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CALIBRATION OF A STRAIN-GAUGED CT4-A UNDERCARRIAGE.(U)
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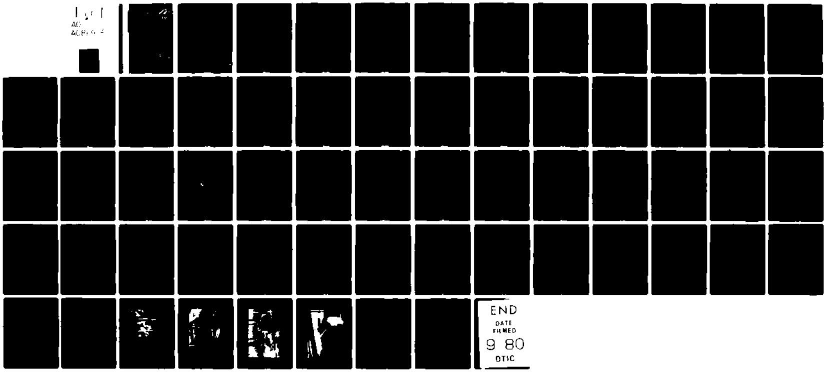

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MELBOURNE, VICTORIA

Structures Technical Memorandum 308

CALIBRATION OF A STRAIN-GAUGED CT4-A UNDERCARRIAGE

V. ROMEO

THIS REPORT

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SUMMARY

This memo presents the basic equations required to relate strains to components of flight and landing loads acting on CT4-A undercarriage legs. Details of strain gauge locations are contained in ARL Drawing No. 53432 and photographs and details of the test rig are included herein. The results of the calibration in February 1977 are recorded with details of the subsequent analysis. The application to flight test data is also described.

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CONTENTS

NOMENCLATURE

$\underset{\sim}{A}$	strain-load response matrix
D	drag force
$\underset{\sim}{e}$	error vector
M_x	normal bending moment
M_y	transverse bending moment
P	axial force
$\underset{\sim}{P}$	generalised load vector
S	side force
T	torque
V	vertical force
Δ	a change in a quantity
$\underset{\sim}{\varepsilon}$	strain vector
θ	angular measure in degrees
ρ	moment arm, where subscripts are used in conjunction with this symbol the meaning will be given

Units

N	Newton
Nm	Newton-metre
$\mu\varepsilon$	micro-strain

1. INTRODUCTION

This memo presents formulae for the determination of flight and landing loads acting on the CT4-A undercarriage from strains to be recorded on the flight test aircraft A19-031. The locations of the strain gauges are contained in ARL Drawing No. 53432.

The components of flight load to be measured at the strain-gauge locations are:

(a) side and drag bending moments;

(b) axial force; and

(c) torsion.

Photographs of the calibration rig for three typical loading cases are enclosed (plates 1,2,3). They show that the rig was bolted to the bed of a large testing machine with the leg lying horizontally and loads applied through a tie rod to a dummy axle. The different cases were simulated by turning the undercarriage legs through 90^{o} and 180^{o}. The loads were measured by a standard load cell except for the torsion test which employed dead weights. In the calibration the loads were considered to be known much more accurately than the strain-gauge readings so the statistical model attributes the error to strain readings only.

After preliminary runs, the measurements taken for the calibration were:

(a) strain gauge readings on a Hottinger; Strain Gauge Bridge Measuring Unit (Serial No. 4423) - abbreviated to "Hottinger".

(b) deflection measurements by dial gauges near each end of the leg; and

(c) coarser deflection measurements of leg deflection with Vernier tapes.

Measurement (c) was made at right angles to the line of action of the applied force. The intention here was to monitor the possibly large deflections of the leg so that their effect on applied bending moments could be allowed for in the calibration.

To analyse the results it was necessary to relate applied jack loads to the flight load components and then relate these to strain-gauge responses. As expected, preliminary flight tests and the calibration have shown that axial load response is extremely small.

The CT4-A undercarriage calibration test was done in February 1977 but analysis of results only began in July 1979 which meant that any discrepancies arising from the analysis could not be checked. In September 1979 while aircraft A19-031 was at ARL the inclination of the undercarriage legs under three conditions was checked and this assisted further analysis. These measurements are included herein (see table 4 and plate 4).

2. CALIBRATION LOADS

The jack loads were applied in the vertical, side and drag directions as shown in fig. 1. The predominant effect of vertical and side forces is to bend the leg about the x-axis (normal bending) and the predominant effect of the drag force is to bend the leg about the y-axis (transverse bending). Secondary effects are transverse bending from vertical and side forces and twisting from vertical, side and drag loads.

We have attributed the secondary bending and twisting to the loading method since the loads were not applied along flexural axes nor through the shear centre (for drag loading). This simplifies the analysis and by relating the predominant strains to bending moments and these back to forces it is possible to calculate the vertical, side and drag forces for a given set of strains. The significant load interaction term is discussed later.

The inclination of the undercarriage legs with respect to the aircraft body axes changes considerably during a landing cycle. Even under static 1-g conditions there is considerable deflection and rotation from the zero load state as shown in plate 4 and table 4. Although in the calibration the direction of loading is not critical because it can be allowed for it is convenient to have the calibration forces closely representing the components envisaged for the fatigue test. The side forces were applied at 33.5° to the legs which is also approximately the horizontal direction as shown in plate 4. In the port leg calibration the vertical forces were applied in the direction that closely approximated the actual vertical for the undercarriage orientation just prior to touchdown (plate 4).

3. DATA REDUCTION

The strain gauges on the undercarriage are sensitive to bending moments, torque and axial force. Since the leg remained elastic during the calibration it was expected that linear relations would be fitted to strain-load responses provided the large deflections were accounted for.

From the recorded strains $\underset{\sim}{\varepsilon} = \{\varepsilon_x, \varepsilon_y, \gamma, \varepsilon_p\}$ the loads $\underset{\sim}{P} = \{M_x, M_y, T, P\}$ acting near the fixed end are obtained through fitted linear relations.* From the moments and axial force three flight load components vertical (V), side (S) and drag (D) forces may be calculated. V and S are calculated by solving two equations (4.1) relating V and S to M_x and P which are geometrically non-linear however, because of large deflections under load. In the solution for V and S the geometry of the loaded leg is corrected iteratively. The equations describing the corrections are non-linear in V but linear in S. The transverse bending strain (ε_y) responds to two component moments, one from D the other from V and S. Because of small deflections in the drag direction a linear relation was fitted directly to the ε_y-D response however a non-linear relation for the ε_y-V response was required. A linear relation was fitted to the shear strain (γ) - torque (T) response but it was not needed to calculate the forces of interest V,S and D.

The strains were computed from records of the Hottinger strain gauge bridge outputs by applying gauge factors as shown in Appendix B.

The deflection data (contained in Appendix C) was used to calculate the normal bending moments and axial forces from jack loads. Table 1 summarises the steps in calculating M_x from V. Similar calculations were done for finding M_x from S. Table 2 summarises the steps to calculate axial forces (P) from V again; similar calculations for finding P from S were done.

Preliminary plots of bending strains versus bending moments and shear strain versus torque indicated that straight lines would adequately fit the data. Straight lines were fitted to:

1. Bending strains recorded by gauges 45 and 46BE (ε_x) versus bending moment about the x-axis. The individual data of vertical and side forces were combined;

2. Bending strains recorded by gauges 47 and 48BE (ε_y) versus drag force. Data for positive and negative drag forces were combined;

3. Shear strains recorded by gauges 49 and 50SE (γ) versus torque about the longitudinal axis of the leg; and

4. Compressive axial strains recorded by gauges 43 and 44CE (ε_p) were plotted against the components of vertical and side forces in the longitudinal direction. For simplicity a straight line was fitted for vertical and inboard side loads only (which represent the service loads most likely to occur) and the regression line representing tensile axial forces was obtained by extrapolation through the origin. *

* see page 9.

The plotted data and the fitted lines are shown in figures 2 to 5 and the statistics are summarised in table 3. The calibration data is given in Appendix A.

3.1 Variability between port and starboard legs

Intuitively we would not expect substantial differences in the strain-load responses between the port and starboard legs, once differences in loading geometry are taken into account. The test for "significant" differences between the slopes of the regression lines is part of an analysis of variance (ANOVA), examples of which are contained in ref. 1 and Appendix D. The purpose of the test is to determine whether the observed differences in slopes can be attributed to a chance variation in the data or to an actual systematic difference between the data of each undercarriage leg

F-tests done on all pairs of regression lines found significant differences in the slopes. (See Appendix D).

3.2 Linear strain-load equations

Using the ANOVA the significant strain-load relationships can be determined. The results are expressed in both metric (SI) and Imperial units (with the Imperial units shown in brackets). In metric units the moments and torques are expressed in Newton-metres and the forces in Newtons. Strains are expressed in units of micro-strain ($\mu\varepsilon$). It should be noted that all the calculations and regressions were done in Imperial units and only the final results were then converted to metric units. For the starboard leg the relations are:

$$
\begin{aligned}
\varepsilon_x &= 0.859756\ (1.165675)\ M_x + 16.72 \qquad (\mu\varepsilon) \\
\varepsilon_y &= 0.067738\ (0.301313)\ D \\
\gamma &= 1.080719\ (1.465260)\ T + 0.46 \\
\varepsilon_p &= -0.003687\ (-0.016403)\ P^*
\end{aligned}
\tag{3.1}
$$

For the port leg the equations are:

$$
\begin{aligned}
\varepsilon_x &= 0.818383\ (1.109580)\ M_x + 9.24 \qquad (\mu\varepsilon) \\
\varepsilon_y &= 0.069622\ (0.309695)\ D \\
\gamma &= 1.047794\ (1.420620)\ T - 0.50 \\
\varepsilon_p &= -0.004152\ (-0.018261)\ P^*
\end{aligned}
\tag{3.2}
$$

The transverse bending strain (ε_y) also depends on vertical load. This component of strain denoted ε_{yv} is considered in the following section.

* see page 9.

3.3 Load coupling

The only significant interactive or coupling load is the vertical load (V) which produces both normal and transverse bending (see Appendix B). A plot of transverse bending strain due to vertical load (ϵ_{yv}) against V is shown in fig. 6 and this indicates that a power curve would adequately fit the data. The curve fitted to the data is:-

$$\epsilon_{yv} = \begin{array}{lll} -0.0034173\ V^{1.122105} & (\mu\epsilon) & \text{(for V in N)} \\ -(0.018239)\ V^{1.122105} & (\mu\epsilon) & \text{(for V in lb)} \end{array} \quad (3.3)$$

The negative sign indicates the strain response is opposite to that for drag loading. The total transverse bending strain (ϵ_y) is the sum of the drag loading and vertical load responses, viz.

$$\epsilon_y = \begin{bmatrix} 0.0685674 - 0.0034173\ V^{0.122105} \end{bmatrix} \begin{bmatrix} D \\ V \end{bmatrix} (\mu\epsilon) \quad (3.4)$$
$$\quad (0.305003) \quad (0.018239)$$

It should be noted that the expression for ϵ_{yv} was found by considering the port leg data only as it is more representative of the loading in a landing.

4. VERTICAL, SIDE AND DRAG FORCES FROM A GENERAL LOAD STATE

Equations (3.1) and (3.4) can be manipulated to express the bending moments, torsion and axial force in terms of strains $\epsilon_x, \epsilon_y, \gamma$ and ϵ_p respectively. It is desirable, however, to relate these back to three orthogonal forces V,S and D. The combined effect of loads must be considered (see fig. a) and the equations to be solved simultaneously for D,S and V are:

$$\begin{bmatrix} a_1 & 0 & a_2 V^{(b-1)} \\ 0 & -\rho_2 & \rho_1 \\ 0 & \cos\theta & \sin\theta \end{bmatrix} \cdot \begin{bmatrix} D \\ S \\ V \end{bmatrix} = \begin{bmatrix} \epsilon_y \\ M_x \\ P \end{bmatrix} \begin{array}{l} \mu\epsilon \\ \text{Nm (Ft-lb)} \\ \text{N(lb)} \end{array} \quad (4.1)$$

where ϵ_y is expressed as:

$$\epsilon_y = a_1 D + a_2 V^b \quad (4.2)$$

and M_x and P are, from equations 3.1 and 3.2:-

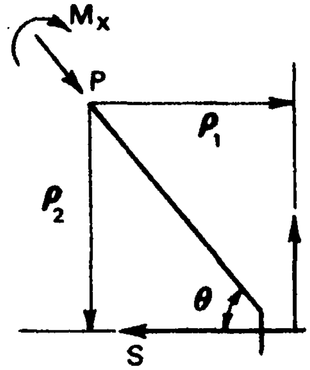
$$M_x = 1.163118\ (0.857872)\ .\ (\epsilon_x - 16.72) \quad \text{Nm (Ft-lb)}$$
$$P = -271.187\ (-60.9654)\ .\ \epsilon_p{}^* \quad \text{N (lb)} \quad (4.3)$$

* see page 9.

for the starboard leg and

$$M_x = 1.221920\ (0.901242)\ .\ (\varepsilon_x - 9.25) \qquad \text{Nm (Ft-lb)}$$
$$P = -243.5958\ (-54.7625)\ .\ \varepsilon_p\ ^* \qquad \text{N (lb)} \qquad (4.4)$$

for the port leg.



$$V\rho_1 - S\rho_2 = M_x$$

$$V\sin\theta + S\cos\theta = P$$

FIG a RELATION BETWEEN COMPONENTS (V,S) OF APPLIED LOAD AND INTERNAL REACTIONS (M_x,P)

The deflection data indicates that the moment arms (ρ_1 and ρ_2) depend upon V and S. To account for these deflections when calculating V and S, relationships have been fitted again to the port leg data only as it is more representative of the actual loading in a landing. The equations fitted are linear in S but still slightly dependent on V (see figs. 7 and 8) viz.

$$\begin{bmatrix} \rho_1 \\ \rho_2 \end{bmatrix} = 10^{-4} \begin{bmatrix} 1.357915\ V^{0.044177} & 1.141\dot{6} \\ -2.003257\ V^{0.074008} & 1.1\dot{6} \end{bmatrix} \cdot \begin{bmatrix} V \\ S \end{bmatrix} + \begin{bmatrix} 1.871 \\ 1.359 \end{bmatrix} \text{(Ft.)} \quad (4.5)$$

Since V and S are independent of D the most direct and rapid method of solving for V,S and D given the strains ε_x,ε_y and ε_p is as follows:

1. Compute M_x and P for each leg using their respective strains (ε_x and ε_p) and equations (4.3) and (4.4)

2. Solve for V and S by iteration (that is by updating the values of ρ_1 and ρ_2 after each solution) using only the second and third lines of equation (4.1) and equation (4.5)

3. Solve for D using equation (3.4) and the current values of V and ε_y.

* see page 9.

