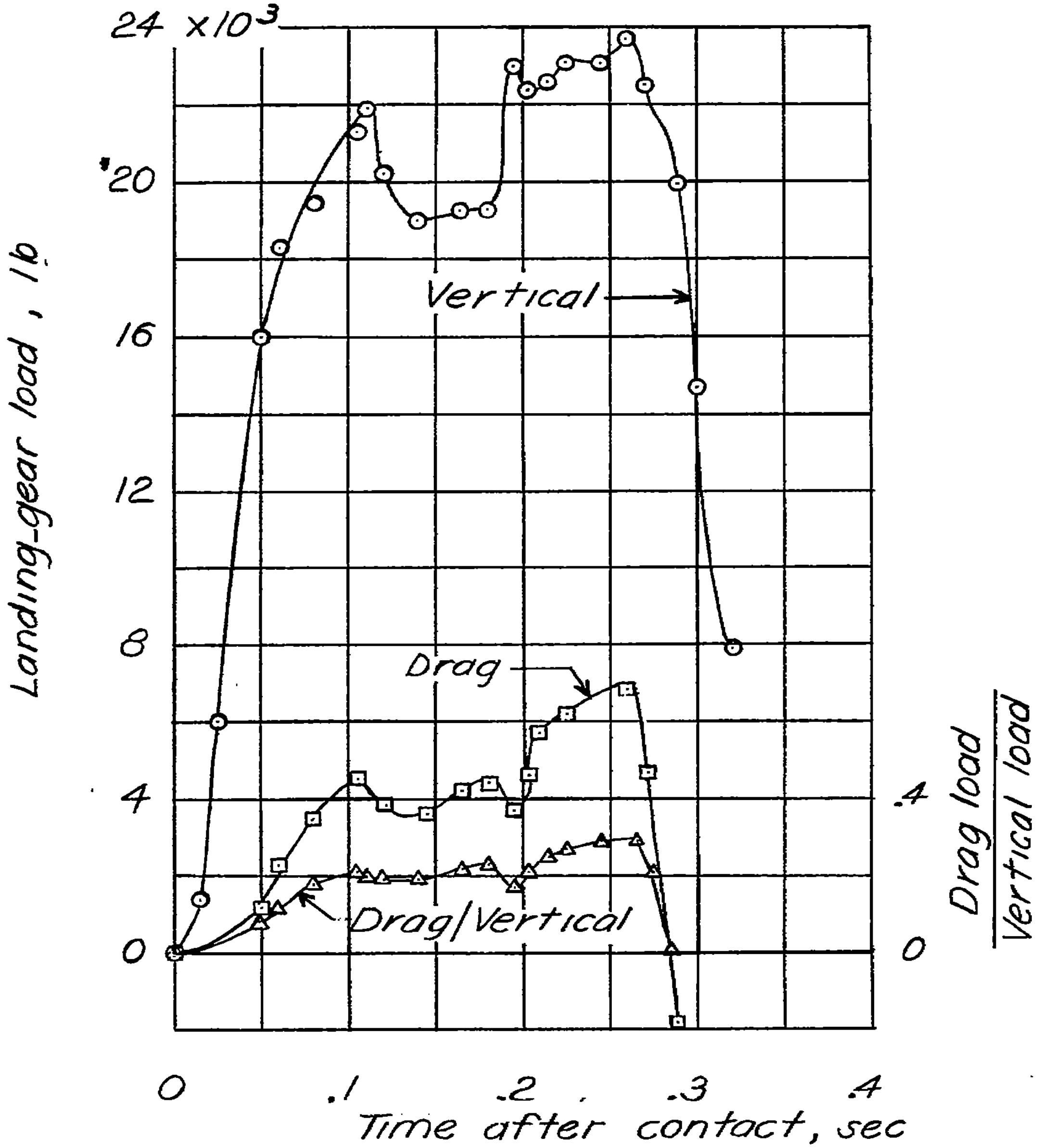

Figure 21.-Time history of loads on left main landing gear during a normal landing. Landing 4.

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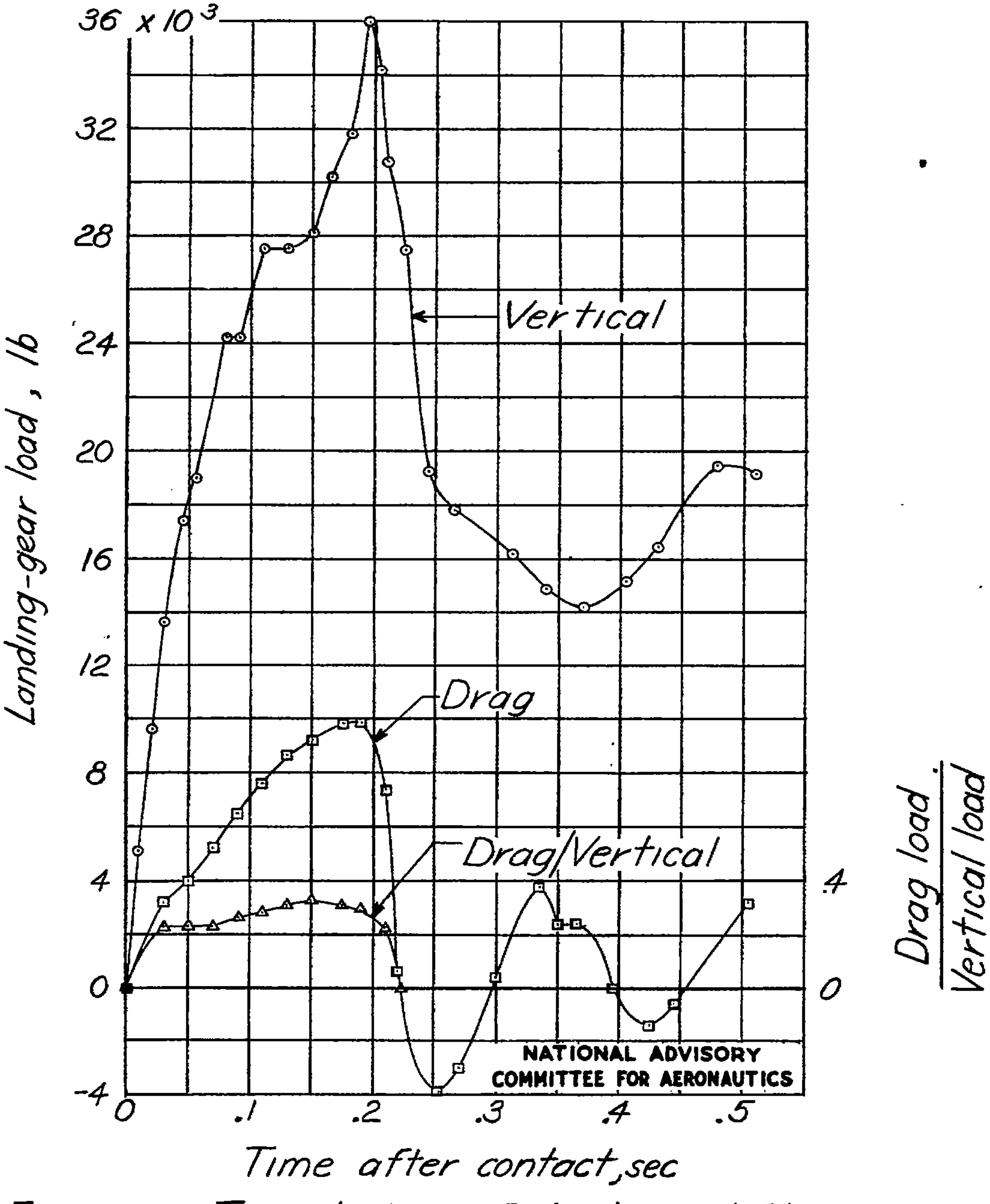


Figure 22.– Time history of loads on left main landing gear during a normal landing. Landing 5.

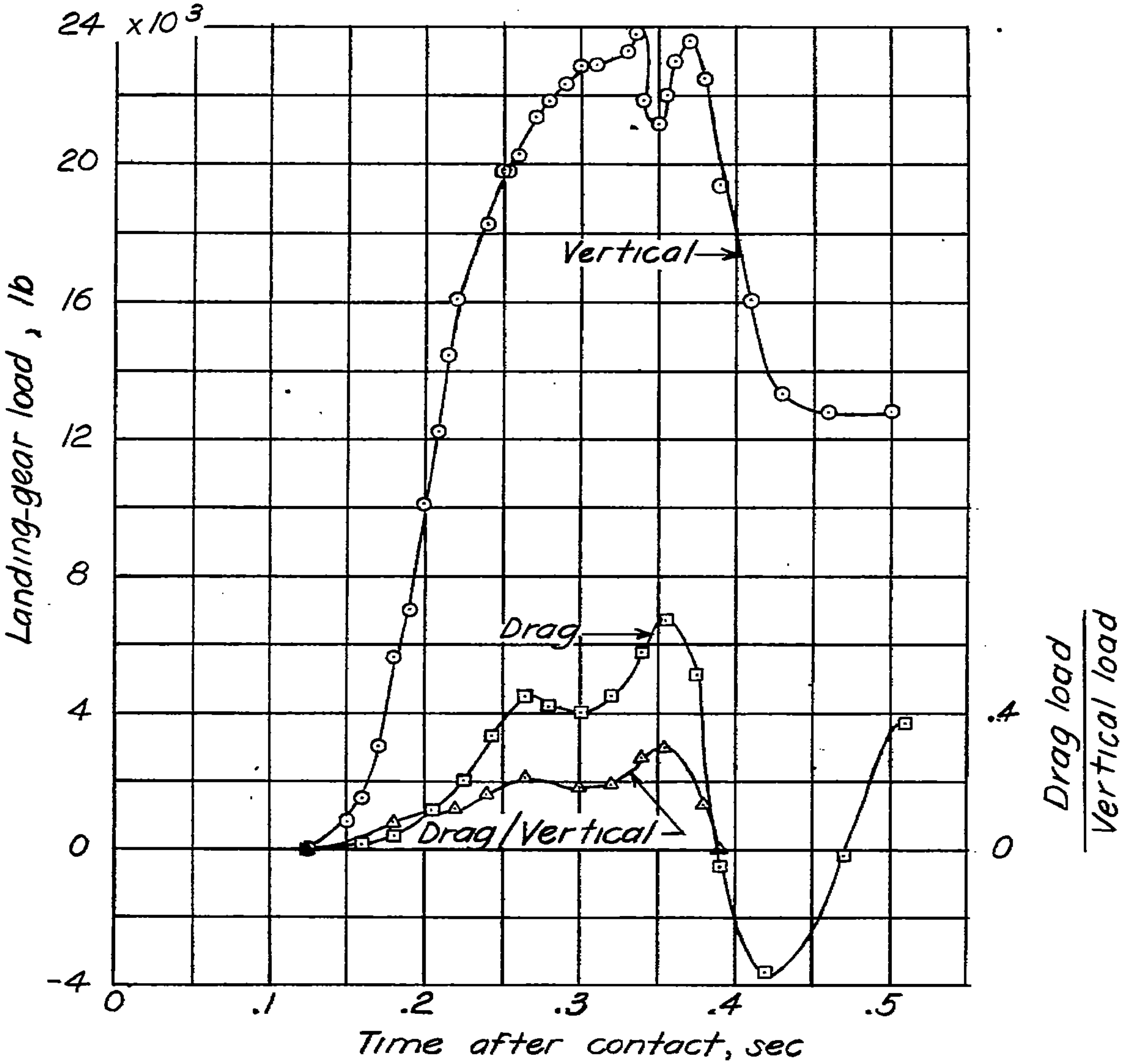


Figure 23.- Time history of loads on left main landing gear during a normal landing. Landing 6.

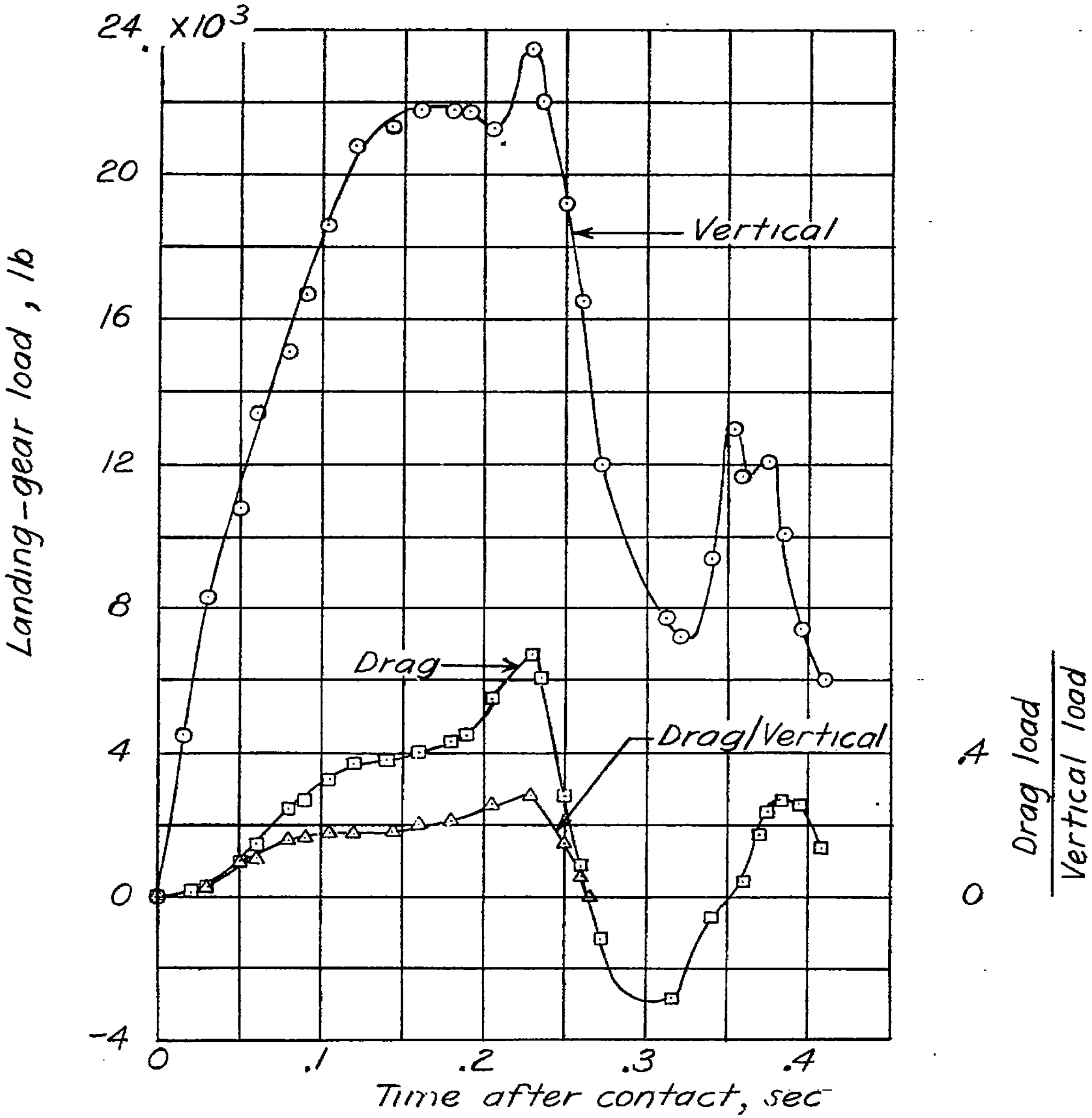


Figure 24.– Time history of loads on left main landing gear during a normal landing. Landing 7.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