5. SECONDARY STRAINS

Although it is theoretically possible to find load vectors, loads that if applied singly to the undercarriage leg will produce a response from one strain gauge only it was neither practical nor necessary to find these for the calibration. Therefore, as expected, a single load applied to the leg produced responses from all gauges although most were negligible. The one significant interaction was discussed in the previous section.

The strains not directly related to loads have been termed secondary strains and are the subject of this section. Although inherently due to loading method they have been explained in terms of an eccentricity or offset (from a flexural axis or shear centre) in the line of action of the applied load.

To estimate these offsets the secondary strains were considered as primary strains for which a strain-moment relation exists. This relation was used to calculate the bending moment or torque that the strain corresponds to which was equated to the applied force times an eccentricity. As an example consider the normal bending strains recorded during the torsion test of the starboard leg (see fig. 11). The ideal rig set up for pure torsion is shown in fig. 9 and the more realistic case is shown in fig. 10 where it is obvious from the loading that some bending of the leg occurs. The normal bending strain recorded on gauge 46BE was 32$\mu\varepsilon$ for the maximum torque of 1900 lb-in. Using the first relation in (3.2) we find that the strain could be produced by a bending moment of 13.11 ft-lb or 157.3 lb-in. The moment arm for the resultant down load is 23.7 in. (see fig. 11) so the net down load is:

$$157.3/23.7 = 6.64 \text{ lb.}$$

We must now find the eccentricity "x" needed to produce a resultant down load of 6.64 lb. Consider the upper beam in fig. 10. From the equivalent free-body-diagram the net down load is 2xW/d so for a load of 100 lb (torque = 1900 lb-in) x is given by:

$$x = \frac{6.64 \times 38.0}{2 \times 100} = 1.26 \text{ in.}$$

This principle of finding an equivalent moment has been used to calculate the moment arm offsets for the other loads. Table A may be thought of as an interaction table and summarises the results. The primary strain responses are indicated by "X" while "0" indicates no appreciable response of the strain gauge to the particular load.

The calculations summarised here are for the maximum load case which gives the maximum response however any of the loads could be used. To check the calculations other loads in the range were used and there was good agreement.

STRAINS	VERTICAL LOAD	SIDE LOAD INBOARD	SIDE LOAD OUTBOARD	DRAG FORCE POSITIVE	DRAG FORCE NEGATIVE	TORSION
	STARBOARD LEG					
ε_x	X	X	X	0	0	1.26
ε_y	X	0	0	X	X	0
γ	1.39	1.39	-1.10	0.38	0.32	X
ε_p	X	X	X	0	0	0
	PORT LEG					
ε_x	X	X	X	0	0	-0.67
ε_y	X	0	0	X	X	0
γ	1.13	0.72	-0.64	-1.03	0.88	X
ε_p	X	X	X	0	0	0

TABLE A. LOAD OFFSETS (inches) PRODUCING THE OBSERVED SECONDARY STRAINS.

6. CONCLUSION

Formulae have been found to compute the vertical, side and drag forces given the strain state defined by $\varepsilon_x, \varepsilon_y$ and ε_p. Time histories of strain states will be available from flight trials so that forces can be found for actual landings. Equations (4.3) and (4.4) provide the right hand side of equation (4.1) from which the vertical (V) and side (S) forces are found by iteration in conjunction with relation (4.5). Having found V the drag force (D) is calculated from equation (3.4).

* Power curve relations were found to give a slightly more accurate representation to the axial force (P) - strain (ϵ_p) data for both legs. Use of the inverse relations improved the results of flight-test data so it is appropriate to include the relations in this memo.

For the starboard leg the equations are:

$$\epsilon_p = 0.000635666\ (0.00388118)\ P^{1.212206}$$

$$P = 433.66329\ (97.491422)\ \epsilon_p^{0.824943}$$

and for the port leg:

$$\epsilon_p = 0.00271739\ (0.0129103)\ P^{1.0441166}$$

$$P = 286.70461\ (64.453784)\ \epsilon_p^{0.957747}$$

REFERENCES

1. ACTON, Forman S. — Analysis of straight line data
   John Wiley 1959.

2. KEMPTHORNE, Oscar — Design and Analysis of Experiments
   John Wiley 1952.

APPENDIX A

CALIBRATION DATA 1. STARBOARD LEG

LOAD TYPE: VERTICAL LOAD		GAUGE 46BE MICRO-STRAIN				GAUGE 44CE MICRO-STRAIN		
LOAD (lb)	BM (ft-lb)	RUNS 1	RUNS 2	RUNS 3	P (lb)	RUNS 1	RUNS 2	RUNS 3
0	0	0	-	0	0	0	0	0
200	315	356	373	366	148.8	-1.87	-1.50	-1.87
400	643	747	753	749	298.1	-3.74	-4.12	-4.12
600	985	1140	1148	1175	447.9	-5.99	-6.36	-6.73
800	1330	1552	1557	1555	598.0	-9.35	-9.73	-9.73
1000	1683	1976	1982	1981	748.4	-13.10	-13.10	-13.10
1200	2037	2415	2416	2415	899.1	-16.84	-16.84	-16.84
0		0	0	1	0	0	-0.37	

INBOARD LOAD

		GAUGE 46BE MICRO-STRAIN				GAUGE 44CE MICRO-STRAIN	
LOAD (lb)	BM (ft-lb)	RUNS 1	RUNS 2	LOAD (lb)	P (lb)	RUNS 1	RUNS 2
0	0	0	-	0	0	0	0
107/-100	-137/-128	-146	-139	107/100	82.3/83.4	-1.12	-1.12
200	-259	-280	-279	200	166.9	-1.87	-1.87
300	-393	-424	-425	300	250.5	-2.62	-2.99
400	-529	-573	-575	400	334.1	-3.37	-3.37
500	-668	-730	-731	500	417.8	-4.12	-4.12
0	0	0	0	0	0	0	0

OUTBOARD LOAD

		GAUGE 46BE MICRO-STRAIN			GAUGE 44CE MICRO-STRAIN	
LOAD (lb)	BM (ft-lb)	RUNS 1	RUNS 2	P (lb)	RUNS 1	RUNS 2
0	0	0	0	0	0	-0.37
100	128	166	167	-83.4	0.75	1.12
200	250	316	311	-166.9	1.87	1.87
300	370	467	463	-250.5	2.24	2.24
400	489	608	605	-334.2	2.62	2.62
500	604	741	745	-417.9	2.62	2.99
0	0	-	0	0	-	-0.37

Note. 107/100 etc. denotes different loads for runs 1 and 2.

POSITIVE DRAG

LAOD lb	BM (ft-lb)	GAUGE 48BE MICRO-STRAIN
0	0	0
70	161	21
151	349	47
237	548	73
337	779	103
427	987	130
500	1156	152
0	0	0
114	263	36
209	483	65
308	712	95
401	927	123
490	1133	150
0	0	0

NEGATIVE DRAG

LOAD lb	BM (ft-lb)	GAUGE 48BE MICRO-STRAIN
0	0	0
-92	-212	-27
-192	-444	-56
-345	-797	-100
-410	-948	-120
-490	-1133	-142
0	0	0
-148	-342	-45
-245	-566	-
-336	-777	-103
-436	-1008	-133
0	0	0

TORSION

TORQUE (lb-in)	GAUGE 50SE MICRO-STRAIN Run 1	Run 2	TORQUE (lb-in)	GAUGE 50SE MICRO-STRAIN Run 1	Run 2
0	0	0	0	0	0
380	46	45	-380	-44	-44
760	91	90	-760	-90	-90
1140	136	134	-1140	-134	-134
1520	183	180	-1520	-180	-180
1900	226	224	-1900	-224	-224

2. CALIBRATION DATA FOR PORT LEG

VERTICAL LOAD

LOAD (lb)	BM (ft-lb)	GAUGE 45BE (MICRO-STRAIN)	P (lb)	GAUGE 43CE (MICRO-STRAIN)
0	0	0	0	0
200	381	437	118	-3.37
400	775	870	236	-5.24
600	1180	1345	355	-6.73
800	1597	1779	475	-9.35
1000	2022	2252	595	-11.97
1200	2456	2725	716	-14.22
0	0	0	0	0
200	381	448	118	-3.37
400	776	885	236	-5.24
600	1183	1329	355	-7.11
800	1601	1789	475	-9.35
1000	2030	2253	595	-11.97
1200	2468	2743	716	-14.59
0	0	0	0	0

INBOARD LOAD

LOAD (lb)	BM (ft-lb)	GAUGE 45BE (MICRO-STRAIN)		P (lb)	GAUGE 43CE (MICRO-STRAIN)	
		RUN 1	RUN 2		RUN 1	RUN 2
0	0	0	0	0	0	0
100	-128	-143	-140	83	-1.12	-1.12
200	-259	-277	-282	167	-1.87	-2.24
300	-393	-422	-425	251	-2.62	-2.99
400	-528	-570	-574	334	-3.74	-4.12
500	-667	-718	-723	418	-4.86	-5.24
0	0	-	0	0	-	0

OUTBOARD LOAD

LOAD (lb)	BM (ft-lb)	GAUGE 45BE (MICRO-STRAIN)		P (lb)	GAUGE 43CE (MICRO-STRAIN)	
		RUN 1	RUN 2		RUN 1	RUN 2
0	0	0	-	0	0	-0.37
100	126	147	154	-83	1.12	1.12
200	250	284	285	-167	1.87	2.24
300	372	423	421	-251	2.99	2.99
400	491	558	558	-334	4.49	4.12
500	608	689	691	-418	5.24	4.86
0	0	0	0	0	-	0

POSITIVE DRAG NEGATIVE DRAG

LOAD (lb)	BM (ft-lb)	GAUGE 47BE (MICRO-STRAIN)	LOAD (lb)	BM (ft-lb)	GAUGE 47BE (MICRO-STRAIN)
0	0	0	0	0	0
156	360	49	-127	-293	-38
269	622	83	-207	-478	-64
364	841	88	-295	-682	-91
450	1040	140	-450	-1040	-138
540	1248	167	-530	-1225	-165
0	0	0	0	0	0
90	208	28	-134	-309	-41
200	462	63	-248	-573	-76
292	675	92	-343	-793	-106
392	906	122	-437	-1010	-135
500	1156	155	-548	-1267	-169
0	0	0	0	0	0

TORSION

	GAUGE 49SE			GAUGE 49SE	
TORQUE (lb-in)	MICRO-STRAIN Run 1	MICRO-STRAIN Run 2	TORQUE (lb-in)	MICRO-STRAIN Run 1	MICRO-STRAIN Run 2
0	0	0	0	0	0
380	47	45	-380	-47	-47
760	92	92	-760	-94	-94
1140	139	139	-1140	-139	-139
1520	185	185	-1520	-185	-185
1900	231	231	-1900	-234	-234

APPENDIX B

SUMMARY OF STRAIN GAUGE DATA FOR CT4-A UNDERCARRIAGE STATIC CALIBRATION

B1 Computation of Strains

(For gauge locations see ARL Drawing No. 53432)

THE FOLLOWING BRIDGE FACTORS AND GAUGE FACTORS APPLY:

GAUGE NO.	BRIDGE FACTOR
43, 44 (CE)	2.66
45, 46, 47, 48 (BE)	4.00
49, 50 (SE)	2.00

FOR ALL GAUGES:

GAUGE FACTOR = 2.11
HOTTINGER K = 2.10

$\therefore$ strain in units of micro-strain is given by

$$\frac{H_x - H_o}{\frac{2.11}{2.10} \times \text{BRIDGE FACTOR}}$$

where H_x = Hottinger reading at Load x
H_o = " " zero load

For example strain for vertical load of 800 lb measured by gauge 46BE $H_x = 30207$
$H_o = 23971$

$$\therefore \quad \varepsilon_x = \frac{30207 - 23971}{\frac{2.11}{2.10} \times 4.00} = 1552 \text{ Micro-strain}$$

B2 <u>Strain Gauge Data</u>

Each table below presents readings from all gauges for two or more loading runs of a particular test set-up. Only the variable part of the Hottinger readings has been presented to save space and improve clarity.

A. STARBOARD LEG

VERTICAL LOAD

LOAD (lb)	HOTTINGER READINGS			
	44CE	46BE	48BE	50SE
0	843	23971	6092	125
200	838	25400	6038	173
400	833	26972	5968	219
600	827	28555	5897	264
800	818	30207	5823	308
1000	808	31915	5749	351
1200	798	33676	5670	393
0	843	23971	6092	125
200	839	25472	6036	173
400	832	26997	5967	220
600	826	28587	5895	264
800	817	30228	5822	308
1000	808	31936	5747	352
1200	798	33683	5670	393
0	842	23973	6093	125
0	843	23968	6093	125
200	838	25441	6033	173
400	832	26979	5965	217
600	825	28691	5894	264
800	817	30220	5825	311
1000	808	31932	5751	356
1200	798	33674	5676	401
0	843	23974	6093	126

SIDE LOAD INBOARD STARBOARD LEG

LOAD (lb)	HOTTINGER READINGS			
	44CE	46BE	48BE	50SE
0	45	3972	88	123
107	42	3385	109	108
200	40	2847	127	94
300	38	2268	144	79
400	36	1668	160	66
500	34	1036	177	49
0	45	3968	89	123
100	42	3410	108	109
200	40	2847	127	93
300	37	2258	143	78
400	36	1656	160	64
500	34	1029	177	48
0	45	3968	89	122

SIDE LOAD OUTBOARD STARBOARD LEG

LOAD (lb)	HOTTINGER READINGS			
	44CE	46BE	48BE	50SE
0	43	3969	90	125
100	45	4636	75	146
200	48	5239	60	165
300	49	5844	44	184
400	50	6411	28	200
500	50	6947	12	215
0	42	3973	89	125
100	45	4646	73	144
200	47	5223	60	162
300	48	5835	43	182
400	49	6406	28	199
500	50	6967	15	219
0	41	3974	90	125

NEGATIVE DRAG STARBOARD LEG

LOAD (lb)	HOTTINGER READINGS			
	44CE	46BE	48BE	50SE
0	45	0	6088	23
92	45	1	5980	30
193	43	2	5861	38
345	37	3	5685	50
410	37	3	5607	55
490	36	3	5516	61
0	37	1	6094	23
148	37	1	5912	34
245	37	2	5891	43
336	37	3	5680	50
436	36	1	5560	58
0	37	0	6092	23

POSITIVE DRAG STARBOARD LEG

LOAD (lb)	HOTTINGER READINGS			
	44CE	46BE	48BE	50SE
0	45	69	6054	128
70	45	69	6140	120
151	45	71	6241	112
237	47	72	6348	104
337	48	74	6468	96
427	50	75	6577	87
500	51	74	6665	81
0	44	69	6054	128
114	45	70	6197	116
209	47	72	6314	107
308	48	72	6434	98
401	49	74	6548	90
490	52	74	6658	83
0	44	69	6055	128

TORSION STARBOARD LEG

A. POSITIVE TORQUE

LOAD (lb)	TORQUE (lb-ins)	HOTTINGER READING			
		44CE	46BE	48BE	50SE
0	0	1	325	8	208
20	380	2	312	8	300
40	760	2	298	8	390
60	1140	2	281	8	482
80	1520	2	264	8	575
100	1900	2	251	8	662
0	0	2	325	8	211
0	0	2	325	8	218
20	380	2	317	8	308
40	760	2	304	8	400
60	1140	2	294	8	490
80	1520	2	286	8	578
100	1900	2	277	8	669
0	0	2	325	8	218

B. NEGATIVE TORQUE

LOAD (lb)	TORQUE (lb-ins)	HOTTINGER READING			
		44CE	46BE	48BE	50SE
0	0	1	360	2	5012
20	-380	1	381	3	4924
40	-760	1	406	4	4831
60	-1140	1	431	5	4742
80	-1520	0	456	6	4650
100	-1900	0	485	6	4562
0	0	0	358	2	5008
20	-380	0	388	3	4922
40	-760	1	410	4	4831
60	-1140	1	435	4	4741
80	-1520	1	460	6	4650
100	-1900	0	438	6	4562
0	0	1	360	2	5012

B. PORT LEG

VERTICAL LOAD

LOAD (lb)	HOTTINGER READING			
	43CE	45BE	47BE	49SE
0	88	22389	344	454
200	79	24147	315	499
400	74	25885	282	538
600	70	27793	248	577
800	63	29539	210	613
1000	56	31440	171	646
1200	50	33342	134	678
0	88	22389	343	453
200	79	24188	314	494
400	74	25947	281	530
600	69	27730	247	561
800	63	29580	211	593
1000	56	31465	174	621
1200	49	33412	135	648
0	89	22391	344	453

SIDE LOADING INBOARD PORT LEG

LOAD (lb)	HOTTINGER READING			
	43CE	45BE	47BE	49SE
0	89	22395	40	53
100	86	21818	46	42
200	84	21282	49	36
300	82	20697	52	29
400	79	20103	55	20
500	76	19510	58	10
0	89	22392	40	53
100	86	21829	46	44
200	83	21260	50	38
300	81	20685	52	30
400	78	20083	55	22
500	75	19486	58	15
0	88	22391	40	53

SIDE LOADING OUTBOARD PORT LEG

LOAD (lb)	HOTTINGER READING			
	43CE	45BE	47BE	49SE
0	86	2388	2	56
100	89	2979	6	65
200	91	3530	10	73
300	94	4089	12	83
400	98	4629	12	93
500	100	5156	15	103
0	87	2392	1	55
100	90	3010	6	65
200	93	3537	7	72
300	95	4085	7	80
400	98	4636	9	88
500	100	5169	11	98
0	87	2392	1	55

POSITIVE DRAG PORT LEG

LOAD (lb)	HOTTINGER READING			
	43CE	45BE	47BE	49SE
0	6	386	310	462
156	10	404	505	421
269	12	417	645	392
364	12	428	665	371
450	12	438	873	350
540	12	448	981	330
0	6	387	310	462
90	8	397	423	438
200	11	410	562	410
292	12	421	678	386
392	13	432	801	363
500	13	444	934	339
0	7	387	309	462

NEGATIVE DRAG PORT LEG

LOAD (lb)	HOTTINGER READING			
	43CE	45BE	47BE	49SE
0	13	10	5345	56
127	10	8	5192	79
207	8	4	5087	96
295	9	2	4978	113
450	10	3	4789	144
530	9	2	4683	161
0	9	8	5345	56
134	6	6	5180	81
248	8	4	5038	105
343	8	2	4918	124
437	8	1	4801	144
548	9	0	4665	165
0	9	8	5345	56

TORSION PORT LEG

A. NEGATIVE TORQUE

LOAD (lb)	TORQUE (lb-ins)	HOTTINGER READING			
		43CE	45BE	47BE	49SE
0	0	6	4	0	6441
20	-380	6	10	2	6347
40	-760	6	12	5	6252
60	-1140	10	12	7	6160
80	-1520	12	14	10	6068
100	-1900	15	16	12	5972
0	0	7	7	0	6440
20	-380	7	7	2	6347
40	-760	8	7	5	6251
60	-1140	10	8	7	6158
80	-1520	12	11	10	6066
100	-1900	12	12	12	5972
0	0	6	5	0	6440

B. POSITIVE TORQUE

LOAD (lb)	TORQUE (lb-ins)	HOTTINGER READING			
		43CE	45BE	47BE	49SE
0	0	202	340	74	6653
20	380	201	330	71	6747
40	760	200	315	70	6838
60	1140	197	302	67	6932
80	1552	196	290	65	7025
100	1900	195	272	63	7118
0	0	201	340	74	6654
20	380	200	325	72	6745
40	760	199	315	70	6840
60	1140	197	300	67	6932
80	1552	196	288	65	7026
100	1900	194	273	62	7118
0	0	201	340	74	6653

APPENDIX C

DEFLECTION DATA INCLUDING
LOCATION OF VERNIER TAPES AND GAUGES.

RIG DATA

	θ_1	θ_2	θ_3	θ_4
Stb'd leg	8°	50°	14°	122°
Port leg	9°	63°	3°	122°

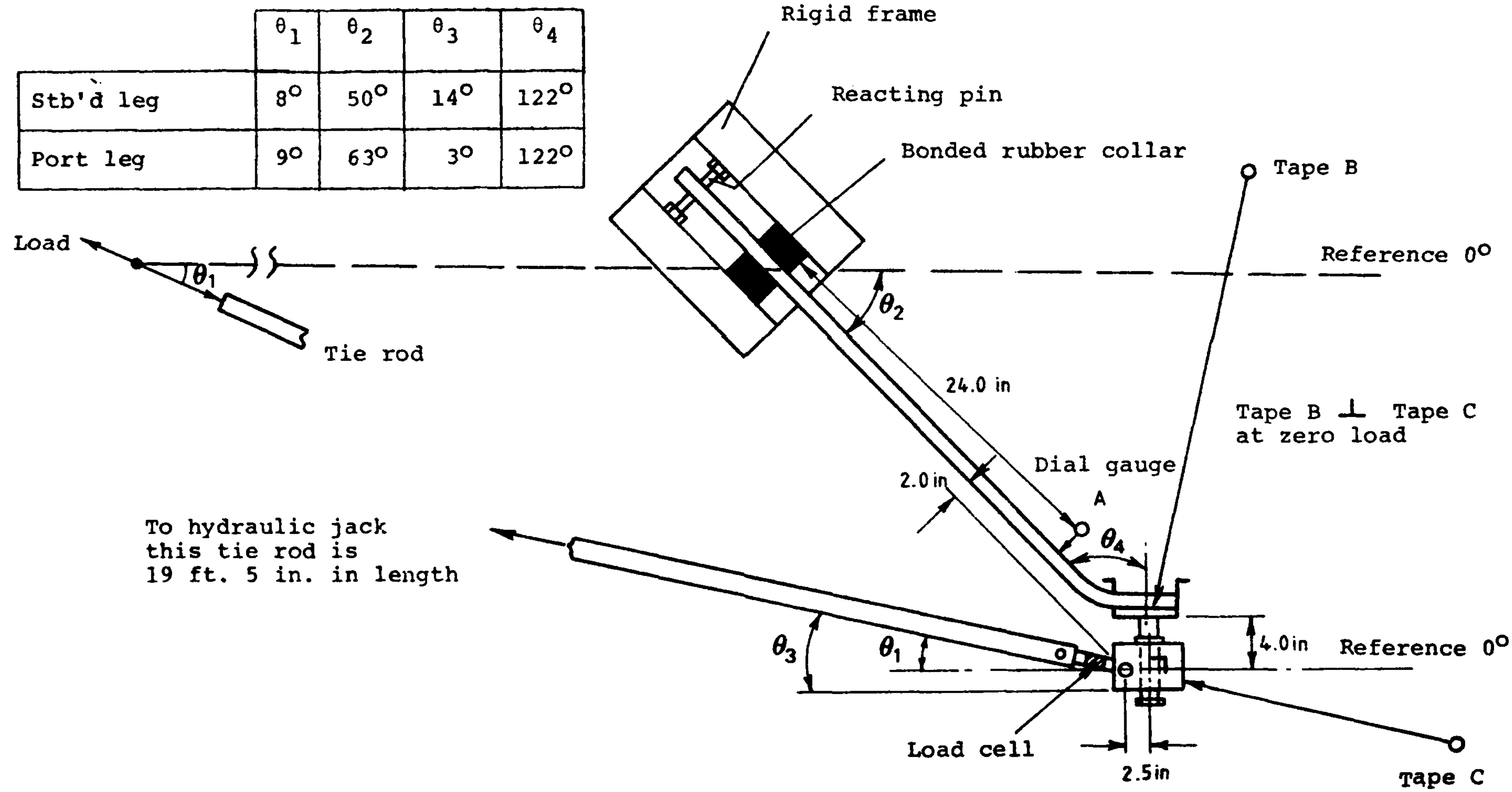


FIG. C1 LOCATIONS OF VERNIER TAPES AND DIAL GAUGES FOR VERTICAL LOAD CALIBRATION

NB For side load cases
tape B measures transverse deflections
and observation of tape deflections
will indicate the side on which the
tape is fixed.

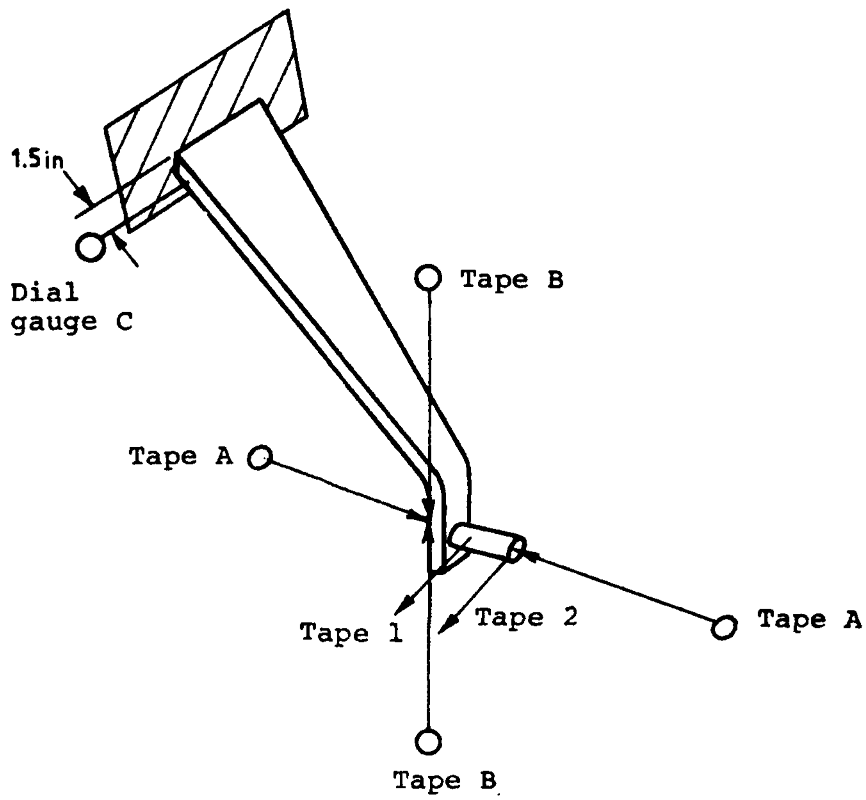


FIG. C2 VERNIER TAPE LOCATIONS FOR SIDE FORCE AND DRAG CALIBRATION

DEFLECTION DATA

VERTICAL LOADING STARBOARD LEG

LOAD (lb)	DIAL GAUGE A (10^{-3} in)	TAPE B (in)	TAPE C (in)	θ_3 (Deg.)
0	125	19.1	13.81	14.0
200	520	18.74	14.19	10.5
400	975	18.34	14.68	9.5
600	1455	17.95	15.12	8.0
800	1943→125*	17.59	15.8	6.5
1000	668	17.25	16.42	4.0
1200	1213	16.95	17.07	1.5

* gauge reset to 125.

STARBOARD LEG

INBOARD SIDE LOADING

LOAD (lb)	TAPE A (in)	TAPE B (in)
0	12.98	10.10
107	13.11	10.23
200	13.25	10.37
300	13.40	10.51
400	13.57	10.66
500	13.75	10.83
0	12.98	10.11
100	13.11	10.23
200	13.25	10.37
300	13.41	10.52
400	13.58	10.68
500	13.75	10.83
0	12.98	10.11

STARBOARD LEG

OUTBOARD SIDE LOADING

LOAD (lb)	TAPE A (in)	TAPE B (in)
0	15.09	14.47
100	15.25	14.31
200	15.41	14.14
300	15.56	13 97
400	15.71	13.81
500	15.83	13.66
0	15.10	14.47
100	15.25	14.29
200	15.39	14.14
300	15.55	13.97
400	15.69	13.81
500	15.83	13.65
0	15.05	14.46

STARBOARD LEG

POSITIVE DRAG

LOAD (lb)	TAPE 1 (in)	TAPE 2 (in)	DIAL GAUGE C (in)
0	11.76	14.74	1.265
70	11.65	14.61	1.263
151	11.47	14.49	1.217
237	11.27	14.15	1.189
337	11.05	13.88	1.140
427	10.83	13.61	1.090
500	10.60	13.34	1.041
0	11.66	14.63	1.246
114	11.44	14.36	1.215
209	11.23	14.10	1.171
308	11.01	13.83	1.127
401	10.79	13.57	1.088
490	10.58	13.32	1.040
0	11.64	14.61	1.242

NEGATIVE DRAG

LOAD (lb)	TAPE 1 (in)	TAPE 2 (in)	DIAL GAUGE C (in)
0	13.00	12.73	1.102
92	12.86	12.55	1.065
192	12.68	12.35	1.039
345	12.25	11.84	0.964
410	12.03	11.57	0.916
490	11.81	11.31	0.874
0	12.70	12.39	1.055
148	12.50	12.13	1.015
245	12.28	11.87	0.969
336	12.06	11.61	0.939
436	11.85	11.36	0.889
0	12.68	12.35	1.047

PORT LEG

VERTICAL LOAD

LOAD (lb)	DIAL GAUGE A (in)	TAPE B (in)	TAPE C (in)	θ_3 (Deg.)
0	15.45	19.00	18.00	3.0
200	15.95	19.41	18.74	2.5
400	16.46	19.84	19.52	1.0
600	16.99	20.27	20.35	-1.0
800	17.55	20.72	21.23	-3.0
1000	18.12	21.18	22.14	-6.0
1200	18.71	21.66	23.08	-7.5
0	15.57	19.41	18.03	3.5
200	16.09	19.83	18.74	2.5
400	16.61	20.27	19.48	1.0
600	17.14	20.71	20.16	-1.0
800	17.69	21.18	21.10	-3.5
1000	18.27	21.66	21.97	-6.0
1200	18.85	22.15	22.89	-7.5
0	15.58	19.42	18.04	3.5