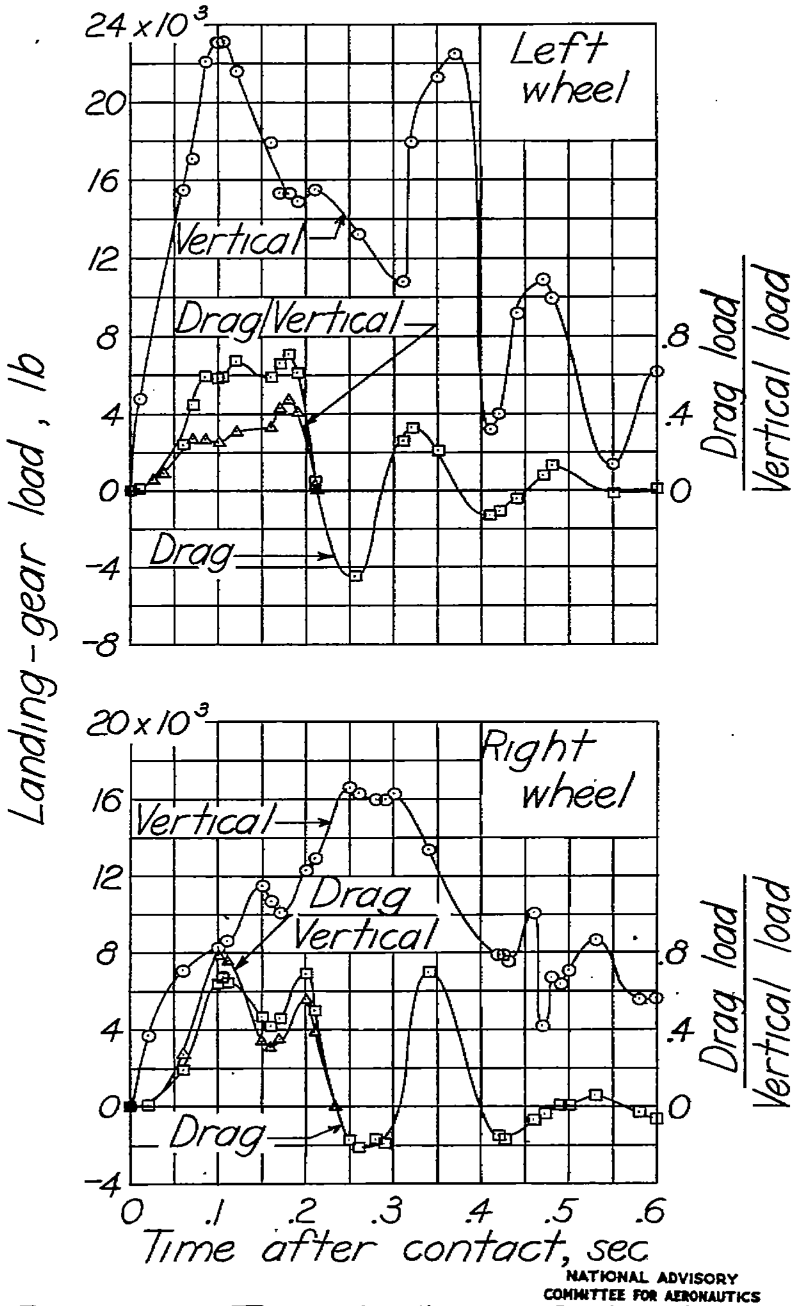


Figure 25.-Time history of loads on main landing gear during a normal landing. Landing 8.

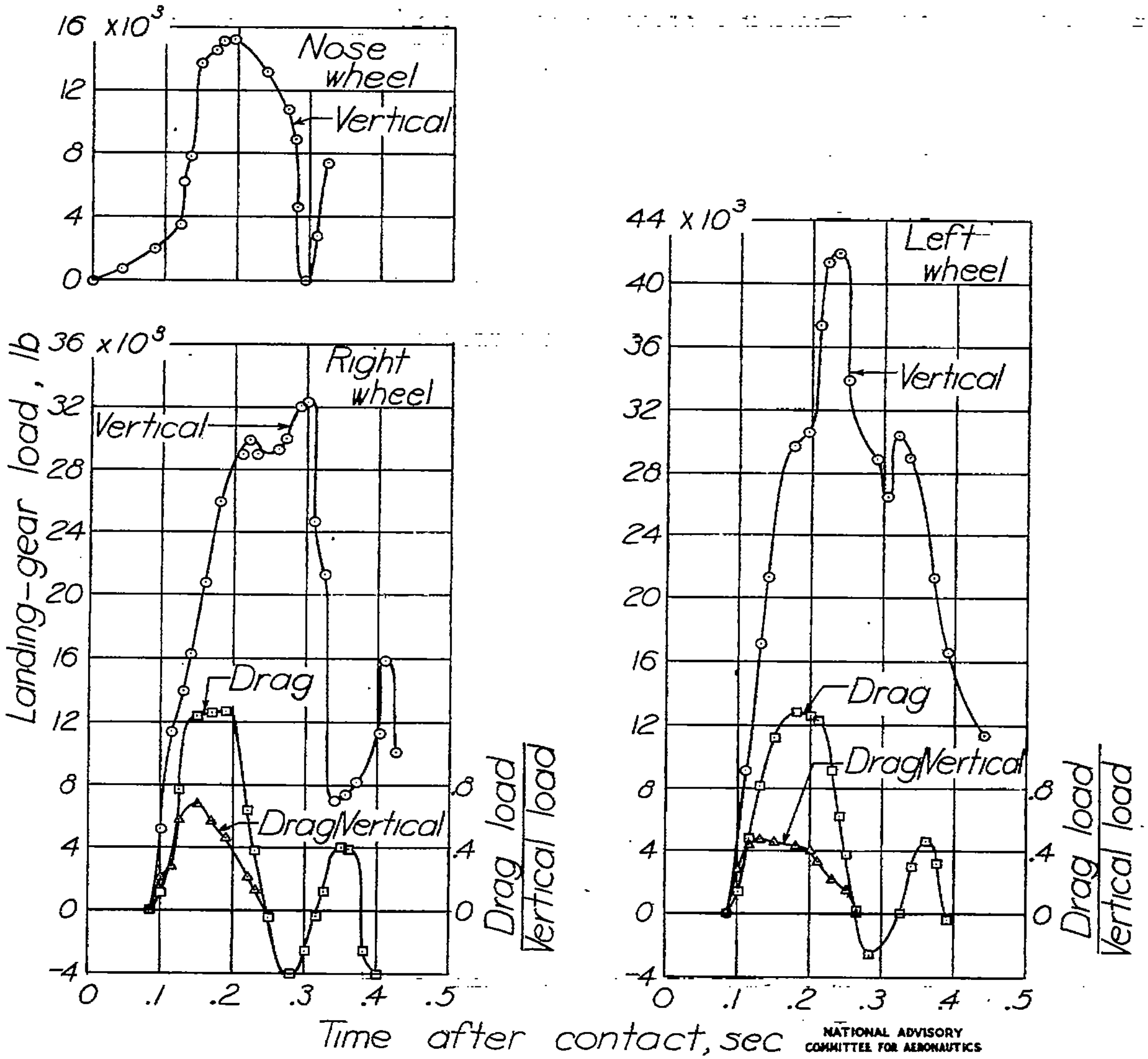


Figure 26.–Time history of loads on landing gear during a normal landing. Landing 10.

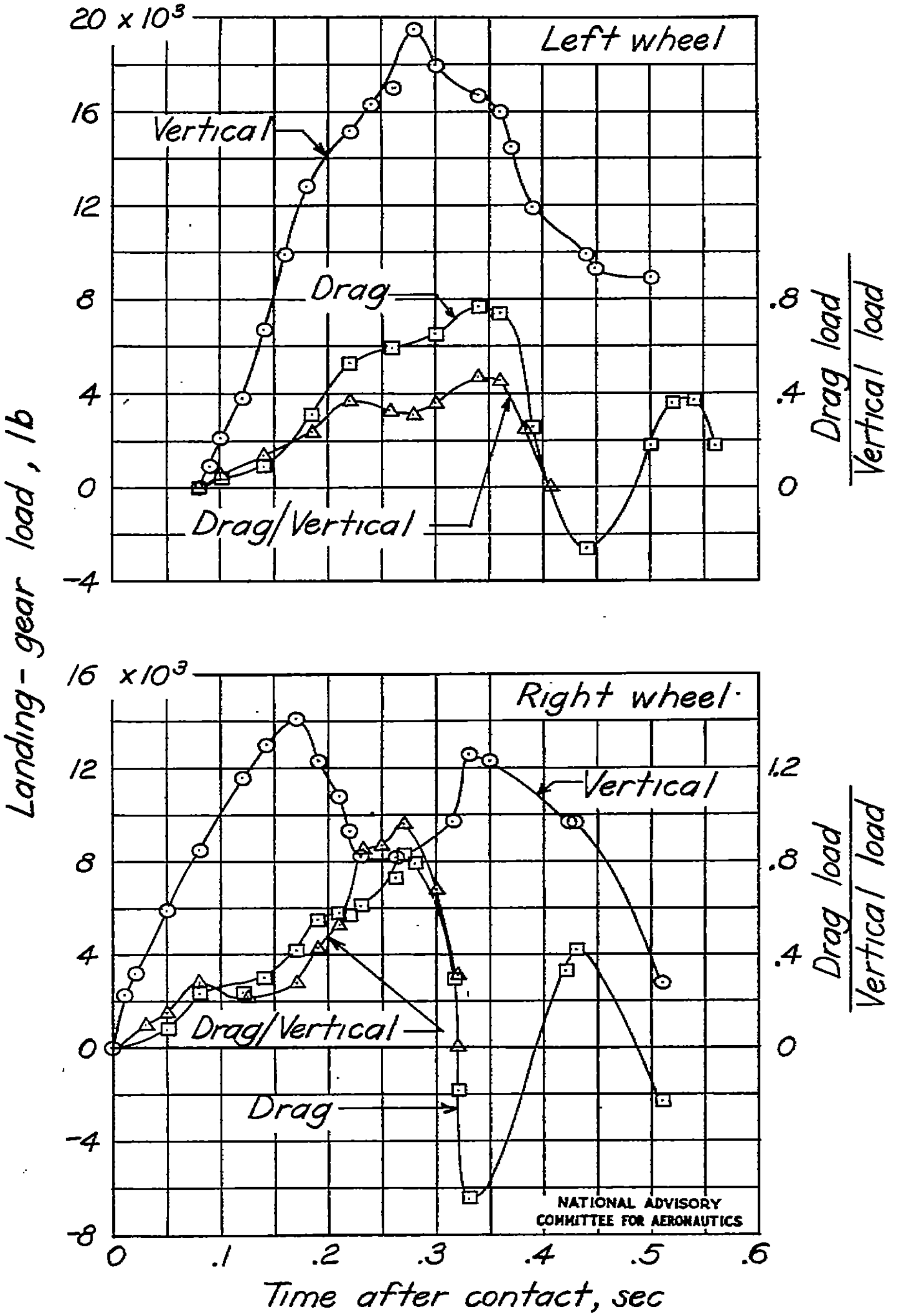


Figure 27.-Time history of loads on main landing gear during a normal landing. Landing 12.

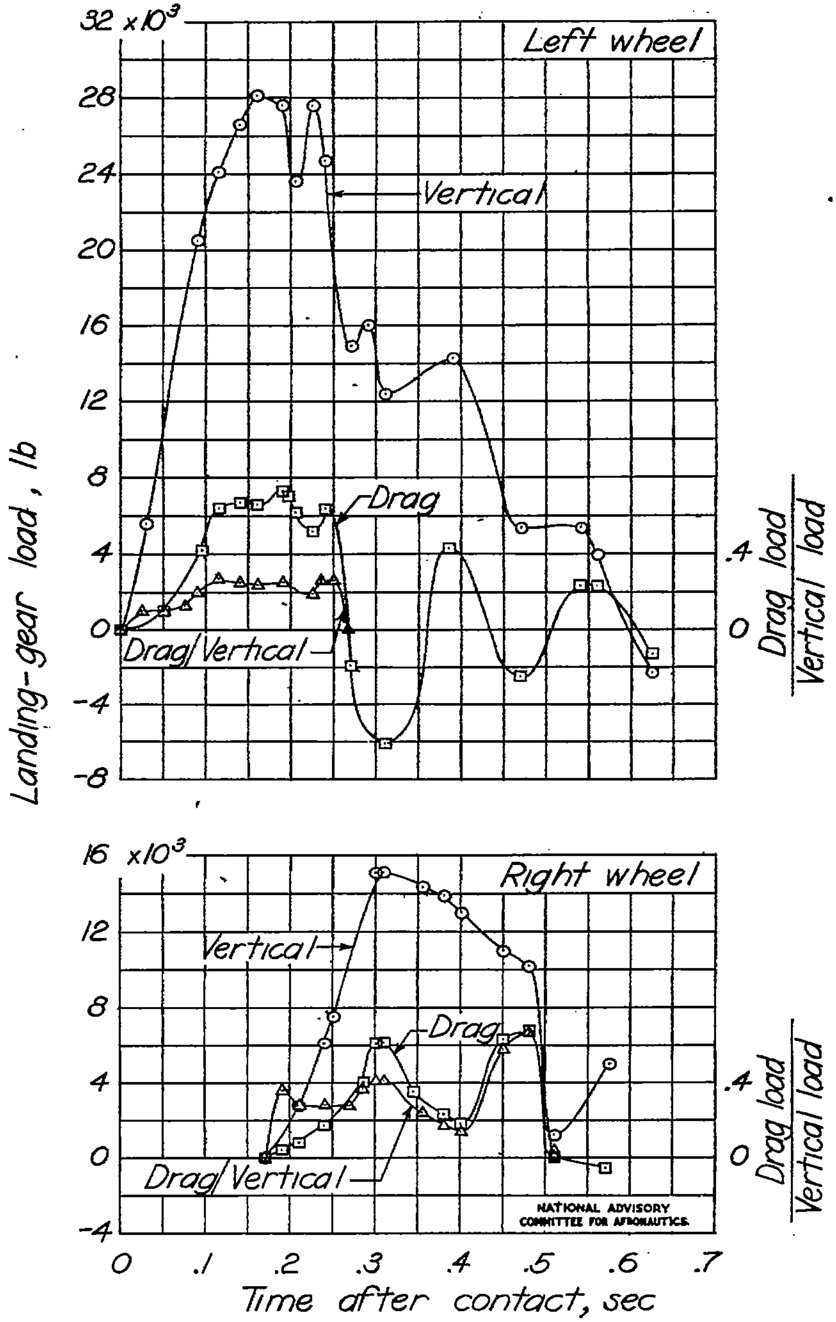


Figure 28.-Time history of loads on main landing gear during a normal landing. Landing 13.

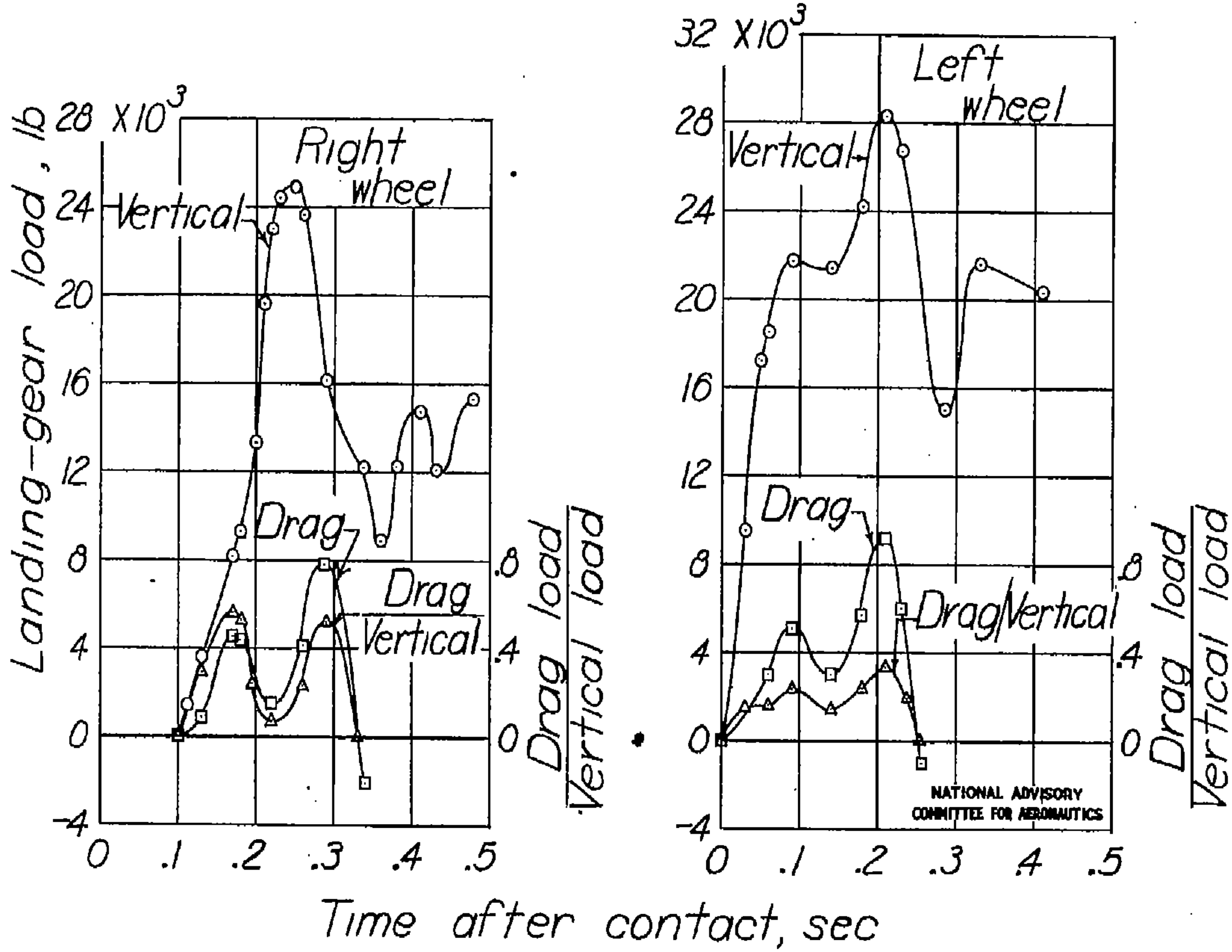


Figure 29.—Time history of loads on main landing gear during a normal landing. Landing 16.

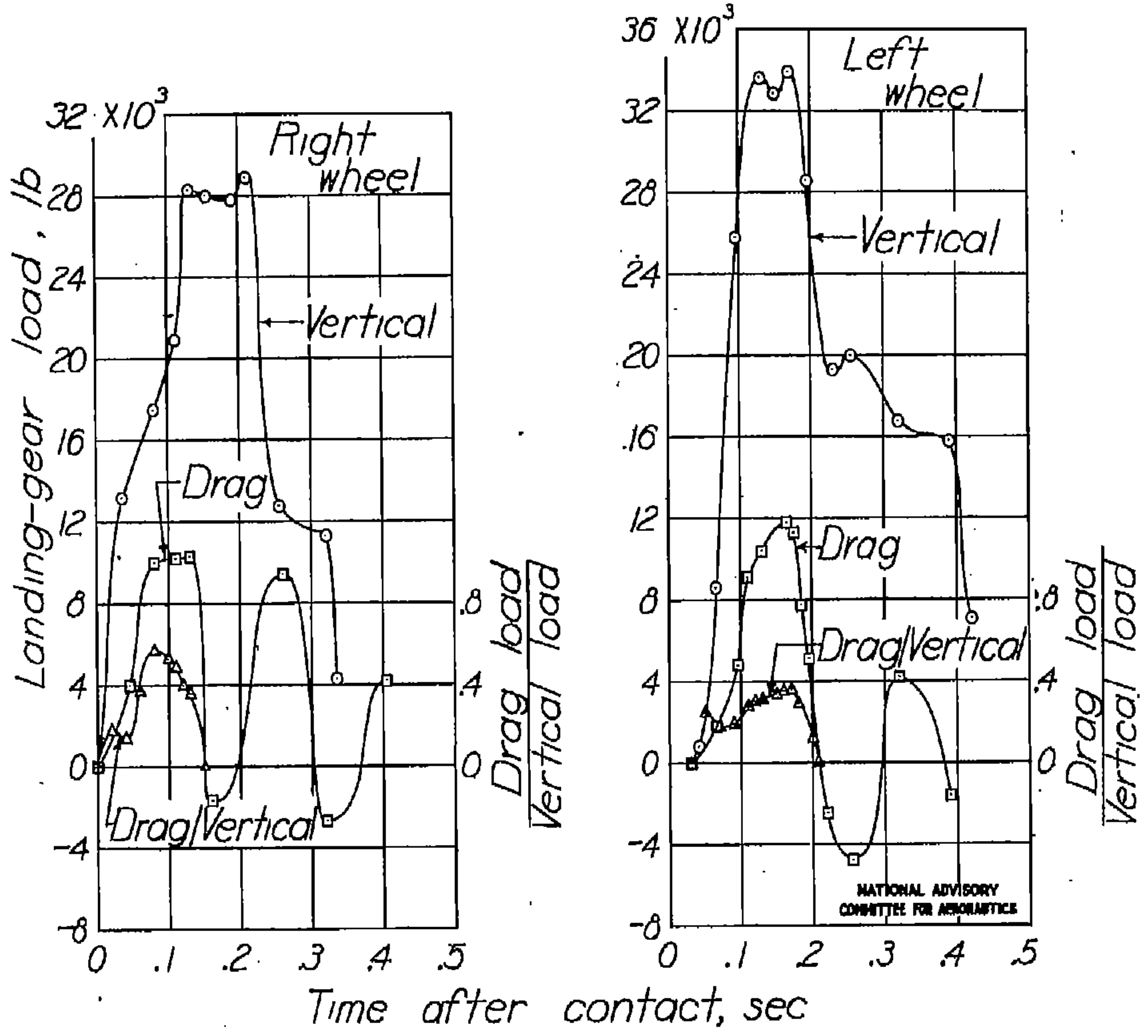


Figure 30.-Time history of loads on main landing gear during a normal landing. Landing 19.

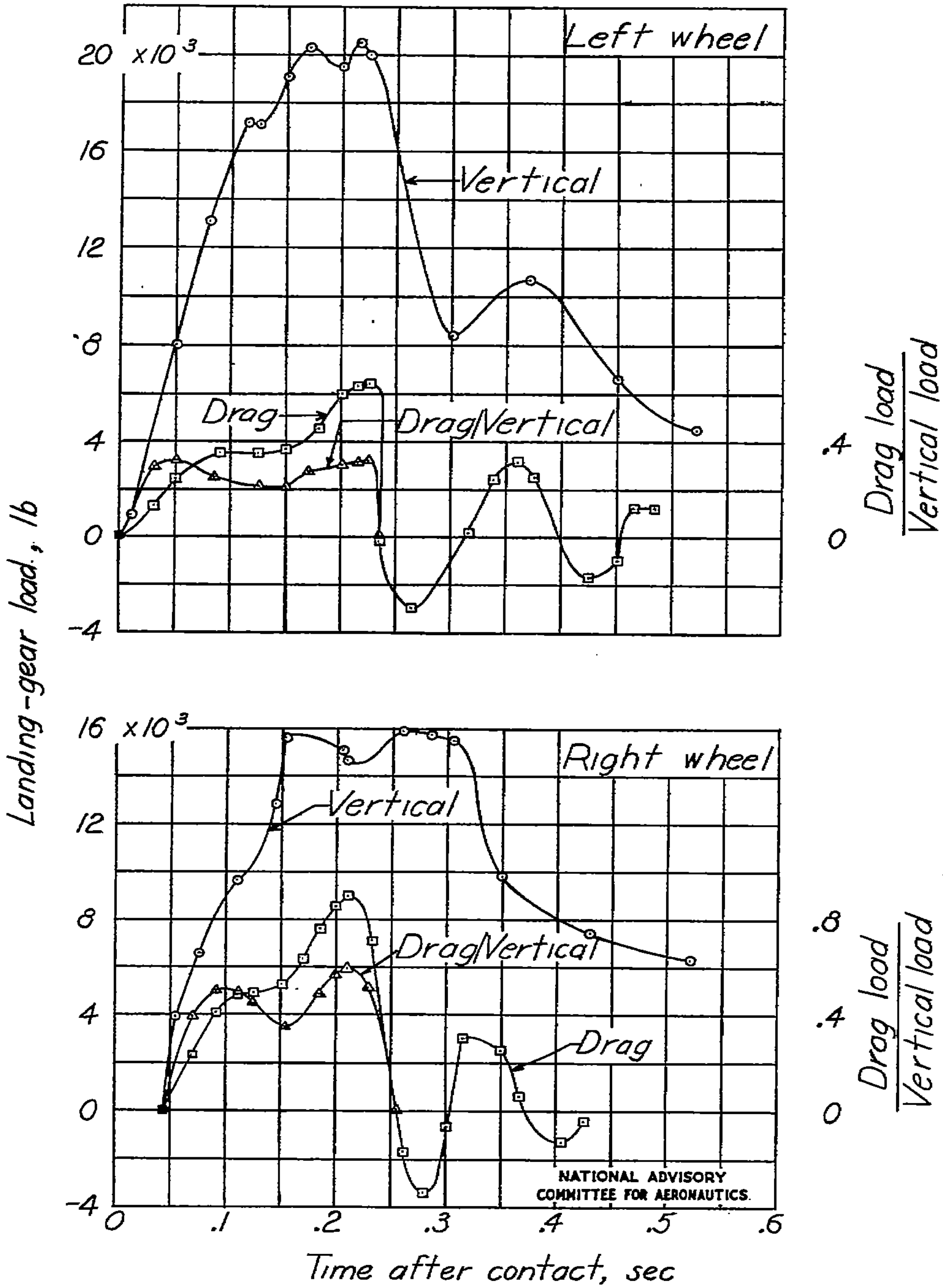


Figure 31.–Time history of loads on main landing gear during a normal landing. Landing 20.

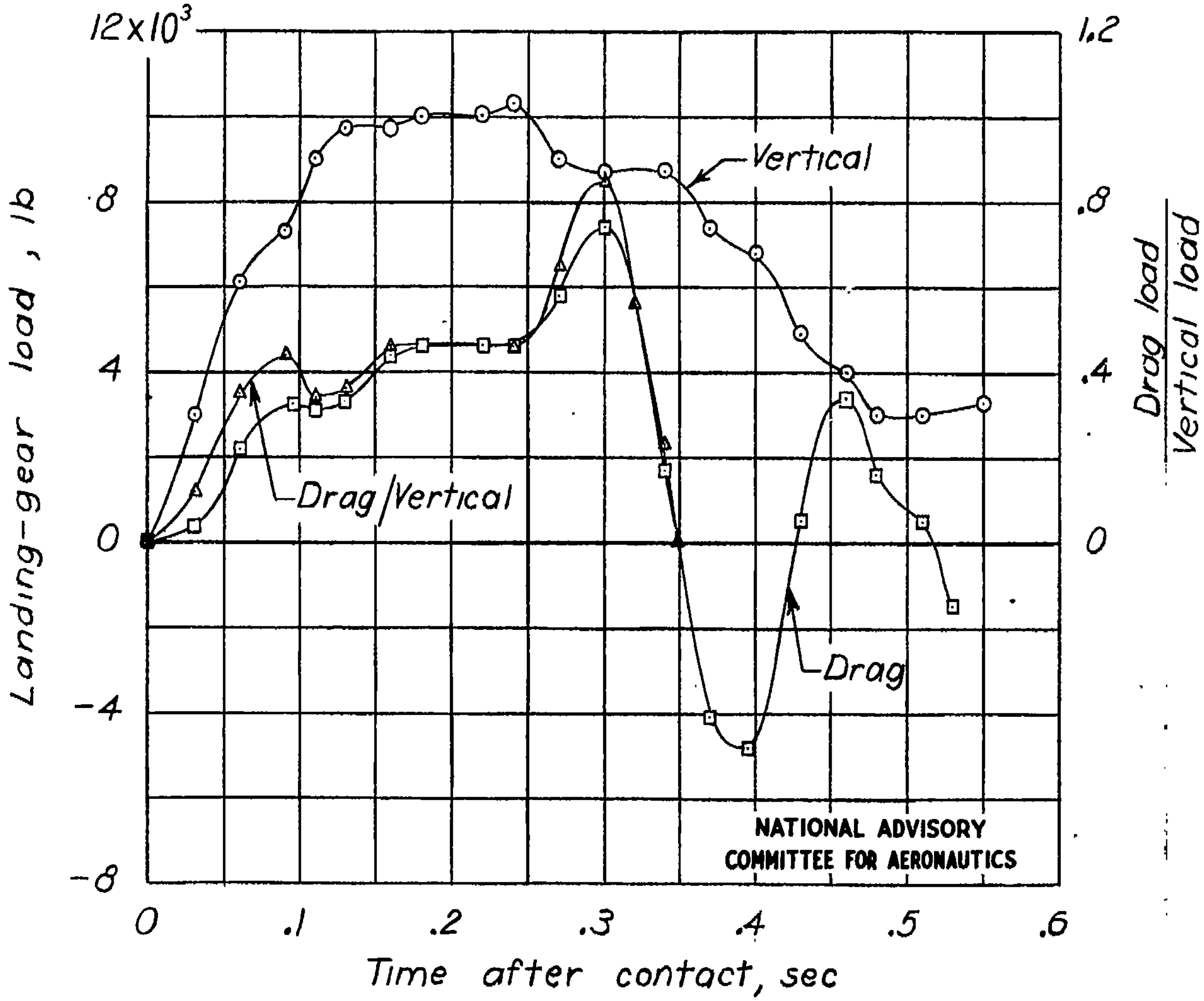


Figure 32.- Time history of loads on right main landing gear during a normal landing. Landing 24.