PORT LEG

INBOARD SIDE LOAD

LOAD (lb)	TAPE A (in)	TAPE B (in)
0	15.00	23.00
100	15.13	23.14
200	15.27	23.26
300	15.42	23.41
400	15.57	23.55
500	15.73	23.70
0	15.01	23.01
100	15.14	23.14
200	15.28	23.27
300	15.42	23.41
400	15.58	23.55
500	15.74	23.71
0	15.01	23.01

OUTBOARD SIDE LOAD

LOAD (lb)	TAPE A (in)	TAPE B (in)
0	12.00	16.86
100	12.13	16.72
200	12.27	16.58
300	12.41	16.44
400	12.55	16.29
500	12.68	16.15
0	12.01	16.85
100	12.15	16.71
200	12.28	16.57
300	12.42	16.42
400	12.55	16.28
500	12.68	16.14
0	12.01	16.84

NEGATIVE DRAG

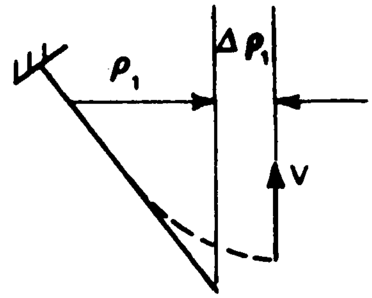
LOAD (lb)	TAPE 1 (in)	TAPE 2 (in)	DIAL GAUGE C (in)
0	11.36	10.89	1.204
127	11.18	10.66	1.164
207	10.98	10.41	1.130
295	10.79	10.19	1.088
450	10.38	9.69	0.994
530	10.16	9.43	0.947
0	11.03	10.48	1.144
134	10.86	10.28	1.114
248	10.77	10.04	1.065
343	10.49	9.83	1.024
437	10.30	9.59	0.979
548	10.08	9.33	0.931
0	11.01	10.46	1.138

POSITIVE DRAG

LOAD (lb)	TAPE 1 (in)	TAPE 2 (in)	DIAL GAUGE C (in)
0	13.62	14.67	0.954
156	13.40	14.39	0.915
269	13.20	14.16	0.868
364	13.02	13.94	0.839
450	12.84	13.71	0.796
540	12.63	13.45	0.764
0	13.55	14.60	0.941
90	13.44	14.45	0.917
200	13.27	14.24	0.888
292	13.09	14.02	0.846
392	12.89	13.76	0.804
500	12.68	12.50	0.765
0	13.54	14.58	0.937

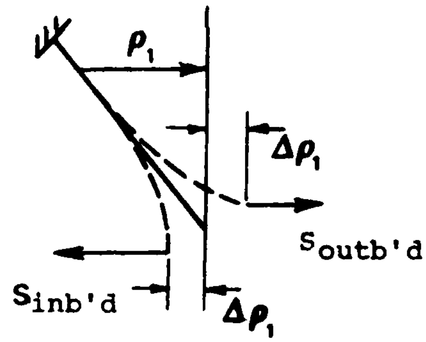
MOMENT ARM (ρ_1,ρ_2) INCREMENTS UNDER LOAD FOR PORT LEG

VERTICAL LOAD (lb)	INCREMENT IN ρ_1 * (inches)	
	RUN 1	RUN 2
0	0	0
200	0.42	0.41
400	0.86	0.84
600	1.30	1.27
800	1.77	1.72
1000	2.25	2.18
1200	2.74	2.68

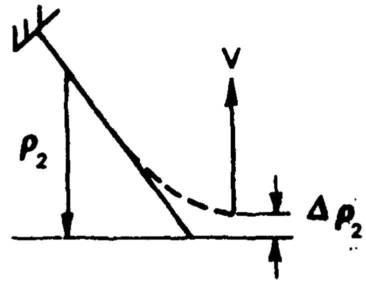


SIDE LOADS

LOAD APPLIED: (lb)	INCREMENT IN ρ_1 * (inches)	
	OUTBOARD	INBOARD
0	0	0
100	0.13	-0.13
200	0.27	-0.27
300	0.41	-0.41
400	0.55	-0.57
500	0.68	-0.73

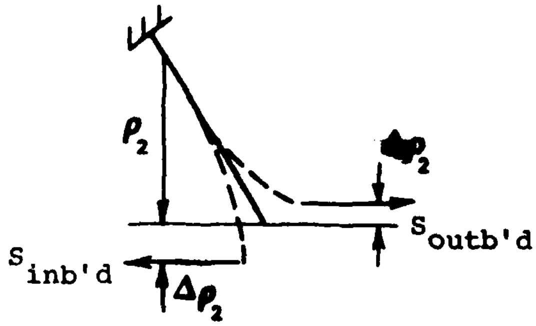


VERTICAL LOAD (lb)	INCREMENT IN ρ_2 * (inches)	
	RUN 1	RUN 2
0	0	0
200	-0.74	-0.71
400	-1.52	-1.45
600	-2.35	-2.13
800	-3.23	-3.07
1000	-4.14	-3.94
1200	-5.08	-4.86



SIDE LOADS

LOAD APPLIED (lb)	INCREMENT IN ρ_2 * (inches)	
	OUTBOARD	INBOARD
0	0	0
100	-0.14	0.14
200	-0.26	0.26
300	-0.42	0.41
400	-0.57	0.55
500	-0.71	0.70



* All these increments were taken from the relevant Vernier tape measurements as recorded in this Appendix. It can be easily seen which tapes were used.

APPENDIX D

ANALYSIS OF VARIANCE FOR DIFFERING RESPONSES

In Table 3 separate slopes have been fitted for various components of strain on the port and starboard legs. Since the legs are the same except for handedness it is plausible to expect the same responses to load even without prior knowledge of the experimental results.

This is checked below by what is an analysis of covariance with emphasis on concomitant variables[1,2]. In this analysis drift or offset corresponds to block (or treatment) effects while response to load is not just a correction but the main point of the test. Since however the calculations are the same they are presented below for the case of drag load vs. strain.

We first distinguish between the centroids of fitted responses of port and starboard legs (i.e. block effects) and then explain these as part of the linear response to load. This explanation amounts to a restructuring of the model. In our case the model is based on a one-way classification and is denoted as Section 3 in the ANOVA table. Comments on the difference between this model and that given in Section 2 are made later.

D1. NOTATION

Where convenient the following notation is used.

y_{ji} i'th observation in block j (e.g. port or stb'd. Block)

x_{ji} corresponding fixed variate (i.e. load)

$X_{j.}, Y_{j.}$ Block totals e.g. $X_{j.} = \sum_{i=1}^{n_j} x_{ji}$

$X.., Y..$ Grand totals $Y.. = \sum_j Y_{j.}$

n_j = Number of observations

$N. = \sum_j n_j$

X_{j2}, Y_{j2}, XY_j Sums of squares and cross products about centroids of block j

$$\text{e.g.} \quad X_{j2} = \sum_{i=1}^{n_j} x_{ji}^2 - X_{j.}^2/n_j$$

$$XY_j = \sum_{i=1}^{n_j} x_{ji} y_{ji} - X_{j.} Y_{j.}/n_j$$

$B_x \; B_y \; B_{xy}$ Block sums and cross products

$$\text{e.g} \quad B_x = \Sigma X_{j.}^2/n_j - X..^2/N.$$

$$B_{xy} = \Sigma X_{j.} Y_{j.}/n_j - X..Y../N.$$

$W_x \; W_y \; W_{xy}$ e.g. $W_x = \sum_j \left(\sum_{i=1}^{n_j} x_{ji}^2 - X_{j.}^2/n_j\right)$

$$W_{xy} = \sum_j \left(\sum_{i=1}^{n_j} x_{ji} y_{ji} - X_{j.} Y_{j.}/n_j\right)$$

Within block sums and cross products.

D2. Covariance Analysis

In this example we use data columns 3,4 of Table 3 to test for significant slope differences. The model used is that of Section 2 in the ANOVA. The block or treatment effects are explained as a block slope while the errors are reduced by a linear within-block effect from the load which is here regarded as a concomitant variable.

Block sum of squares

$$B_y = 269^2/25 + 124^2/25 - (269-124)^2/50$$

$$= 3088.98 \qquad \text{(1 d.f.)}$$

A Block slope

$$\beta_B = \frac{B_{xy}}{B_x} = \frac{(269(794) - 124(-430))/25 - 145(364)/50}{794^2/25 + 430^2/25 - 364^2/50}$$

$$= 9620.64/29963.52 = 0.32107843$$

$$\text{check } SS_{\beta B} = B_{xy}.\beta_B = 3088.98 \qquad \text{(1 d.f.)}$$

Because there are only two blocks, **there remain** no degrees of freedom for offsets from a straight line, explaining why the mean squares B_y and $SS_{\beta B}$ agree.

Combined slope (internal mean slope)

The individual slopes are 0.301313, 0.309695 (Table 3).
These combine as $\frac{W_{xy}}{W_x} = \frac{XY_1 + XY_2}{X_{21} + X_{22}} = \frac{1374247.76}{4493040.56}$

$$\text{i.e. } \beta_w = 0.30586142$$

$$\text{and } SS_{\beta w} = 4493040.56$$

D3. The minimum variance combined slope

Section 3 of the ANOVA postulates one overall slope to be estimated from those above. Using the computations known already

$$\hat{\beta} = \frac{B_{xy} + W_{xy}}{B_x + W_x}$$

$$= \frac{9620.64 + 1374247.76}{29963.52 + 4493040.56}$$

$$= 0.30596223$$

$$\text{and } SS_{\hat{\beta}} = 423411.46 \qquad \text{(1 d.f.)}$$

This is a different model from that of Section D2 in which the block slope and internal slope could differ. The estimator of $\hat{\beta}$ belongs to the same R_2 subspace as the contrasts estimating internal and block slopes. In terms of sums of squares the projection of data onto this subspace R_2 is therefore the same in each model or in terms of the Euclidean norm

$$SS_{\beta B} + SS_{\beta w} = SS_{\hat{\beta}} + SS_{w \text{ vs } B}.$$

Thus

$$S^{\frown}_{w \text{ vs } B} = \text{the difference of block means from combined slope fit}$$

$$= 6.89 \qquad \text{(1 d.f.)}$$

$$\text{and } F_{1,46} = 4.18 \, *$$

which shows a slightly significant slope difference between the combined slope fit and the block slope fit. Also from the ANOVA (part 2) a very highly significant slope difference between the port and starboard leg is found so separate equations will be used for each leg in subsequent analyses.

ANOVA FOR STRAIN vs DRAG REGRESSIONS

Data Columns 3,4 from Table 3

1. SEPARATE LINES

Variability due to port leg line	df	Sum of Squares	Mean Square
Slope	1	233851.23	233851.23
Error	23	7.73	0.3361
Total	24	233858.96	
Starboard leg line			
Slope	1	186556.49	186556.49
Error	23	68.07	2.959
Total	24	186624.56	

2. SEPARATE INTERNAL AND BLOCK SLOPES

Variability due to	df (general)	df	Sum of Squares	F
Between Blocks	k-2	0	0	0
Block slope β_B	1	1	3088.98	
Mean slope β_w	1	1	420329.37	
Between β_j's	k-1	1	78.34	47.54 ***
Error	N-2k	46	75.81	
Total	N-1	49	423572.50	

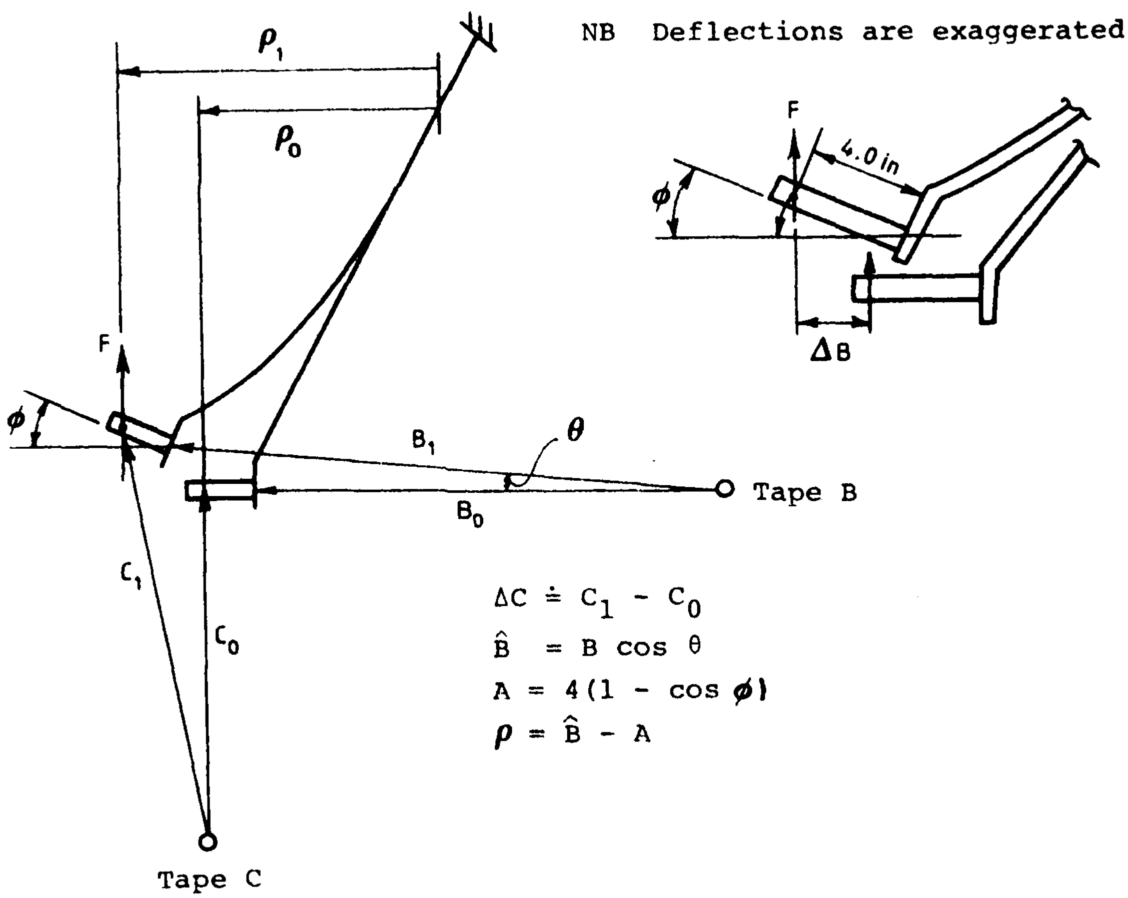
RF-MODEL →

3. ONE OVERALL SLOPE

Variability due to	df (general)	df	Sum of Squares	Mean Square	F
Between Blocks	k-2	0	0	0	
Overall slope $\hat{\beta}$	1	1	423411.46	423411.46	
β_B vs β_w	1	1	6.89		4.19*
Between β_j's	k-1	1	78.34	78.34	47.54 ***
Error	N-2k	46	75.81	1.6480	
Total	N-1	49	423572.50		