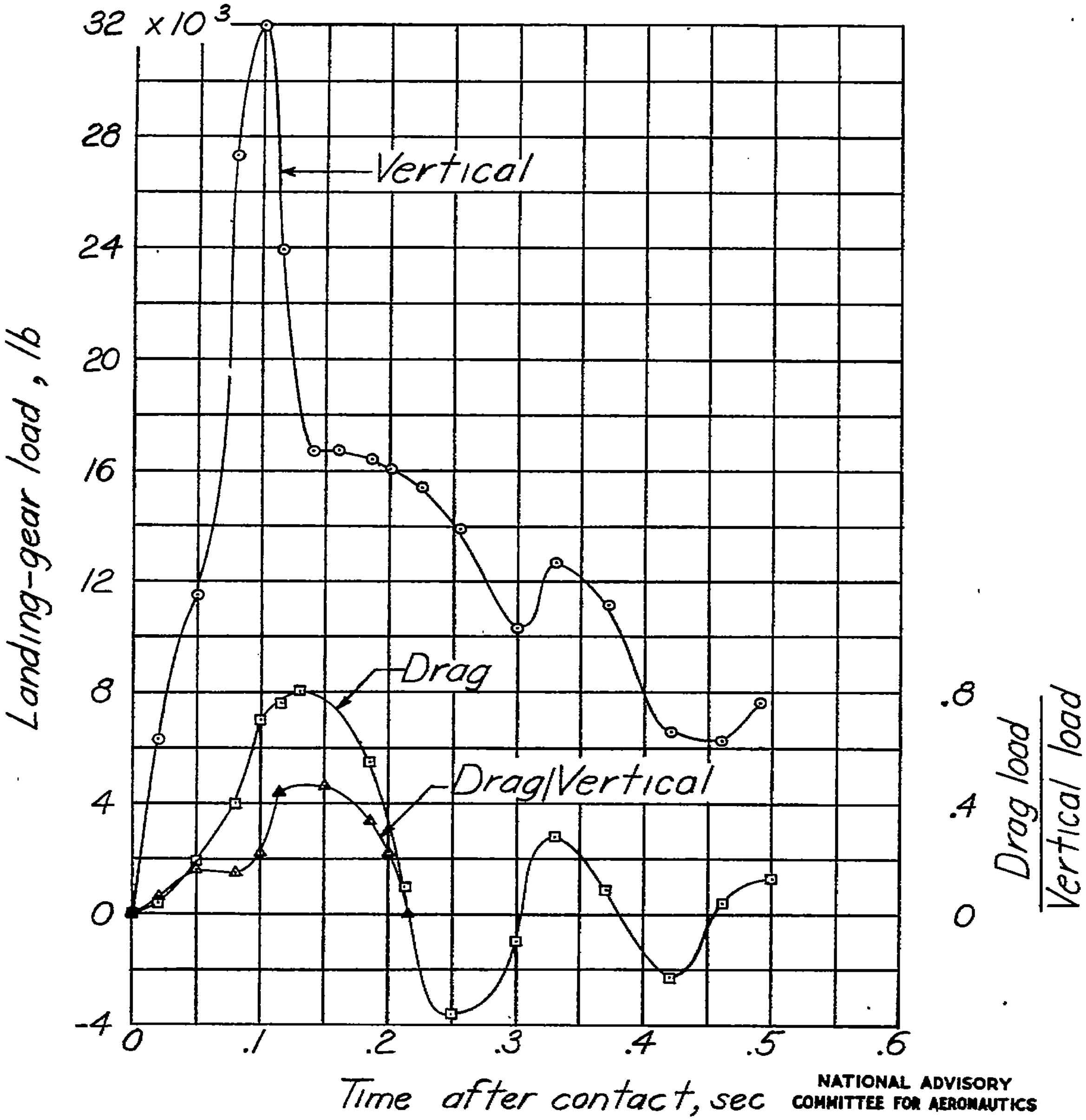


Figure 33.- Time history of loads on left main landing gear during a normal landing. Landing 32,.

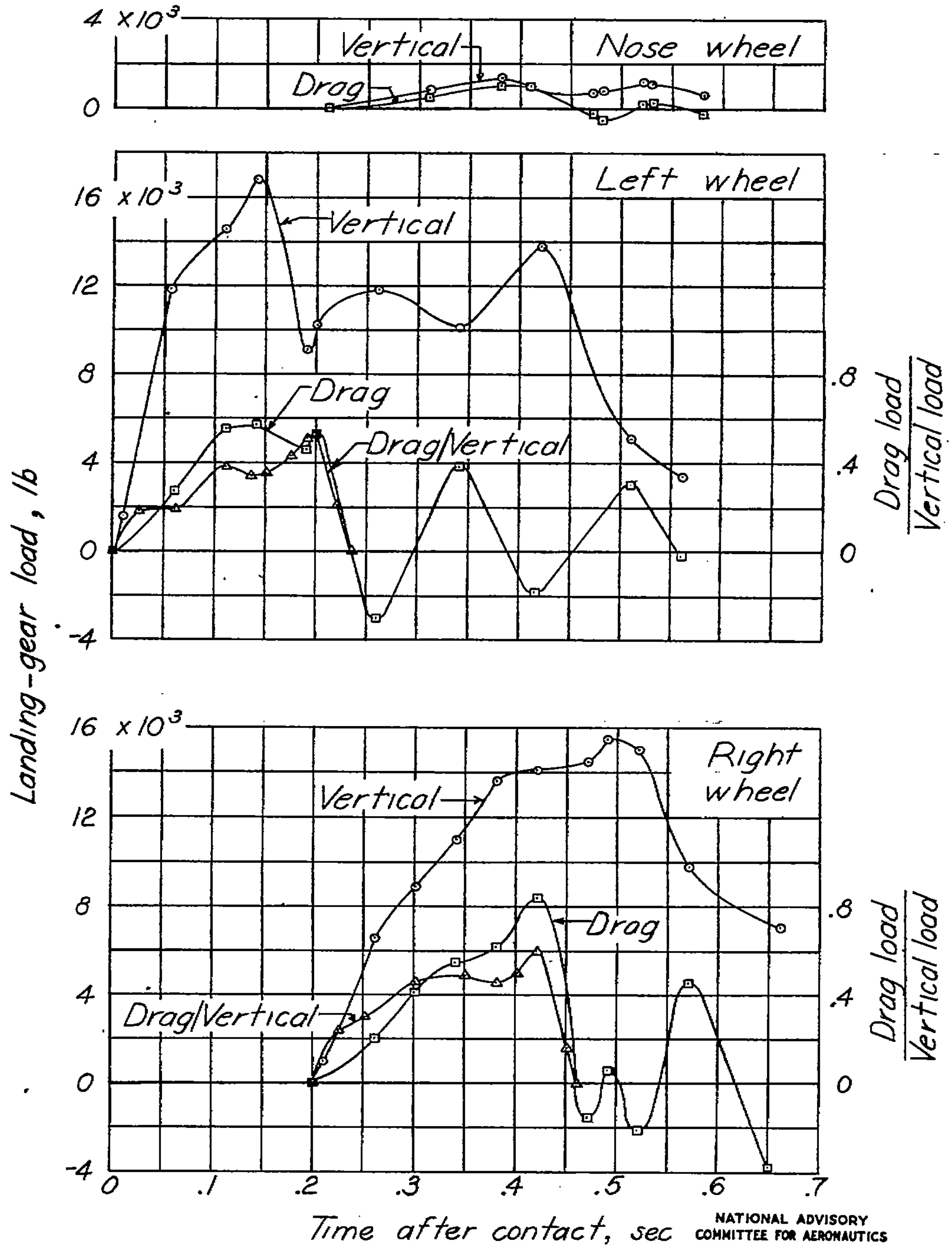
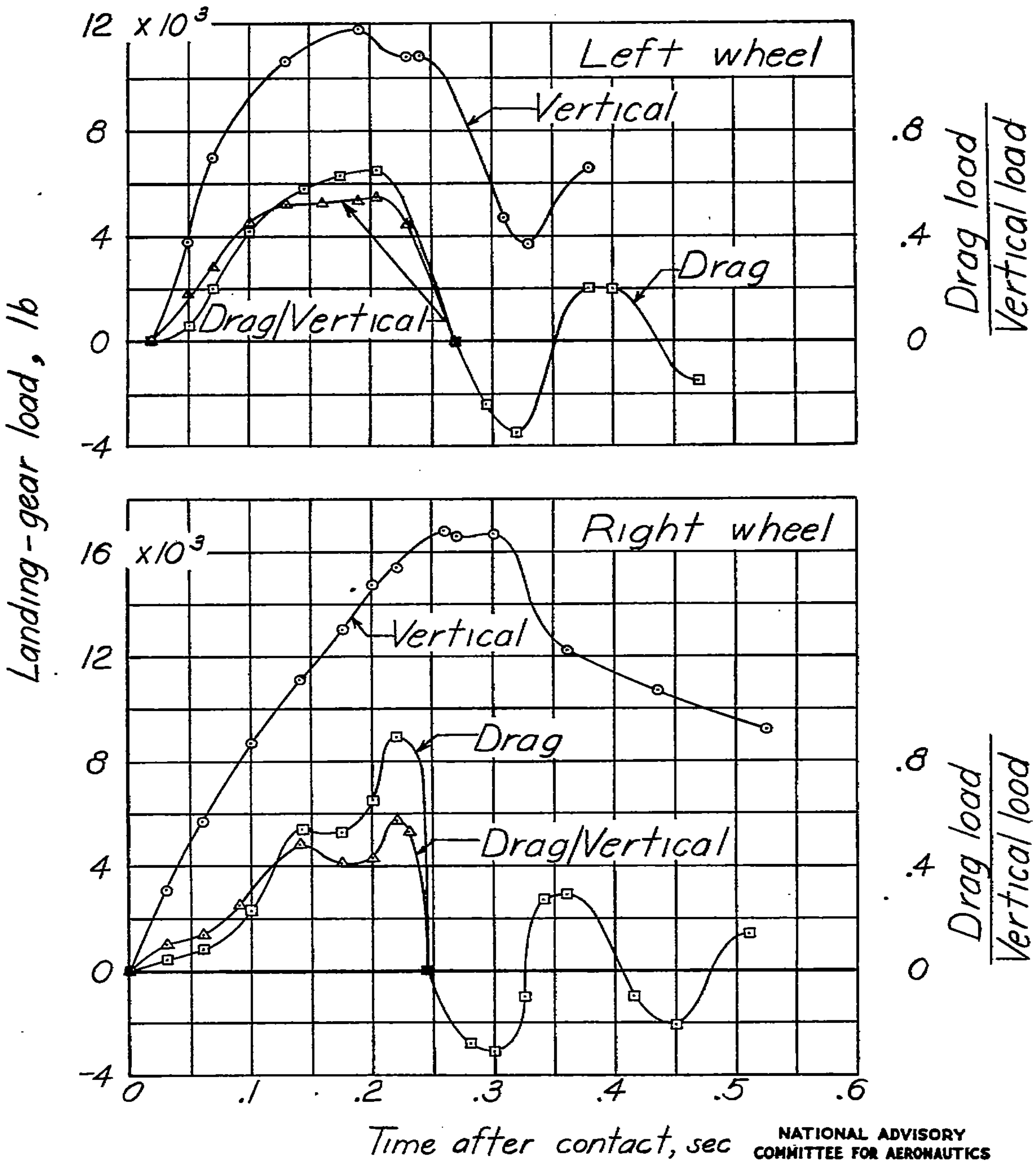


Figure 34.-Time history of loads on landing gear during a normal landing. Landing 33₁.



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 35.–Time history of loads on main landing gear during a normal landing. Landing 38₁.