TABLE 1

LOAD (lb)	ΔC (in)	θ (Deg.)	B (in)	$\hat{B}$ (in)	θ (Deg.)	A (in)	ρ (in)	BM (ft-lbs)
0	0	0	18.57	18.57	0		18.57	0
200	0.38	1.15	18.93	18.93	3.5	0.01	18.92	315.4
400	0.87	2.58	19.33	19.31	4.5	0.01	19.30	643.33
600	1.31	3.81	19.72	19.68	6.0	0.02	19.70	984.9
800	1.99	5.69	20.08	19.98	7.5	0.03	19.95	1329.8
1000	2.61	7.34	20.42	20.25	10.0	0.06	20.19	1682.7
1200	3.26	9.05	20.72	20.46	12.5	0.09	20.37	2036.7



$\Delta C \doteq C_1 - C_0$

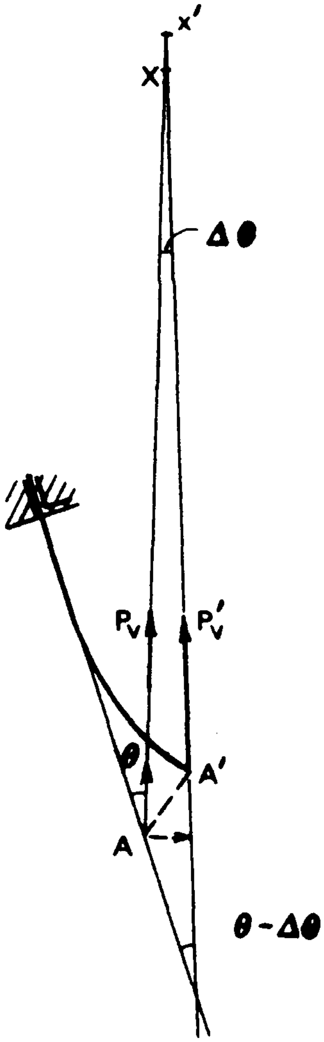
$\hat{B} = B \cos\theta$

$A = 4(1 - \cos\phi)$

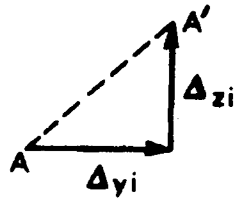
$\rho = \hat{B} - A$

TABLE 2

P (lb)	ΔB (in)	Δθ (Deg.)	θ (Deg.)	P (lb)
0	0	0	42	0
200	0.36	0.09	41.91	148.8
400	0.76	0.19	41.81	298.1
600	1.15	0.28	41.72	447.9
800	1.51	0.37	41.63	597.97
1000	1.85	0.45	41.55	748.4
1200	2.15	0.53	41.47	899.1



NB Deflections are exaggerated



$AX = 233$ in

$$\Delta\theta_i = \tan^{-1} \frac{\Delta y_i}{233} \quad \text{(deg.)}$$

Axial force, $P_i = P_v \cos(\theta - \Delta\theta_i)$

TABLE 3. SUMMARY OF STATISTICS FOR LINEAR REGRESSIONS

	Normal bending moment		Drag force		Torsion		Axial force	
Statistic	Starboard	Port	Starboard	Port	Starboard	Port	Starboard	Port
y_o	16.72	9.235	1.190305	0.36675	0.4583	-0.5000	0.9678	0.3976
$\hat{\beta}$	1.165675	1.109580	0.301313	0.309695	0.122105	0.118385	-0.018081	-0.019152
β_o	1.175771	1.114181	0.301767	0.309630	0.122105	0.118385	-0.016403	-0.018261
r^2	0.9996	0.9999	0.9997	0.99997	0.9999	0.9999	0.96	0.92
Σy^2	47401484	41355559	189519	234474	445251	473360	1903.2645	1158.8243
Σy	24944	18791	269	-124	11	-12	-181.87	-132.43
Σxy	40293959	37112407	627689	757235	3879040	3760860	-112877.2206	-61064
Σx^2	34270248	33309150	2080044	2445610	31768000	31768000	6881601.088	3344020
Σx	20696	16594	794	-430	0	0	11932.12	7496
n	49	41	25	25	24	24	35	28

Where:

$$\text{slope } (\hat{\beta}) = \frac{\Sigma xy - \Sigma x \Sigma y/n}{\Sigma x^2 - (\Sigma x)^2/n}$$

slope of line forced through origin $(\beta_o) = \Sigma xy/\Sigma x^2$

intercept $(y_o) = \bar{y} - \hat{\beta}\,\bar{x}$ and in all cases x = strain in units of micro-strain
any y = variable tabulated above in Imperial units.

TABLE 4. INCLINATION OF UNDERCARRIAGE LEGS FOR THREE LOADING CONDITIONS.

LOADING CONDITION (see plate 4)	INCLINOMETER READING (DEGREES)	
	Starboard	Port
C	33,34,35.5	34,35,36
B	36	37.5
A	39	40

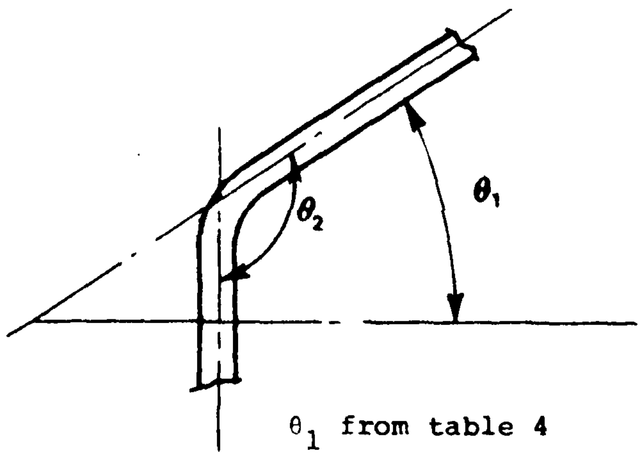
The three values given for condition A are measurements taken near the wheel, approximately mid-length of leg and near the fixed end. The single measurements were taken near the wheel.

Conditions are:

A Aircraft suspendend

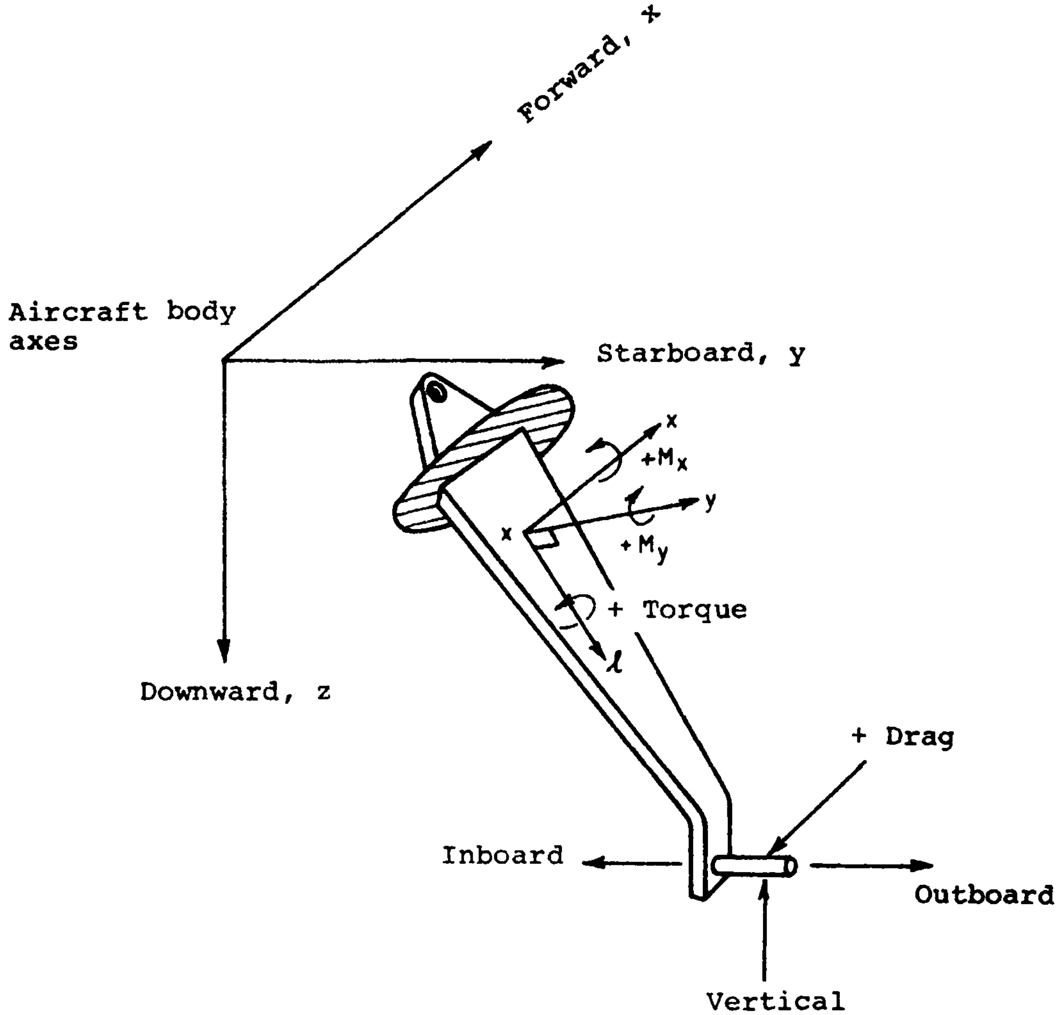
B Touchdown

C Ground Roll



θ_1 from table 4

$\theta_2 = 121.5^{\circ}$ at zero load



Positive torque is clockwise for starboard leg and anti-clockwise for port leg when viewed along l-axis.
Positive drag forces produce positive transverse bending moments M_y.
Vertical and outboard side forces produce positive normal bending moments M_x.
Compressive axial forces are considered positive.

FIG. 1 SIGN CONVENTION FOR FORCES, MOMENTS AND TORQUE

Normal bending strain (gauge 46 BE) ε_x
vs
Normal bending moment for starb'd leg

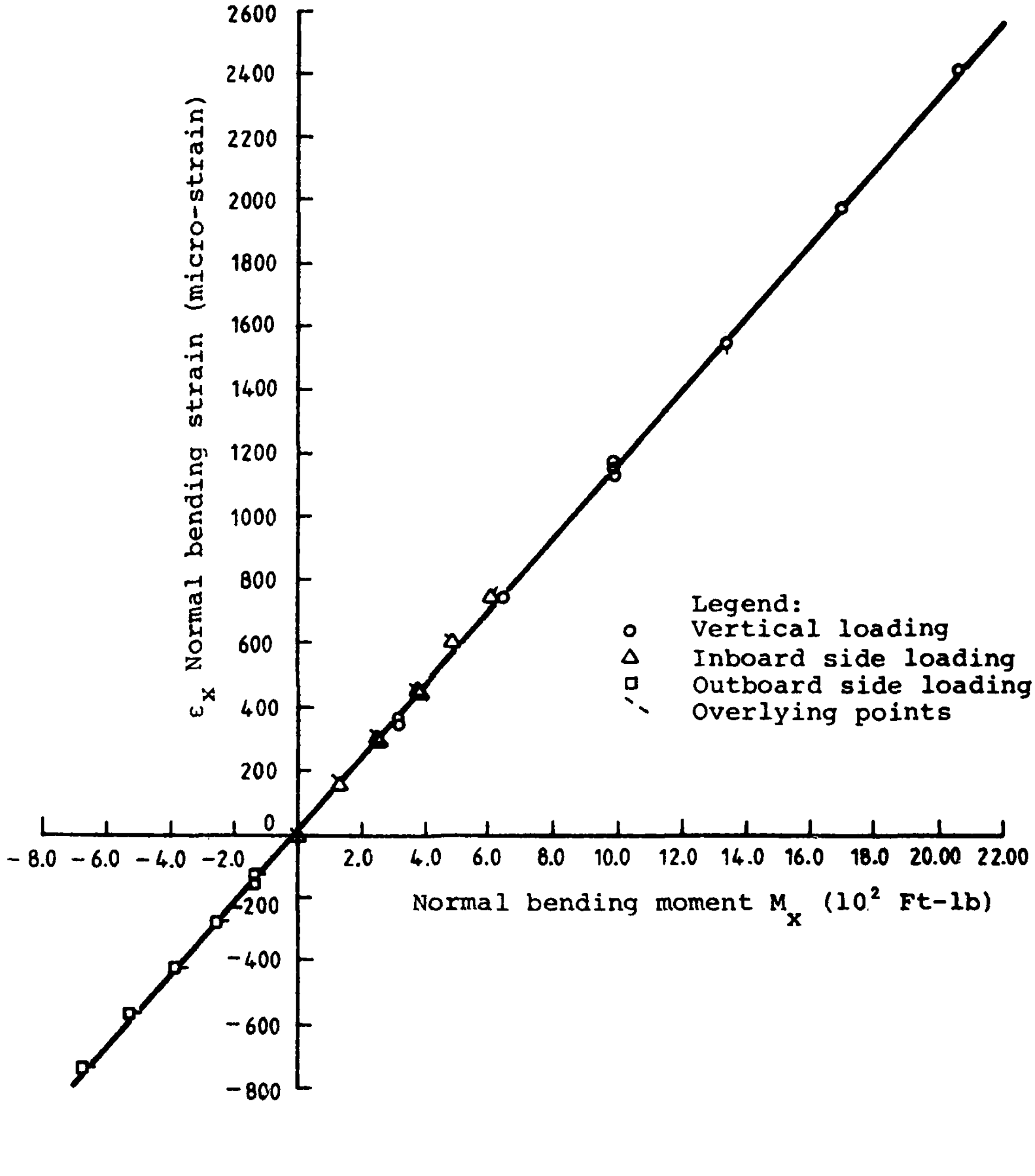


FIG. 2 STRAIN vs BENDING MOMENT ABOUT THE x-AXIS FOR STARBOARD LEG

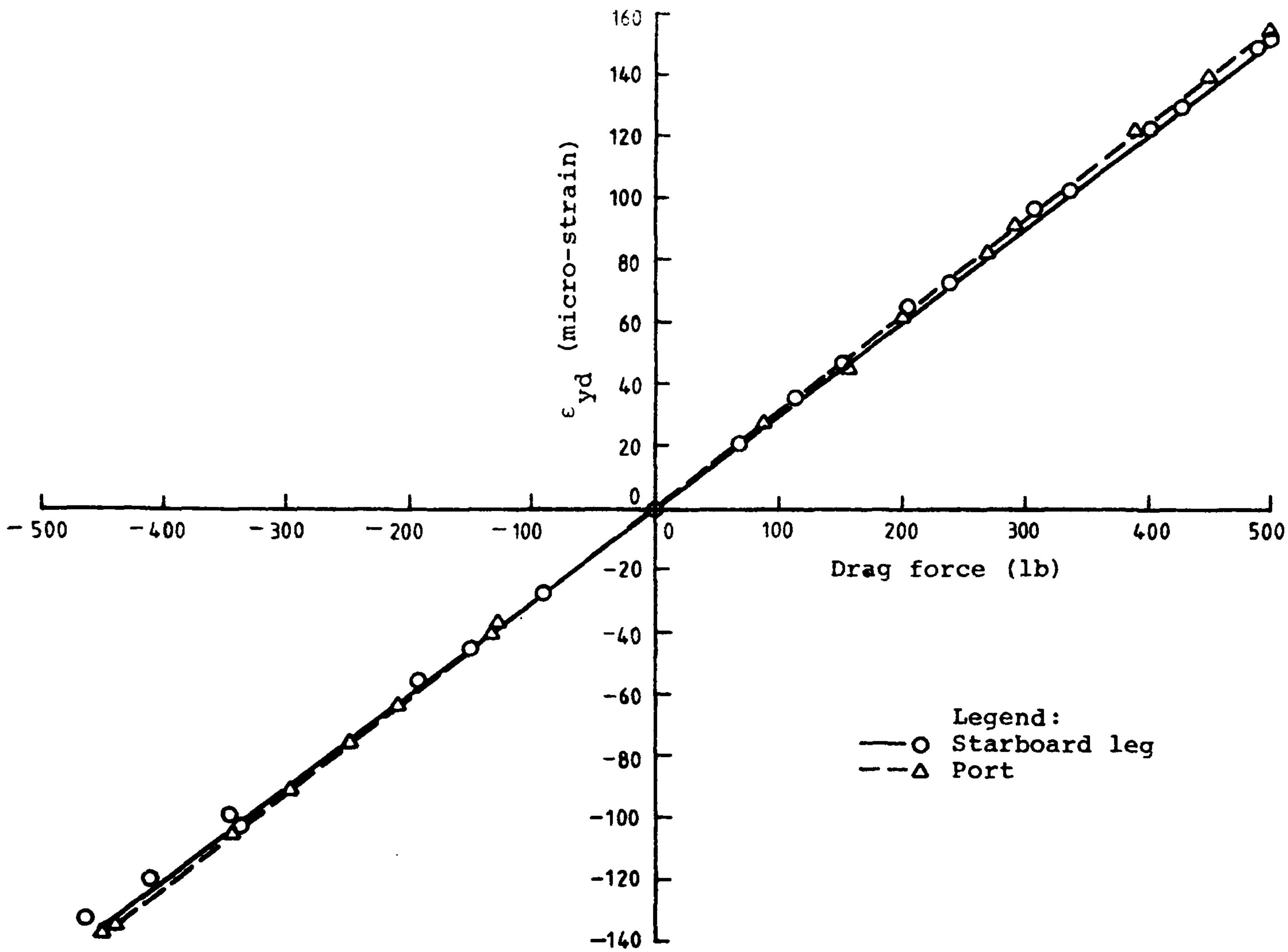


FIG. 3 ε_{yd} vs DRAG FORCE ON UNDERCARRIAGE

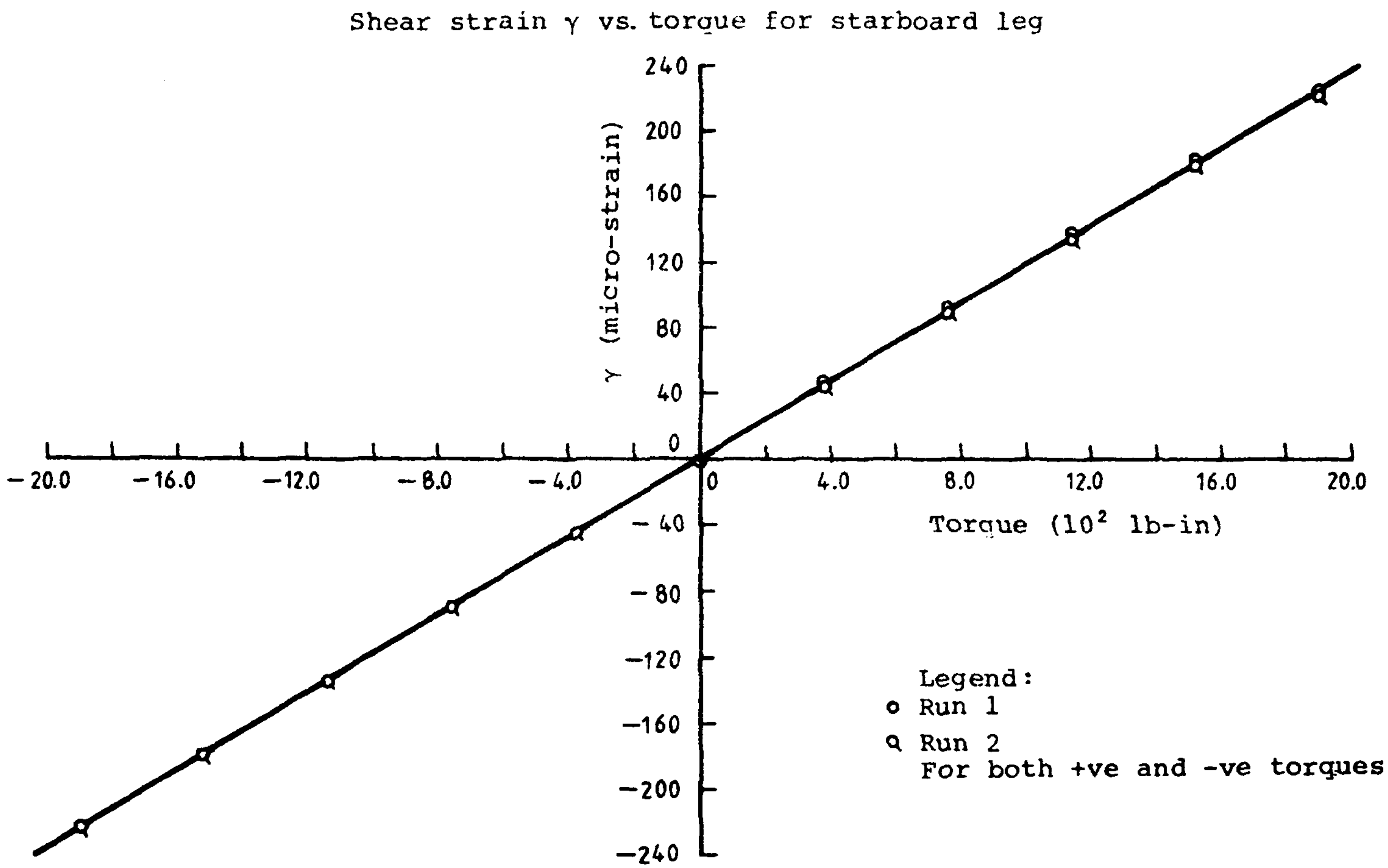


FIG. 4 SHEAR STRAIN vs. TORQUE FOR STARBOARD LEG

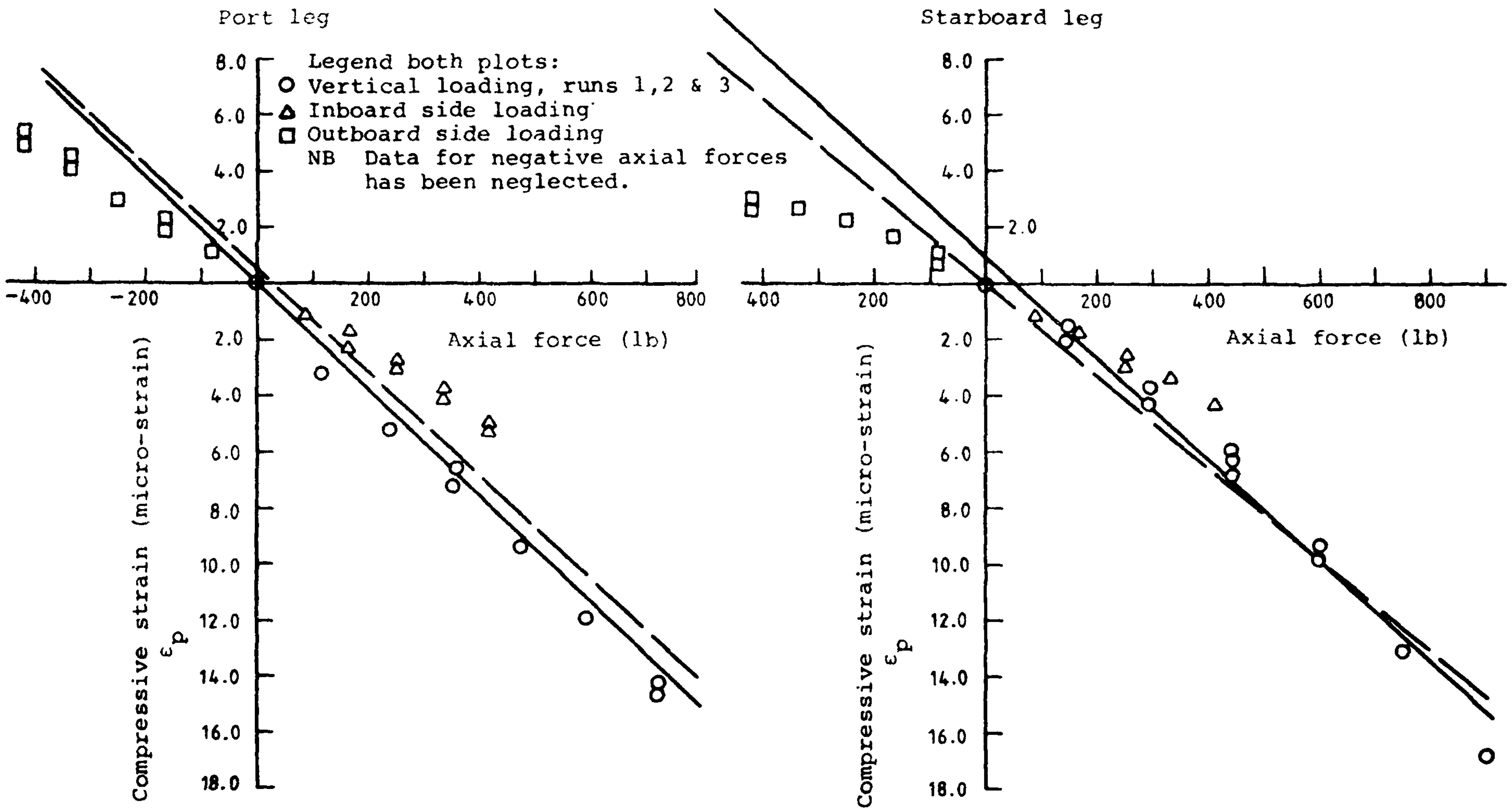


FIG. 5 COMPRESSIVE AXIAL STRAINS (ε_p, GAUGES 43,44CE) vs AXIAL FORCE FOR PORT AND STARBOARD LEGS

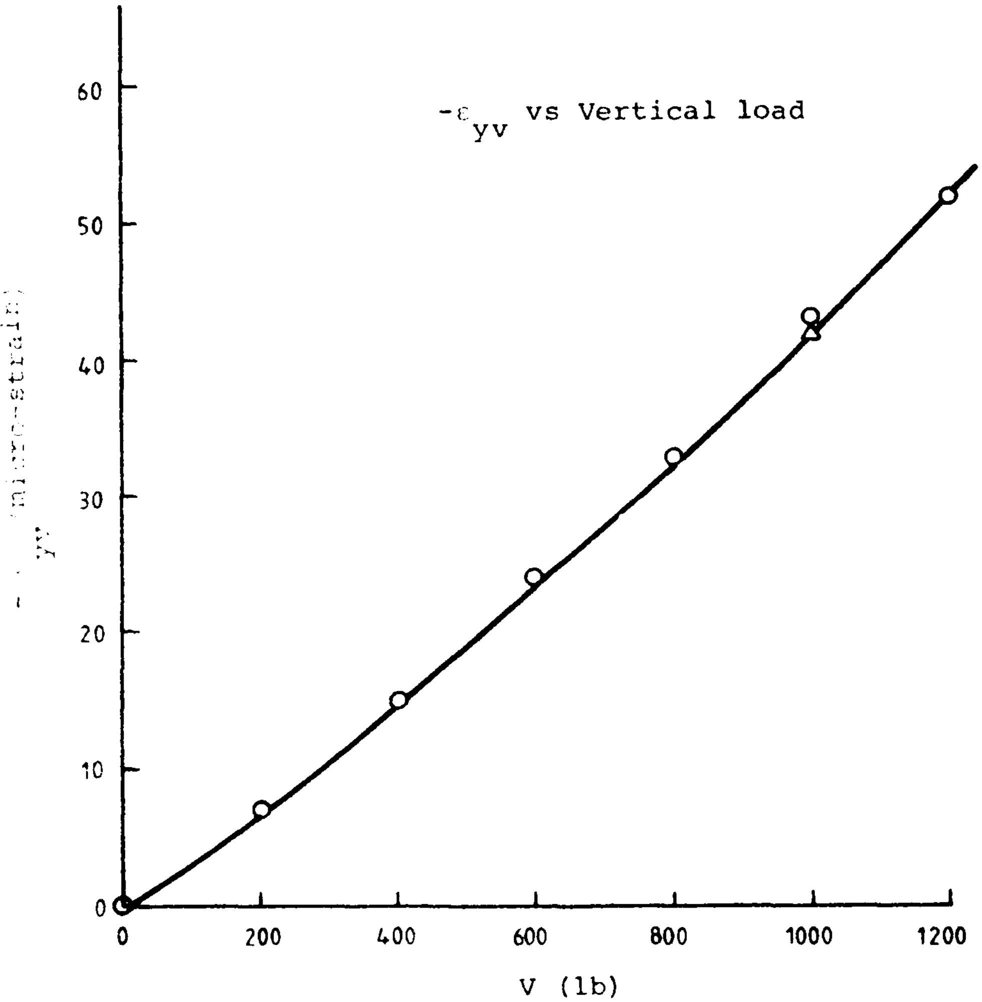