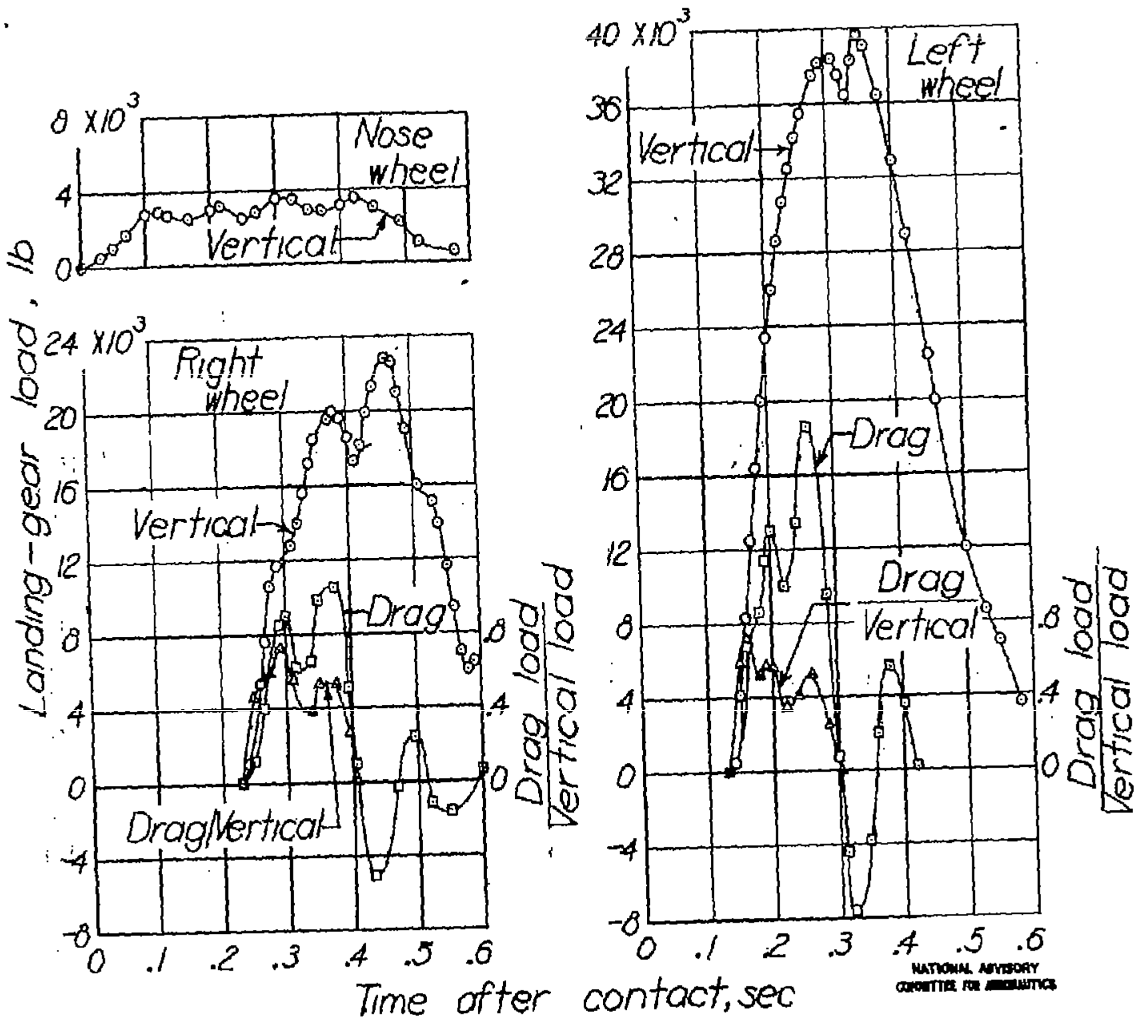


Figure 36.-Time history of loads on landing gear during a normal landing. Landing 42.

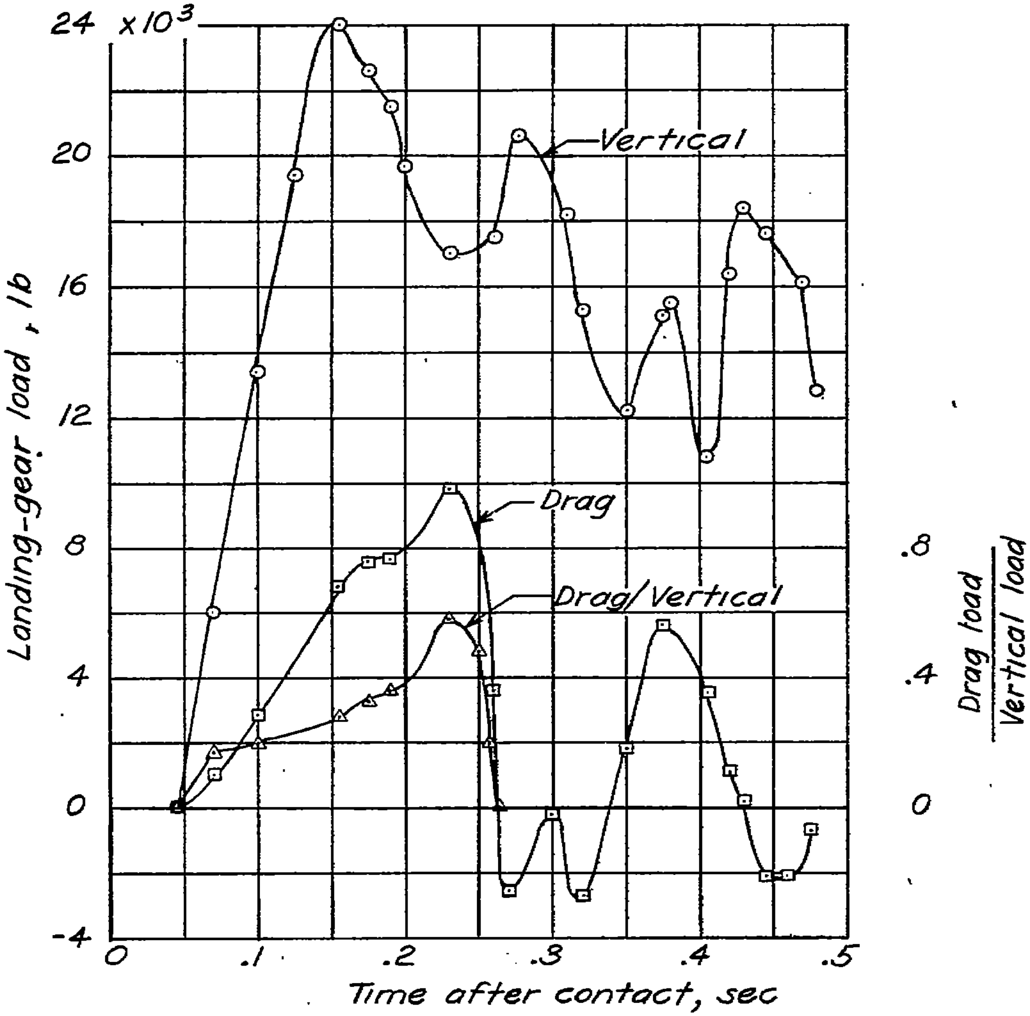


Figure 37.- Time history of loads on right main landing gear during a braked landing. Brake pressure, approximately 5 pounds per square inch. Landing 11.

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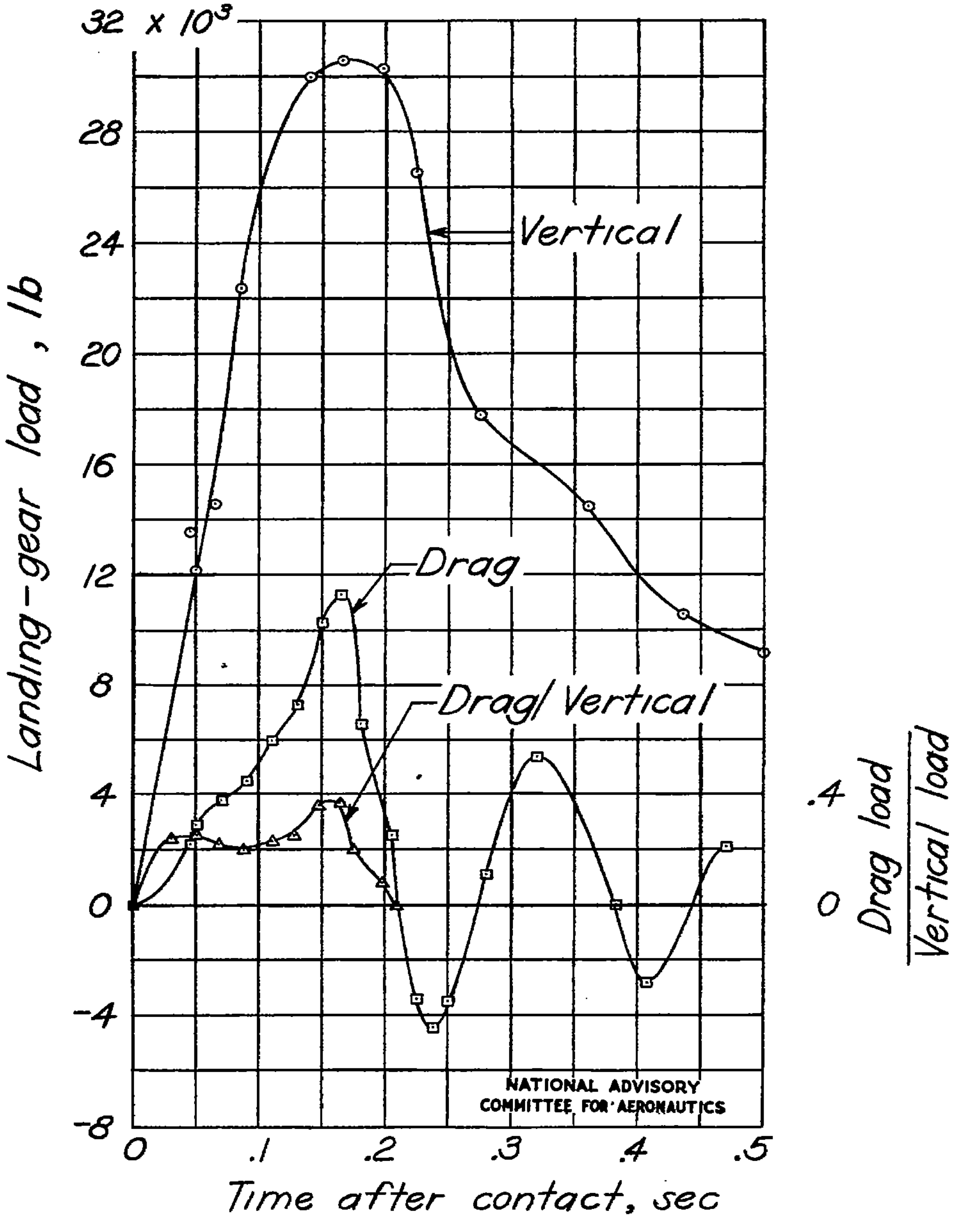


Figure 38.-Time history of loads on left main landing gear during a braked landing. Brake pressure, approximately 5 pounds per square inch. Landing 14.

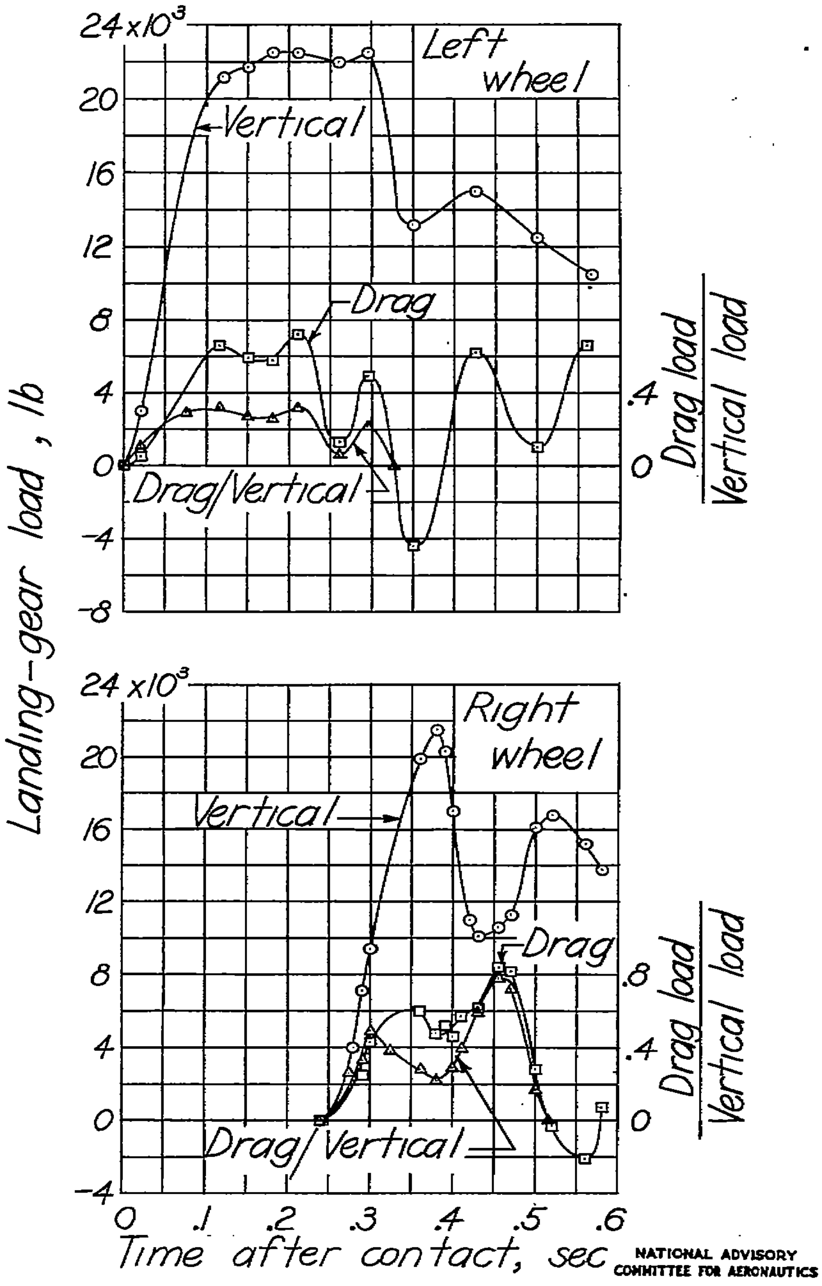


Figure 39.-Time history of loads on main landing gear during a braked landing. Brake pressure, approximately 10 pounds per square inch. Landing 15.