FIG. 6 TRANSVERSE BENDING STRAIN RESPONSE TO VERTICAL LOAD

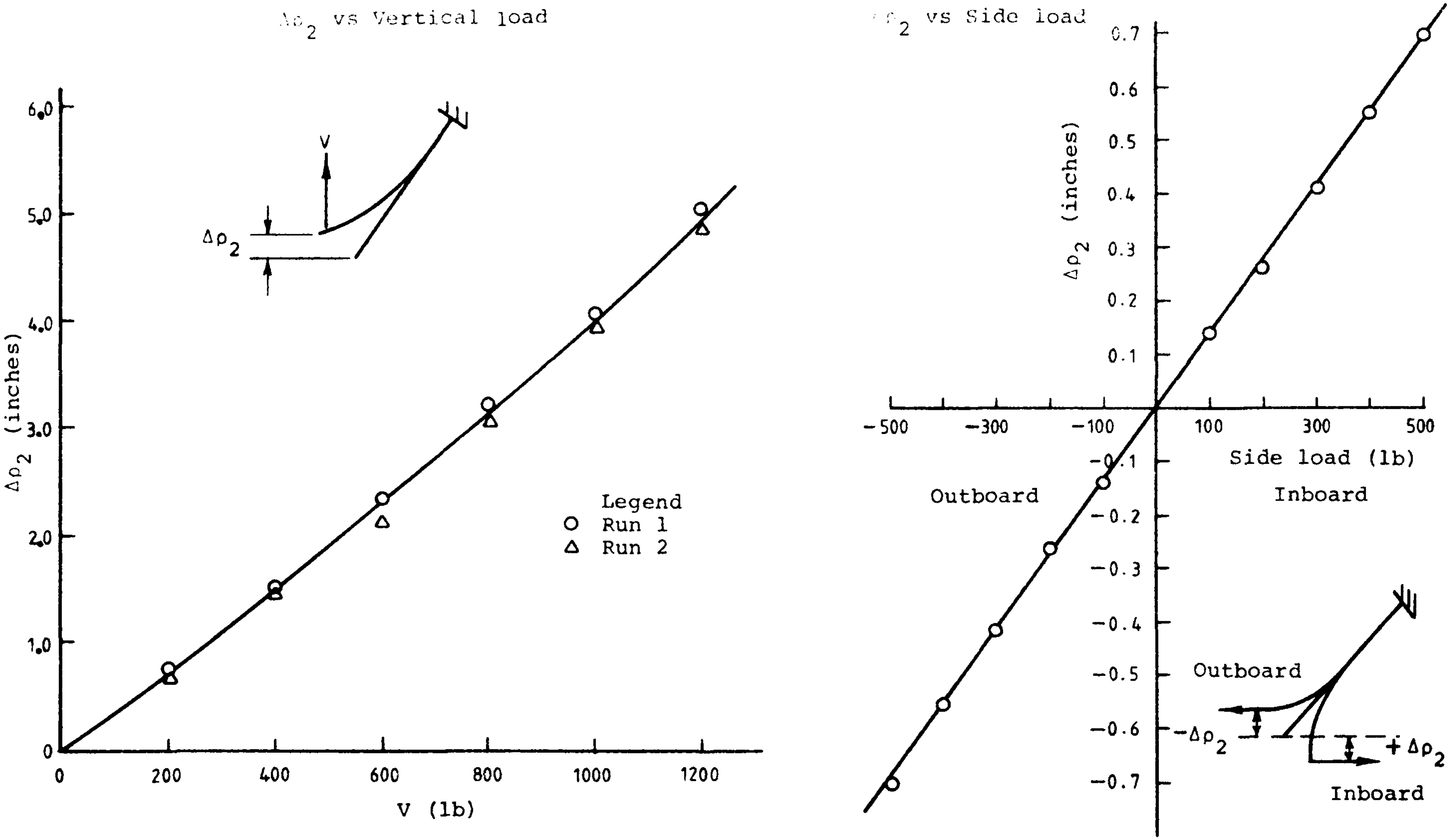


FIG. 7 PLOT OF $\Delta\rho_2$ AGAINST VERTICAL AND SIDE LOADS

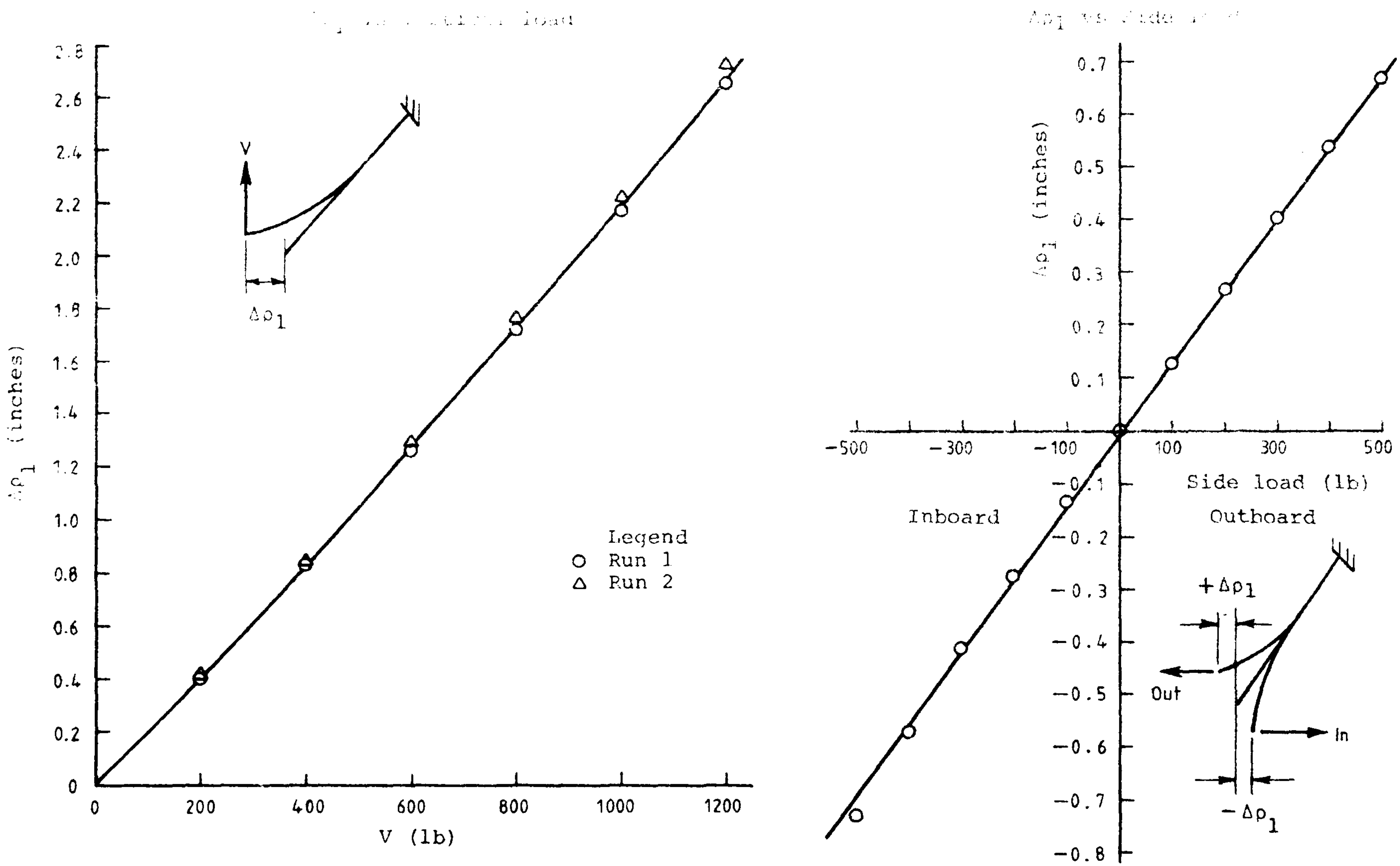


FIG. 8 PLOT OF $\Delta\rho_1$ AGAINST VERTICAL AND SIDE LOADS

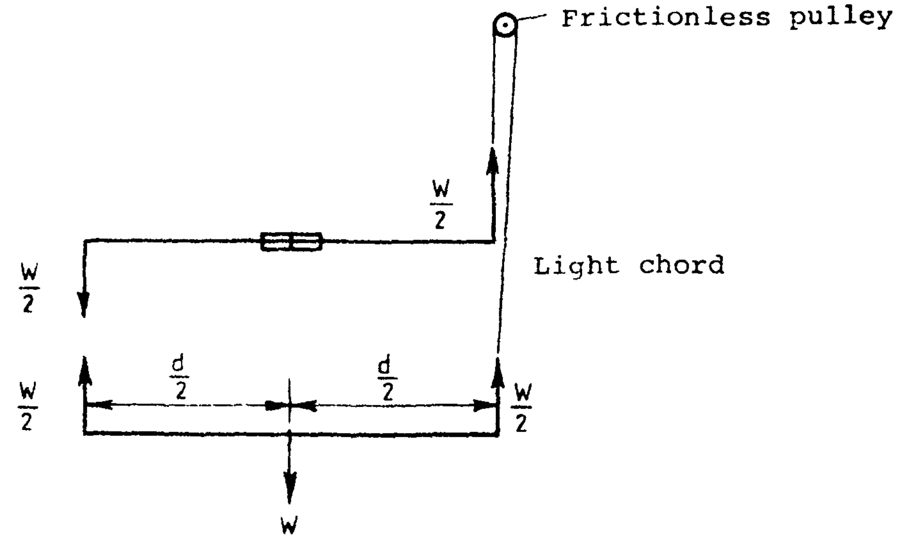


FIG. 9 IDEAL RIG TO APPLY PURE TORSION

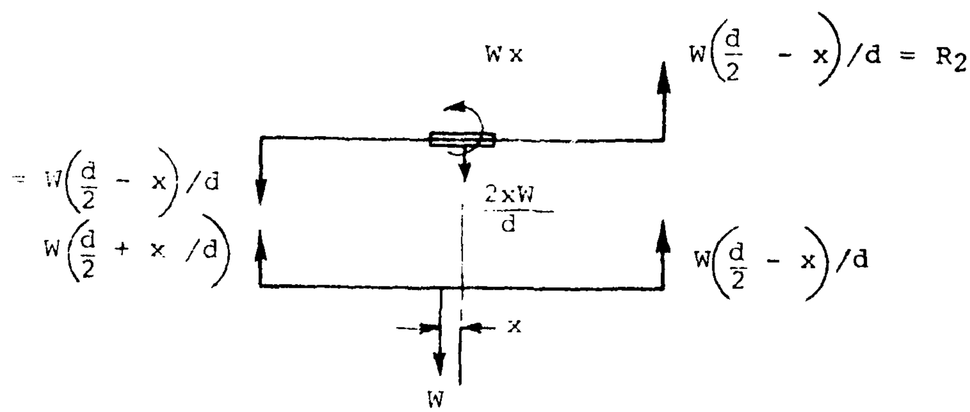
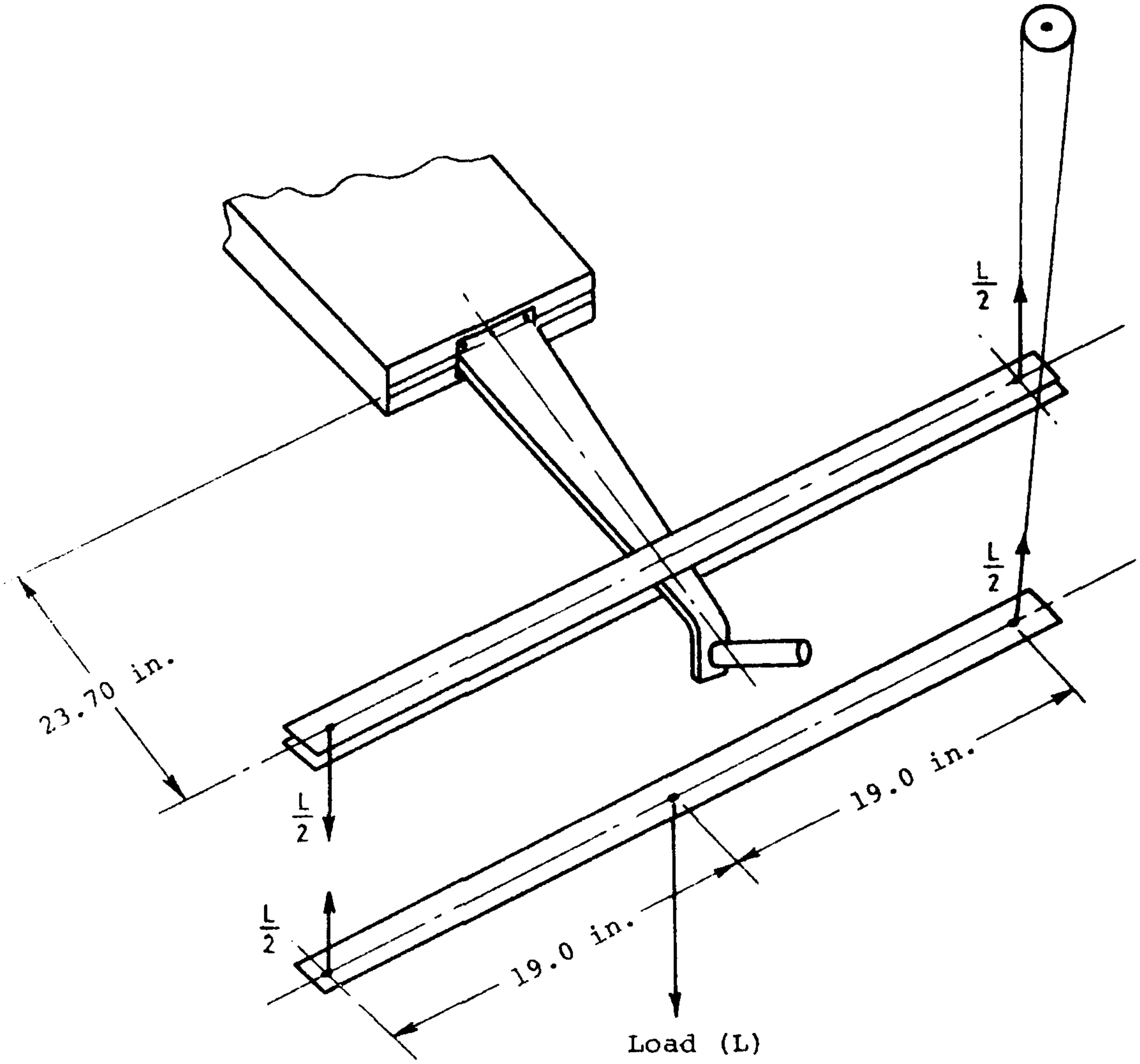


FIG. 10 PRACTICAL TORSION RIG WITH $R_1 \neq R_2$



NB In theory the torque applied to the leg is $\left(\frac{L}{2} + \frac{W}{2}\right)$ x 38.0 lb-in
Where W is weight of loading frame = 19.5 lb.