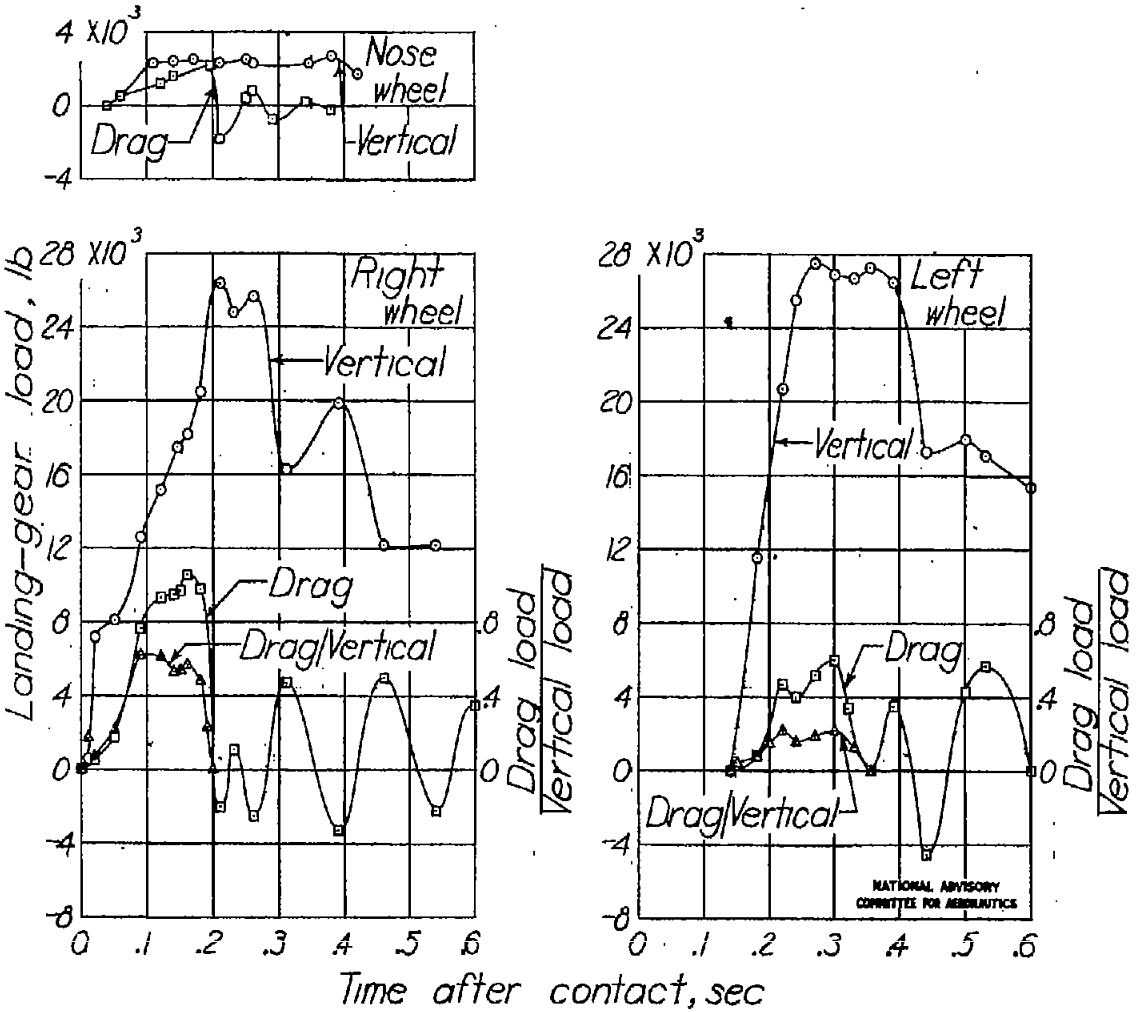


Figure 40.-Time history of loads on landing gear during a braked landing. Brake pressure, approximately 15 pounds per square inch. Landing 21.

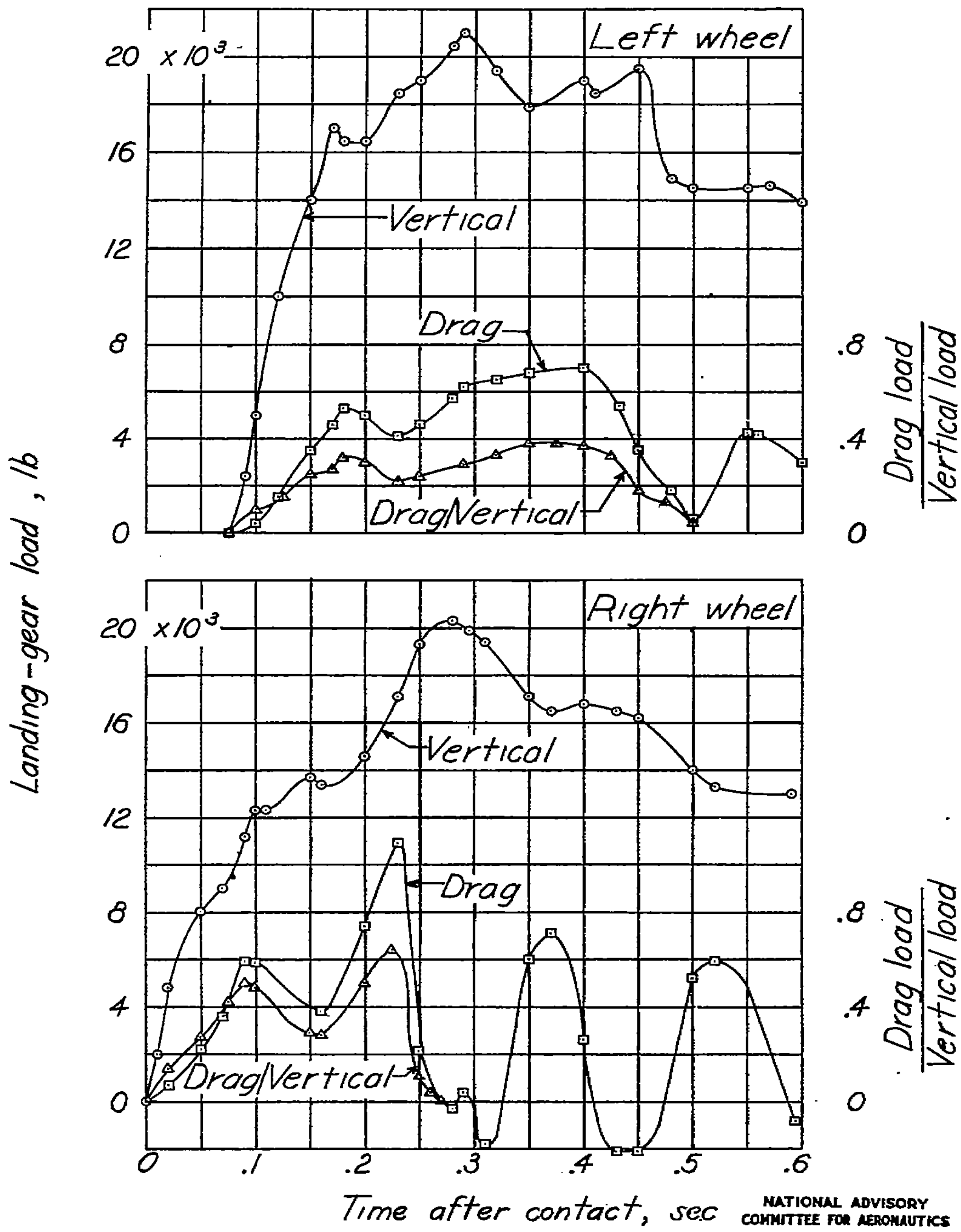
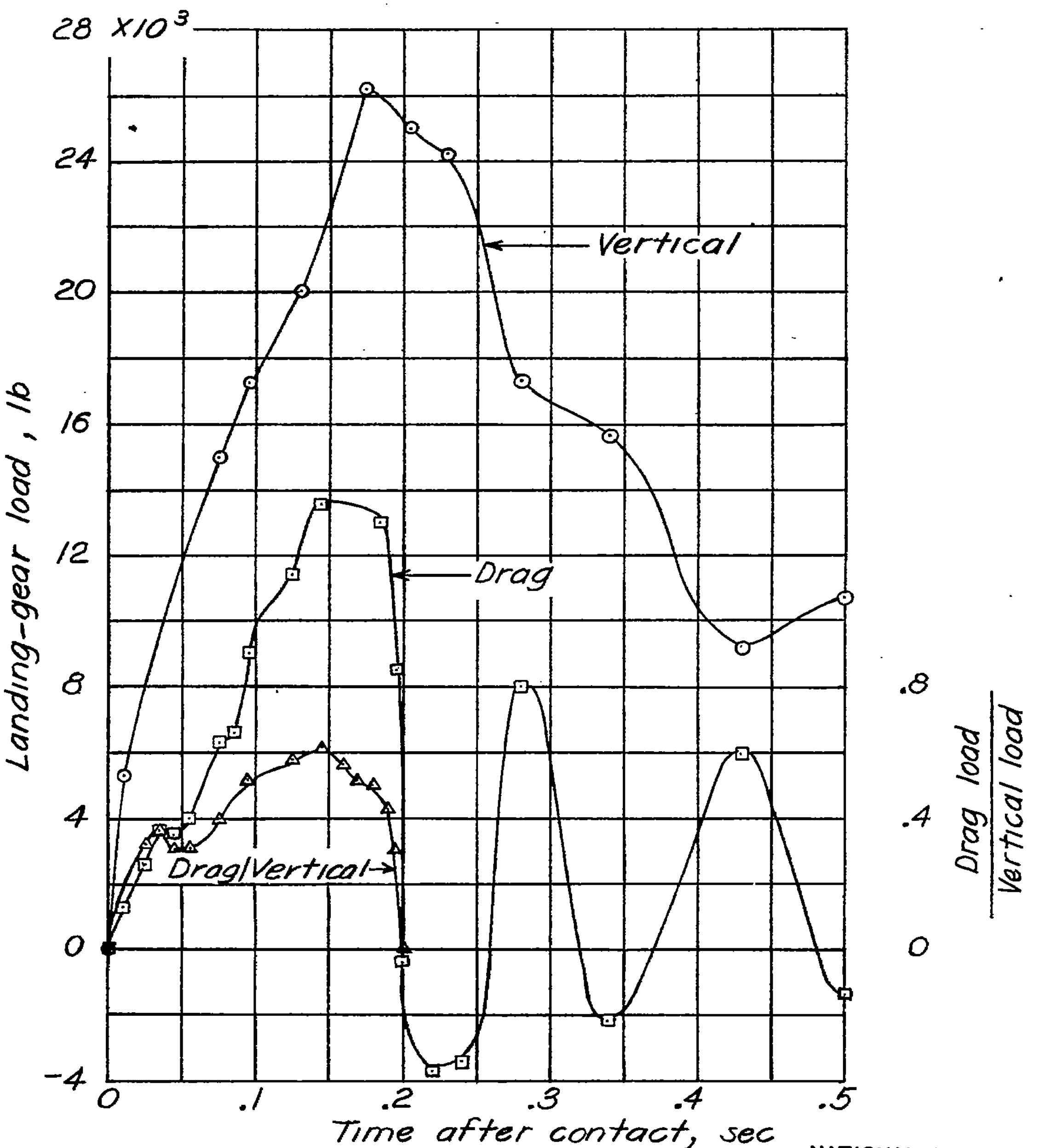


Figure 41.-Time history of loads on main landing gear during a braked landing. Brake pressure, approximately 20 pounds per square inch. Landing 25.



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 42.-Time history of loads on right main landing gear during a braked landing. Brake pressure, approximately 19 pounds per square inch. Landing 34.

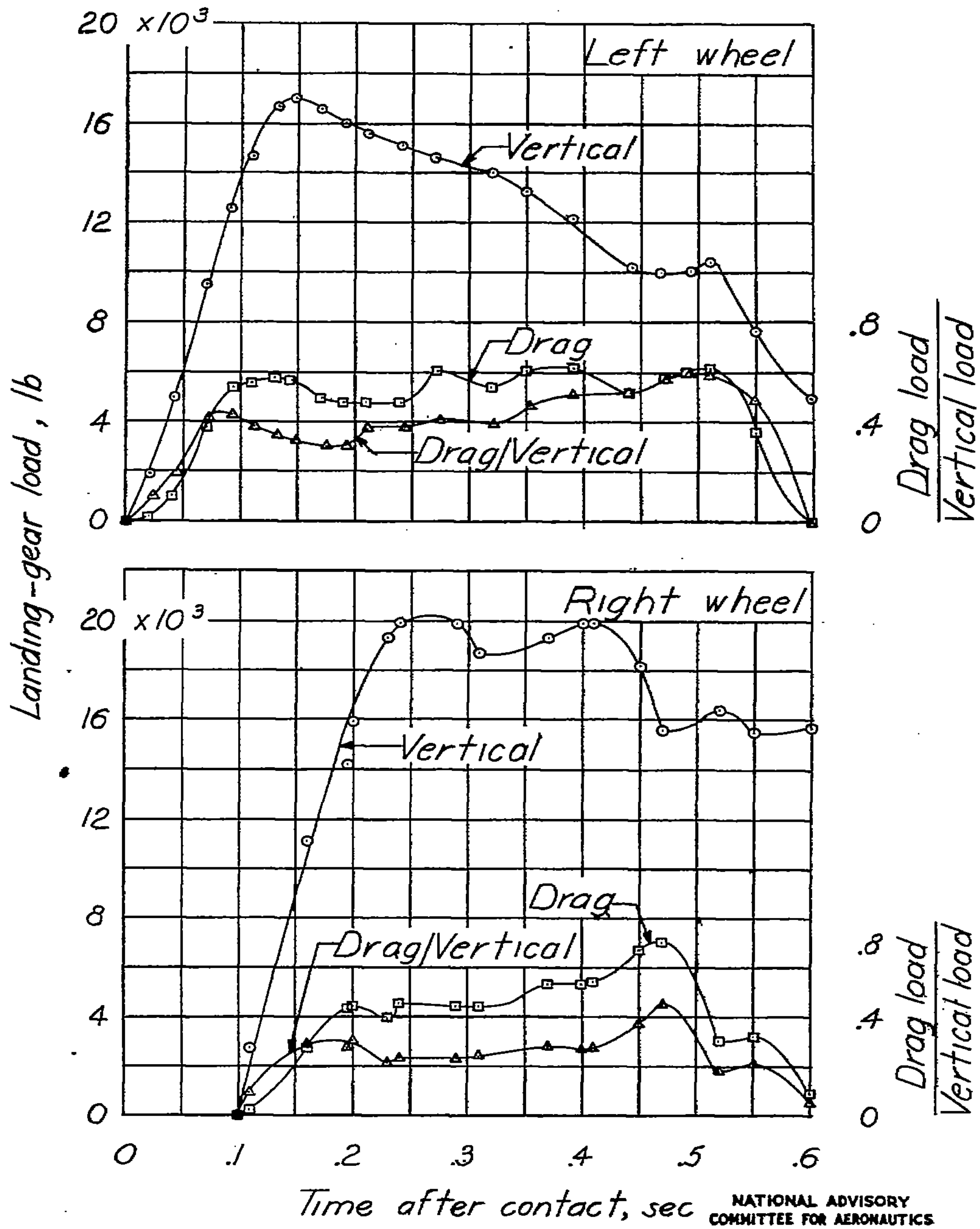


Figure 43.-Time history of loads on main landing gear during a braked landing. Brake pressure, approximately 24 pounds per square inch. Landing 35.

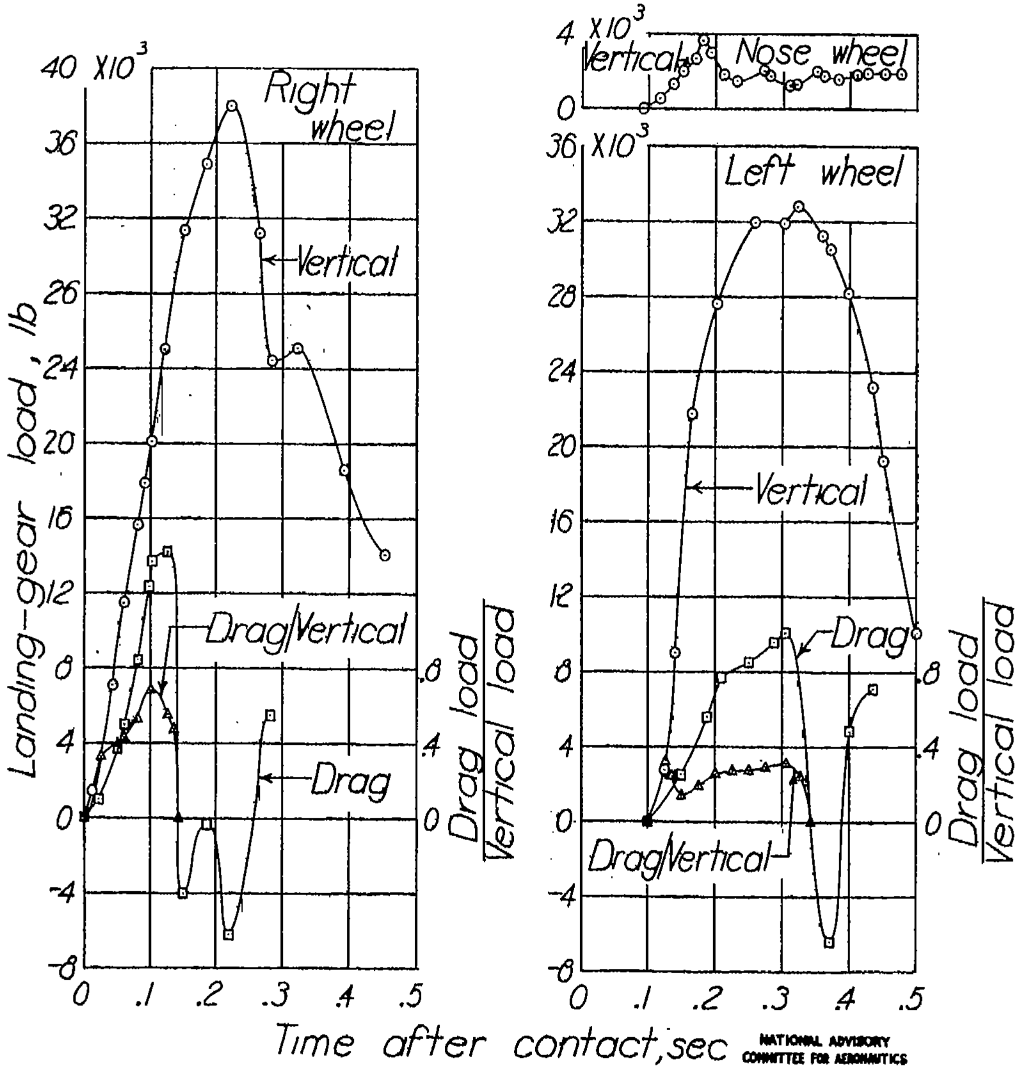


Figure 44.-Time history of loads on landing gear during a braked landing. Brake pressure, approximately 23 pounds per square inch. Landing 44.

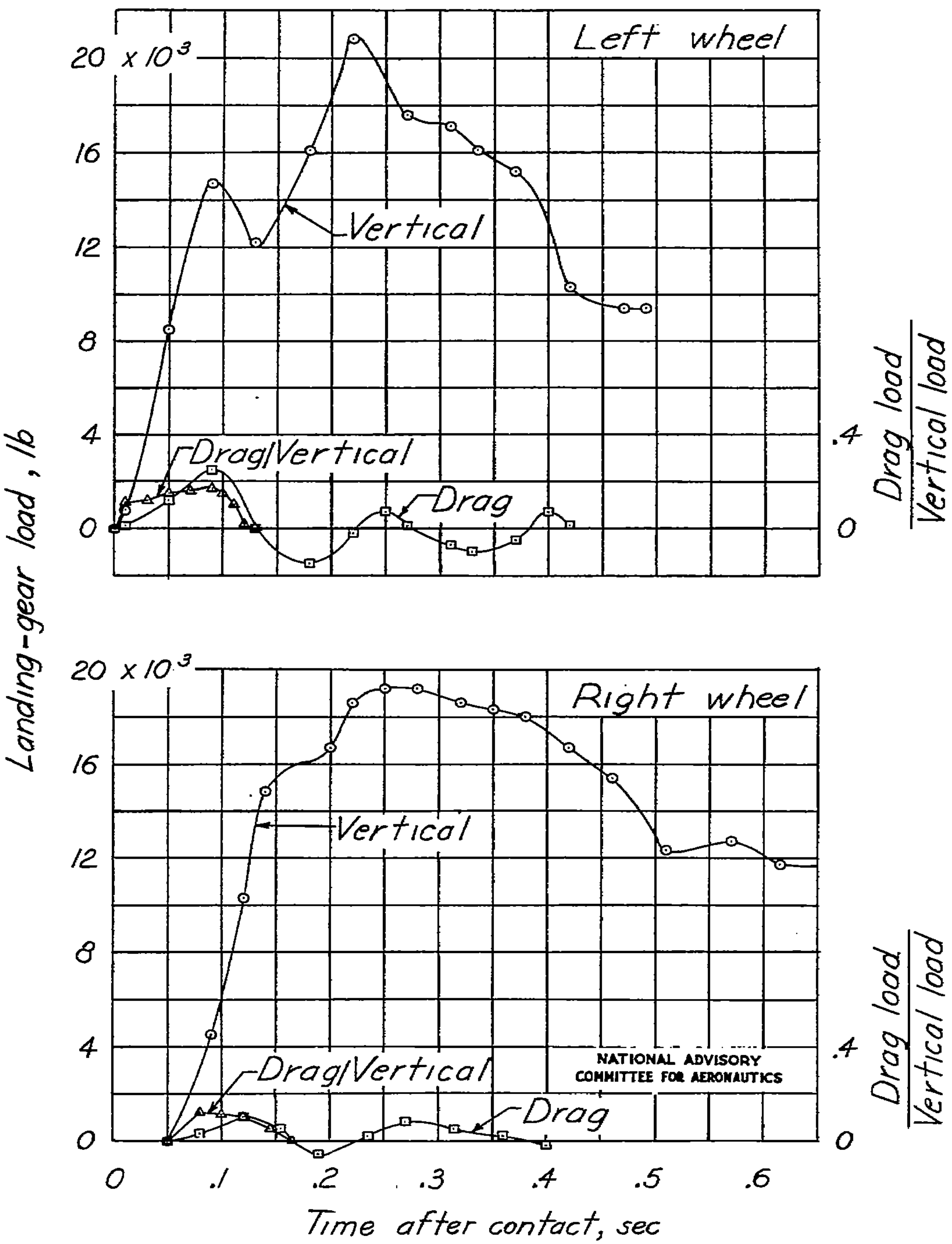


Figure 45.-Time history of loads on main landing gear during a prerotation landing. Landing 27_2 .

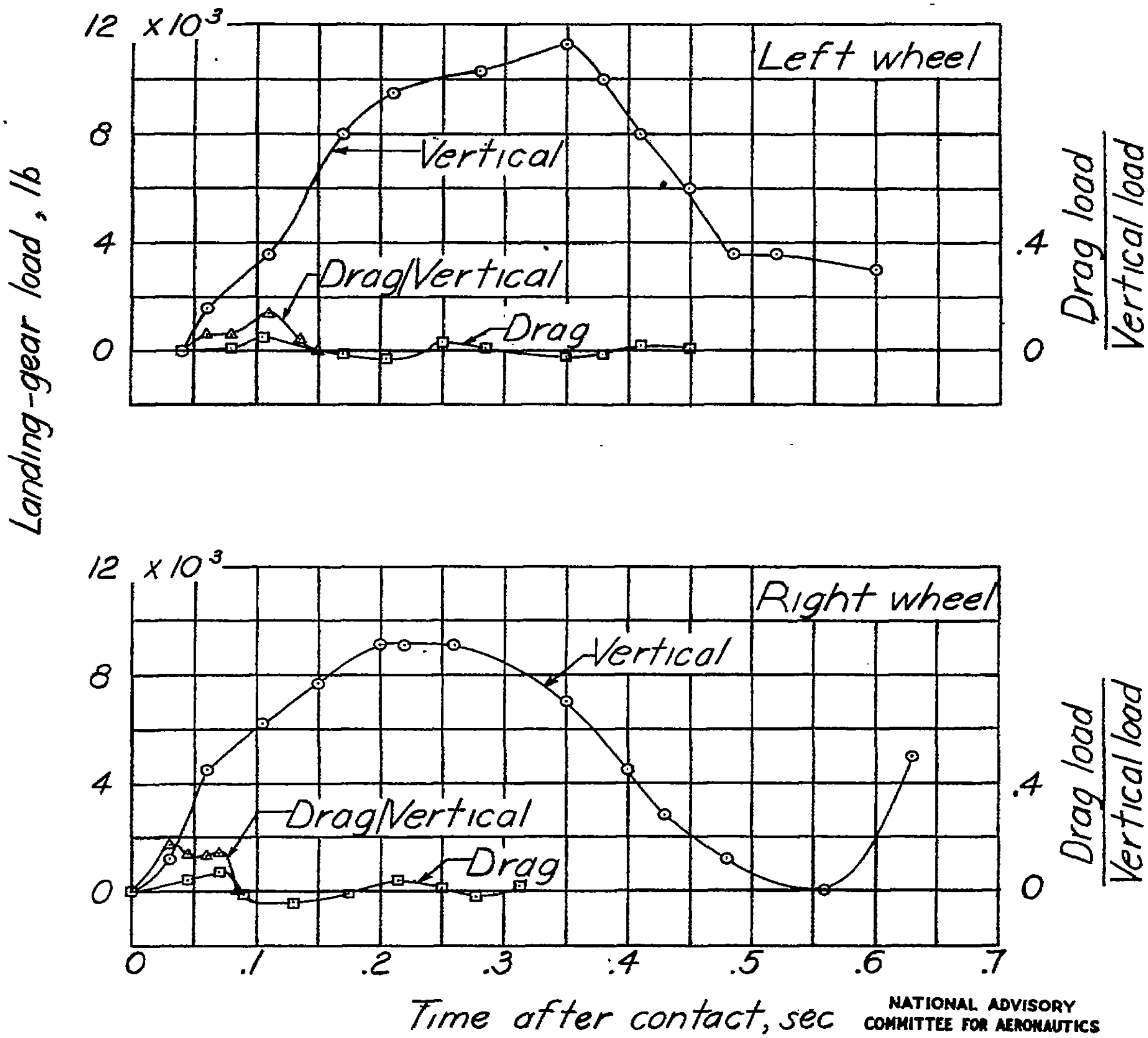


Figure 46.-Time history of loads on main landing gear during a prerotation landing. Landing 28_2.

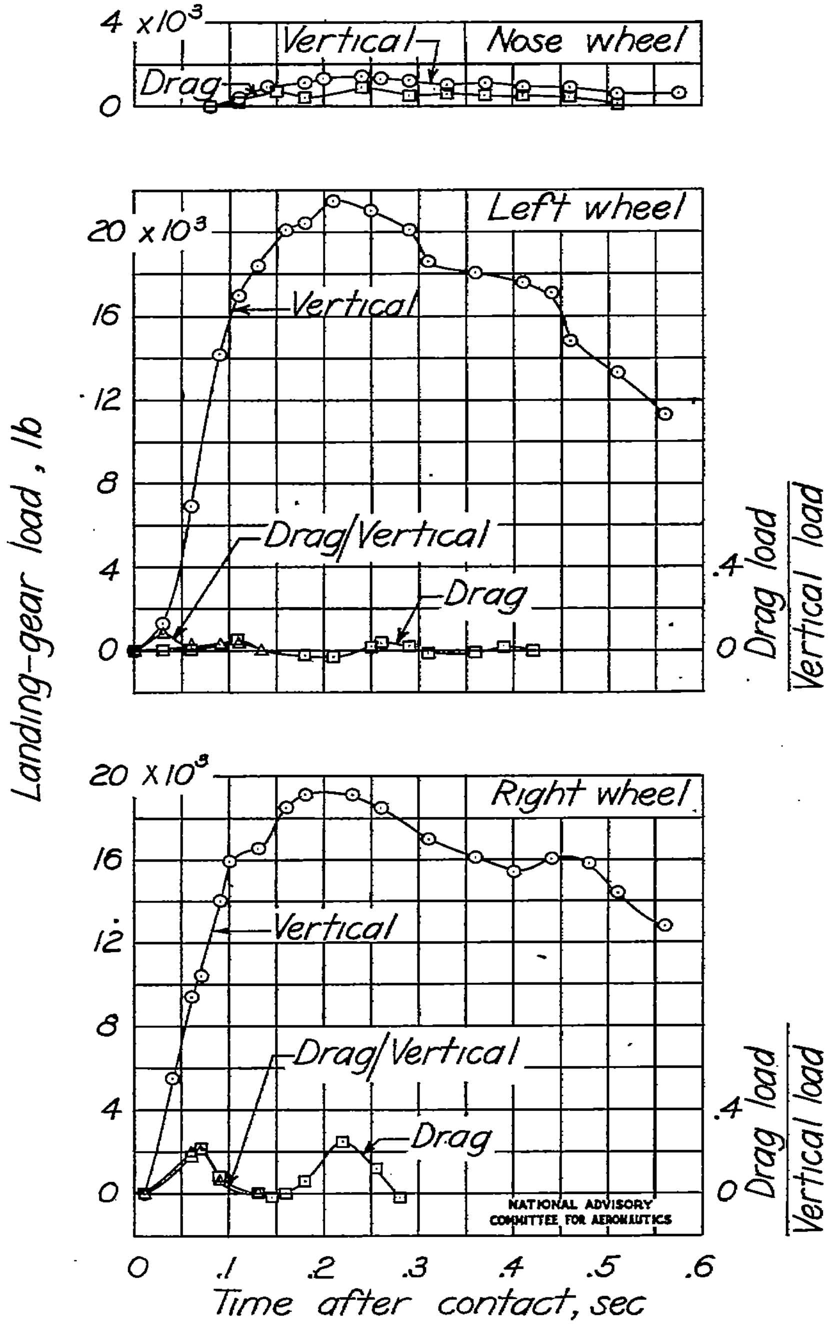


Figure 47.–Time history of loads on landing gear during a prerotation landing. Landing 30_2.