FIG. 11 RIG USED TO APPLY TORSION TO THE UNDERCARRIAGE LEG

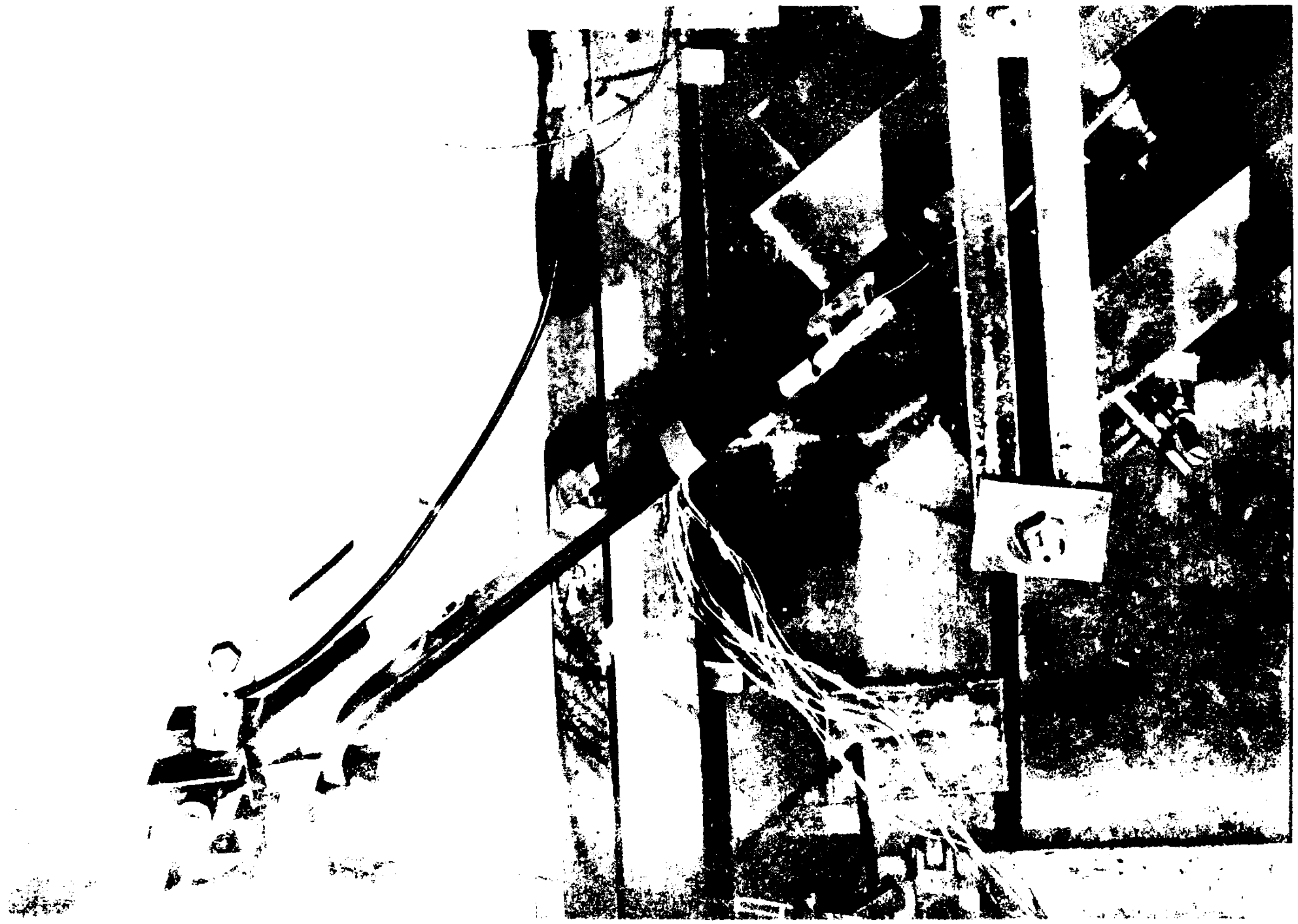


PLATE 1 VIEW OF TEST RIG FROM ABOVE TEST CASE IS VERTICAL LOADING OF STARBOARD LEG

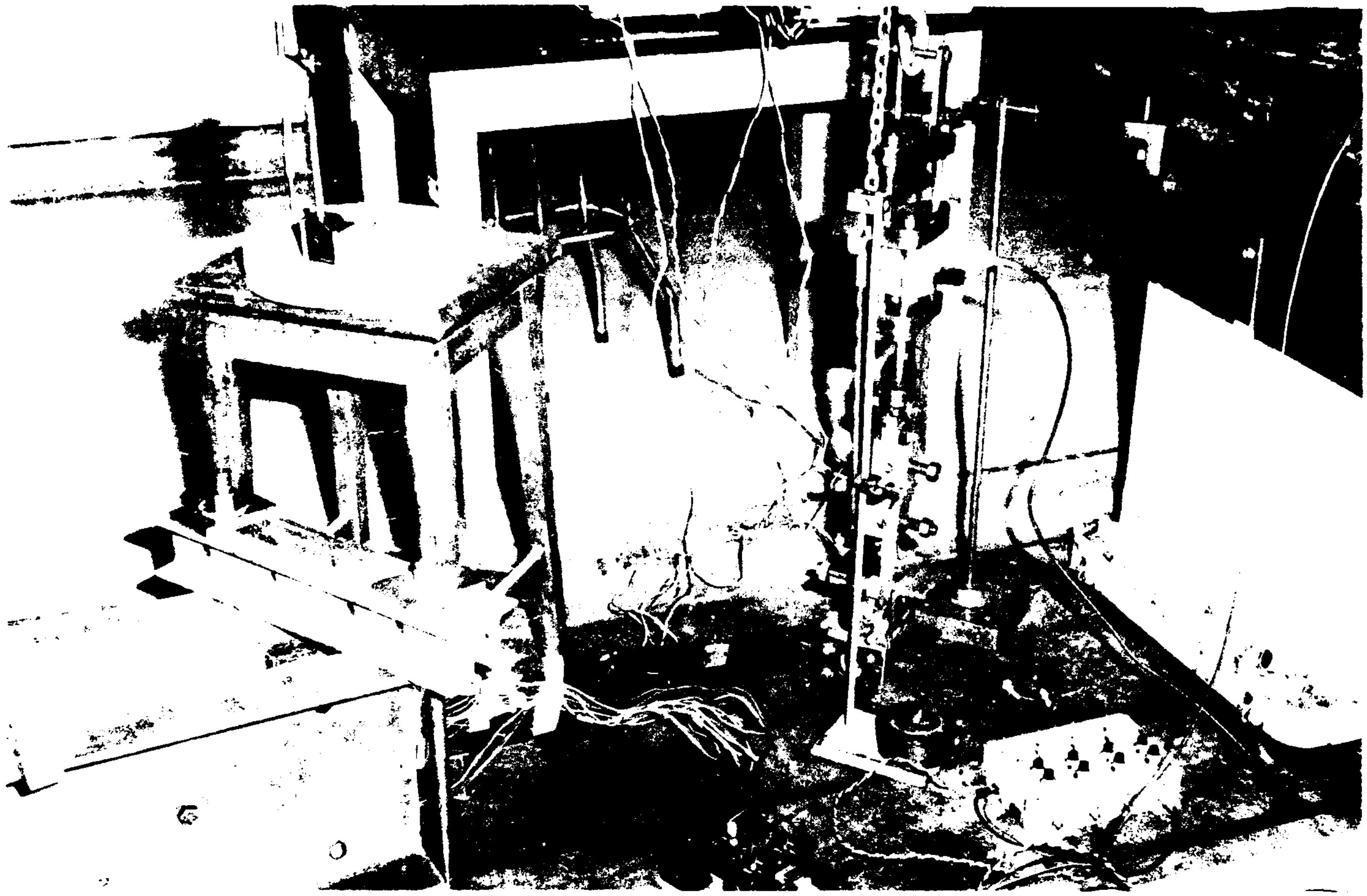


PLATE 2 PORT LEG SUBJECT TO NEGATIVE DRAG LOAD

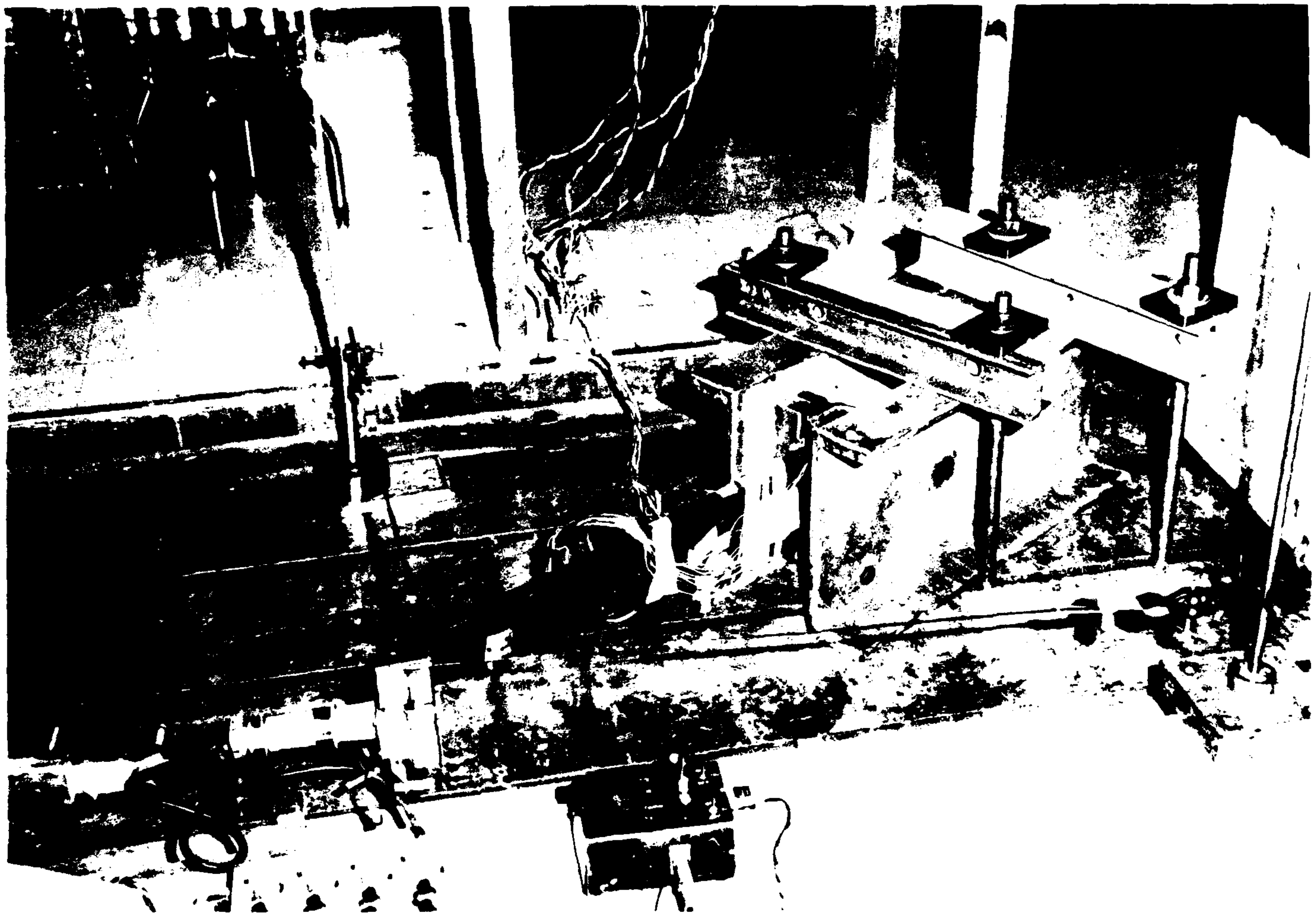


PLATE 3 STARBOARD LEG SUBJECT TO OUTBOARD SIDE LOAD

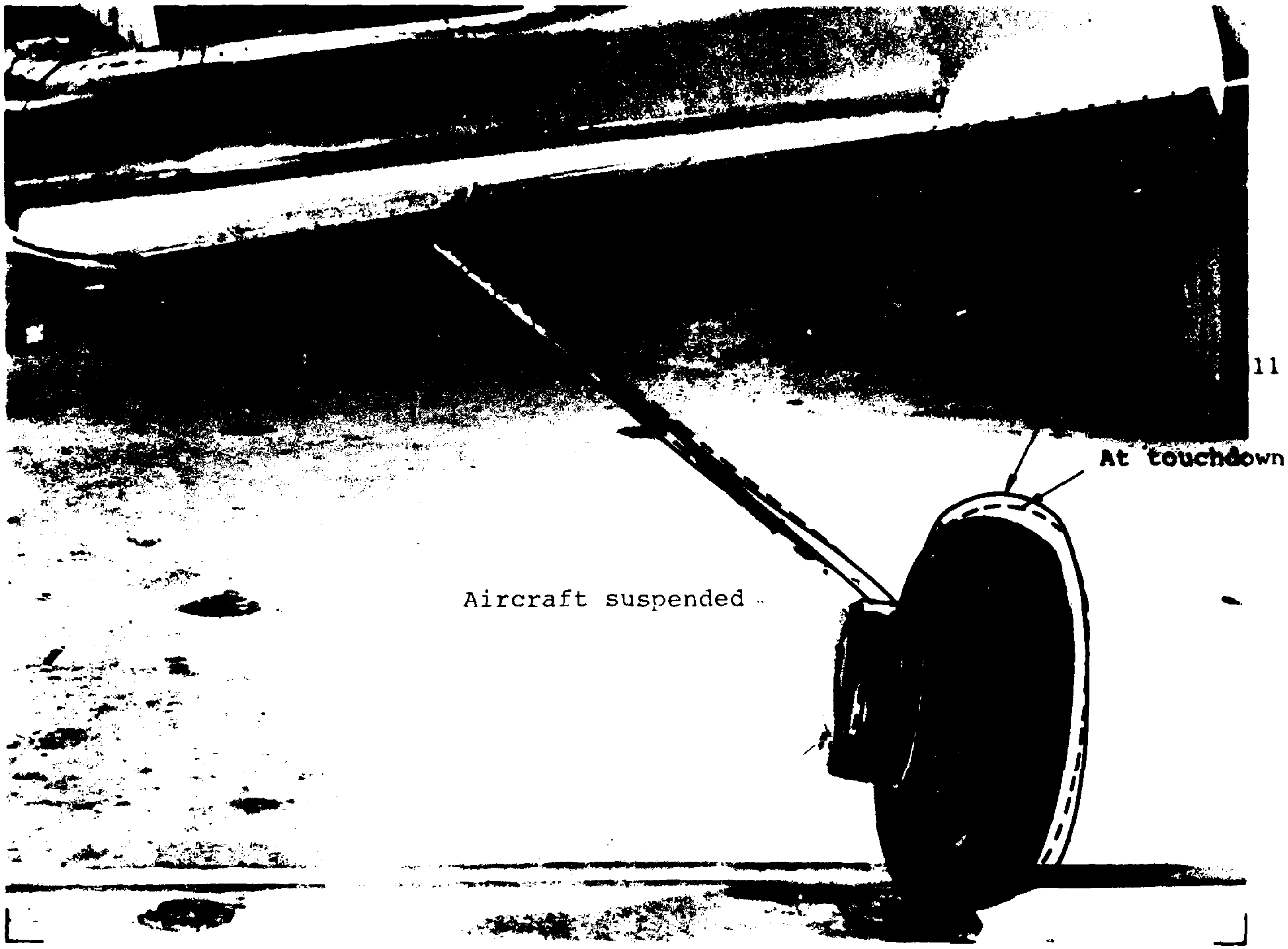


PLATE 4 DEFLECTIONS WITH NO LOAD, AT TOUCHDOWN, AFTER GROUND ROLL

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