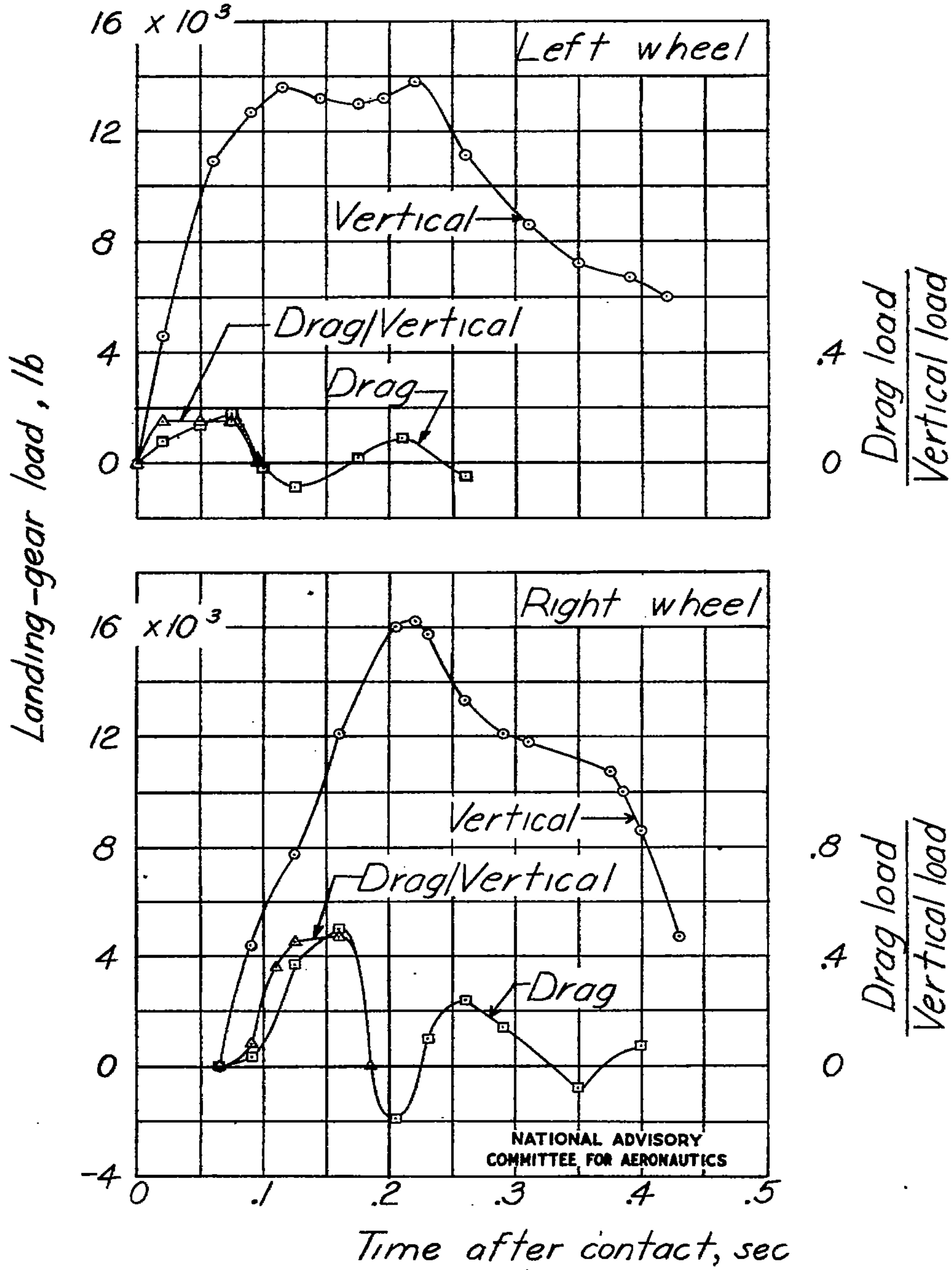
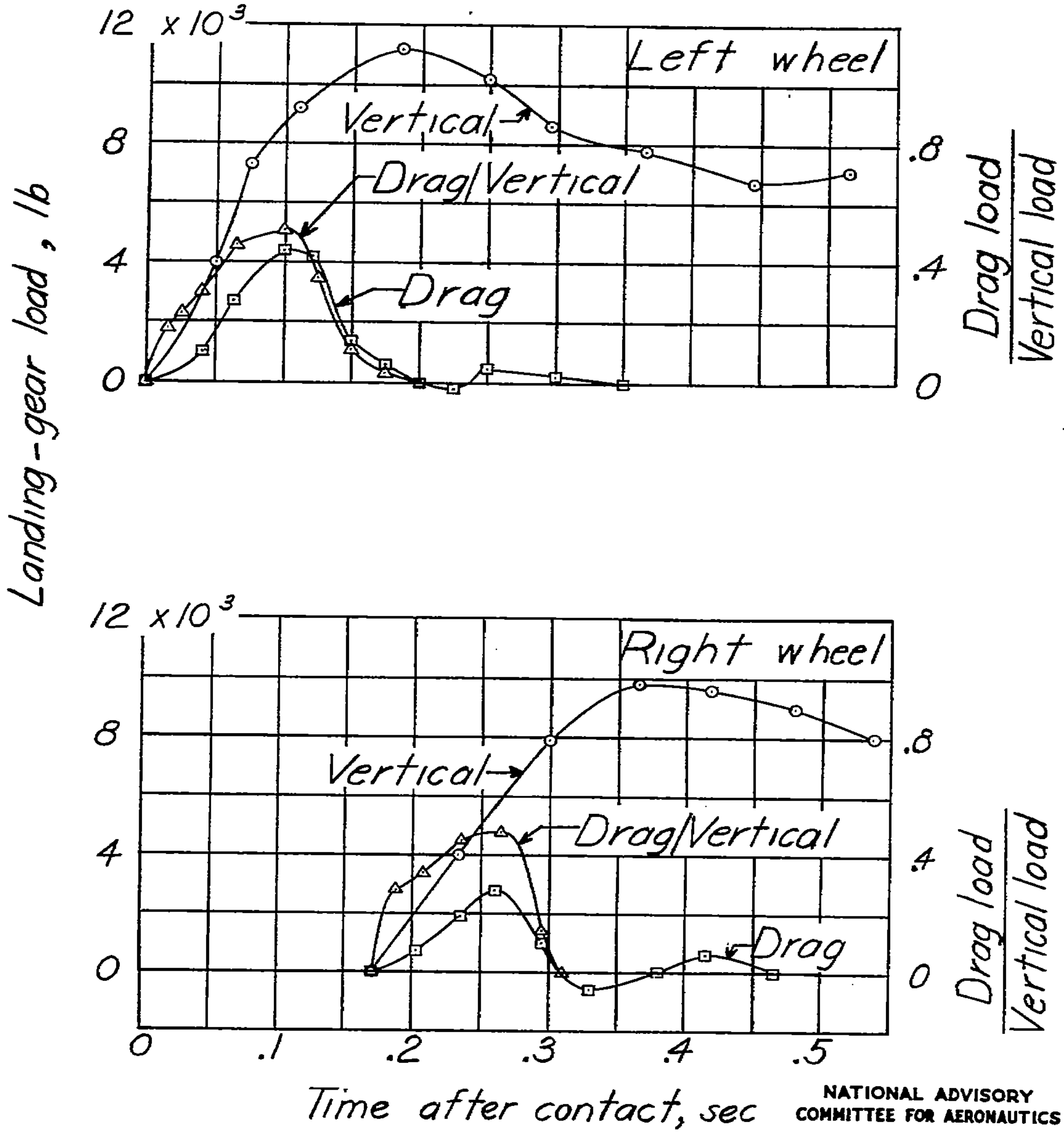


Figure 48.-Time history of loads on main landing gear during a prerotation landing. Landing 32_2



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 49.-Time history of loads on main landing gear during a prerotation landing. Landing $36a_2$.

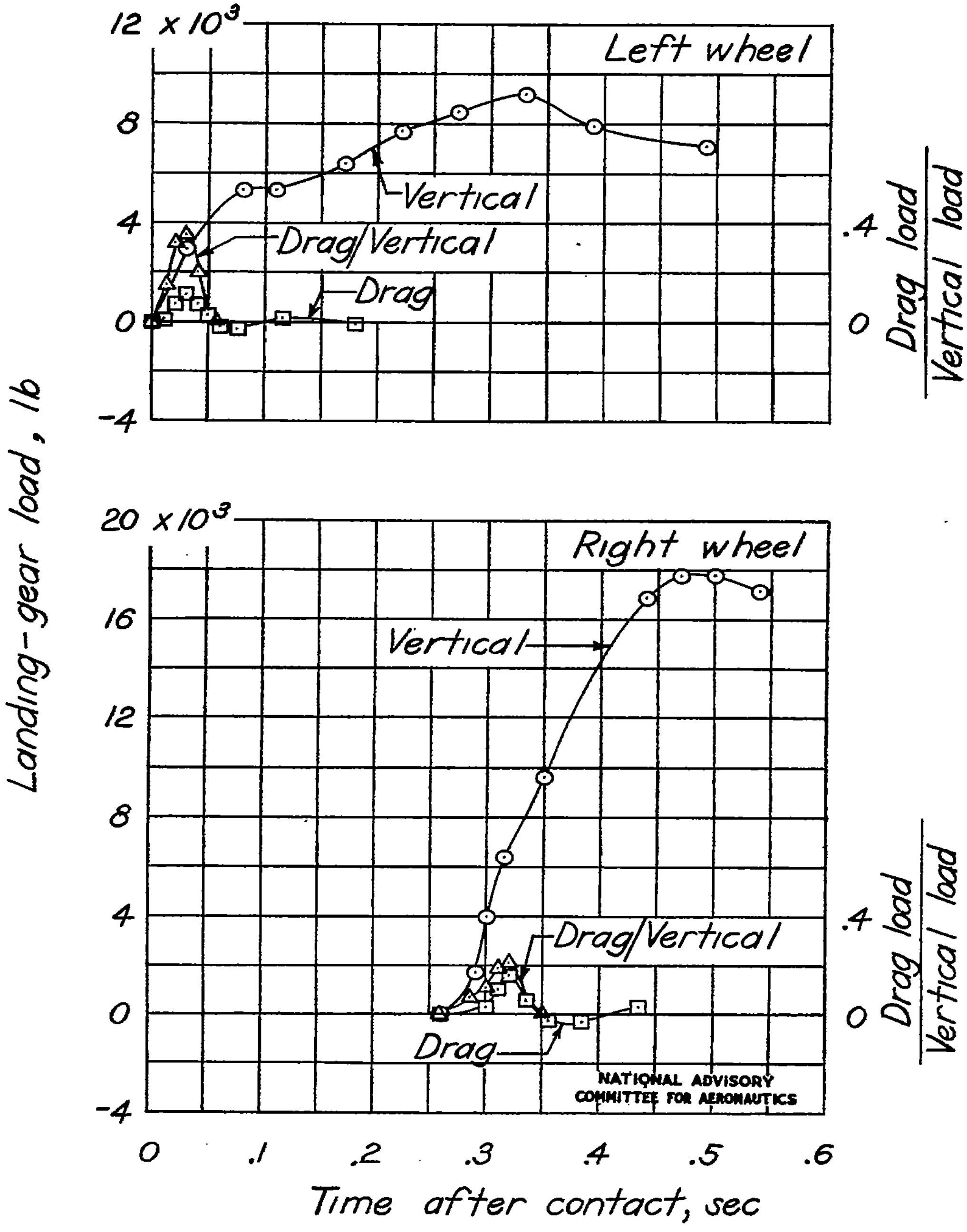


Figure 50.-Time history of loads on main landing gear during a prerotation landing. Landing 38_2.

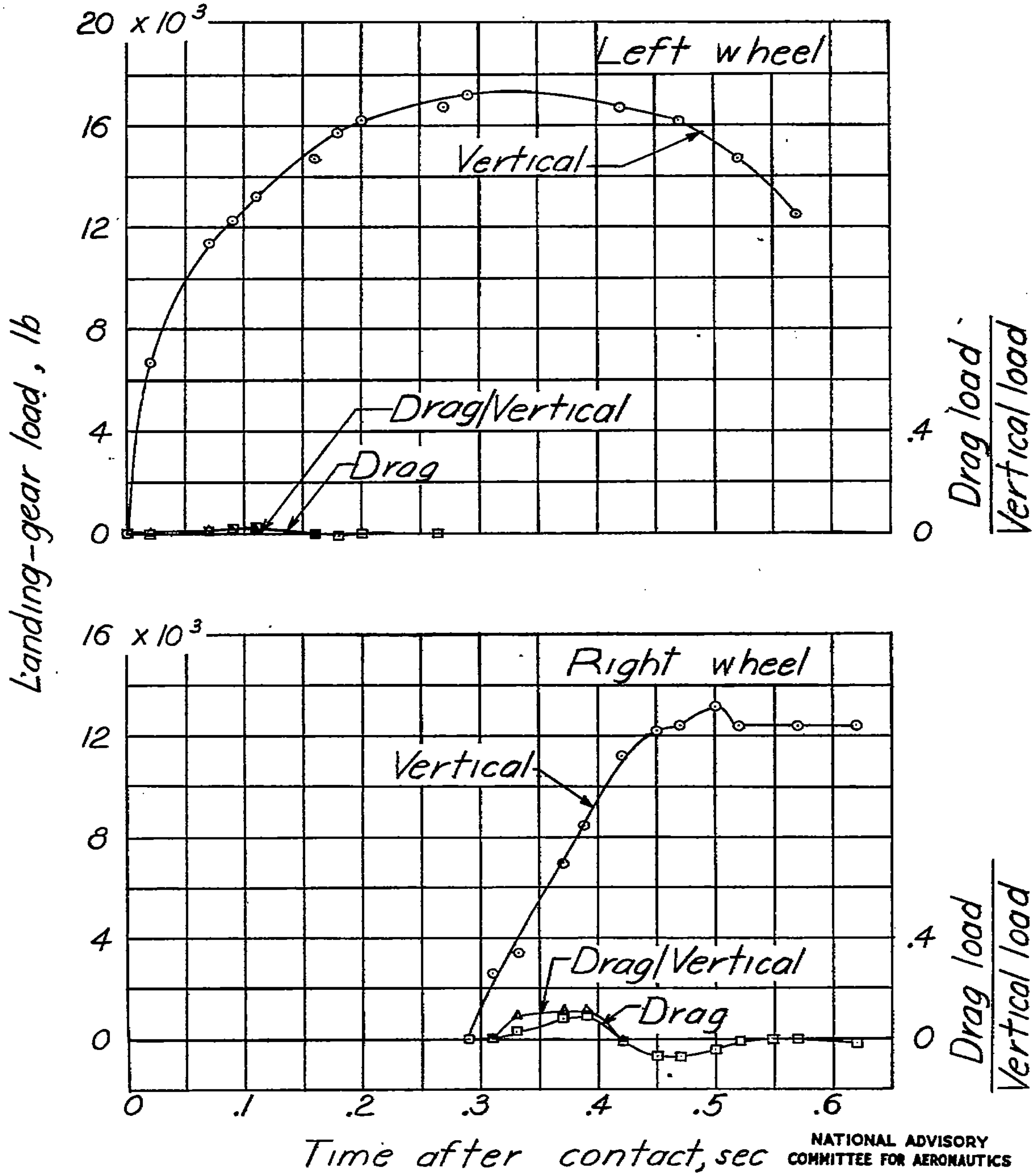


Figure 51.-Time history of loads on main landing gear during a prerotation landing. Landing 39_2.