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SUMMARY

An American statistical technique was evolved for the measurement of flight loads, but is of restricted use when applied to low aspect ratio multispar structures. This Report describes a modification in which a mixture of distributed loads (assembled by superposition of individual loads) and individual loads together with their corresponding strain gauge responses is used as a regression sample. This method is demonstrated on test results from a flight programme to measure fin loads on a Lightning aircraft.

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CONTENTS

1 INTRODUCTION

The difficulties in applying an American statistical technique[1] for the measurement of flight loads on low aspect ratio structures have been discussed in an earlier note[2]. Therein it was concluded that regression equations based on distributed load data were preferable to those based on the original individual load data. A more recent flight programme to measure the fin loads on a Lightning aircraft has led to a further modification in order to include steady sideslip conditions of flight. These developments and the calibration technique as used on the Lightning fin are discussed in this Report.

2 CHOICE OF SAMPLE

Ideally, the magnitude of a particular flight loading could be established by the direct comparison of the responses of installed strain gauges with those obtained in ground tests in which the flight load distribution was applied to the structure. This procedure could be very expensive if a variety of flight conditions were to be investigated and would require a fairly precise knowledge of the various load distributions. In general, it can be expected that this knowledge is not available and recourse has to be made to techniques which allow some variations in either the magnitudes or distributions of the loadings. Such techniques are available in regression analysis in which equations are fitted to samples of appropriate data.

The NACA method[1] was the first application of regression analysis to the problem of the interpretation of strain measurements as flight loads. It uses a sample of gauge responses obtained from the successive application of an individual load at a number of stations on the structure. The gauges are usually installed across a section of the structure to measure the shear and bending strains in the main structural members. These quantities are dependent on the position of the calibration load in a simple or complex manner according to the detail design of the structure. It is then assumed that the responses $\mu_1\ \mu_2 \ldots$ of the gauges $G_1\ G_2 \ldots$ can be combined such that, for example,

$$M = \beta_{11}\,\mu_1 + \beta_{12}\,\mu_2 + \beta_{13}\,\mu_3 \ldots$$

where M is the overall bending moment at the chosen section and β_{11}, β_{12}, etc. are coefficients obtained from the calibration data by regression analysis. Similar equations are obtained for the shear (V) and the torque (T).

There are two possible arguments for the application of these regressions in the estimation of a flight loading:

(a) a statistical argument that the individual load sample is representative of the whole population of loadings and that any flight loading must be a member of that population.

(b) an argument that the flight loading is the summation of proportions of the individual loads. Each of these can be estimated by the regressions and consequently so also can their sum be estimated.

It is extremely difficult to establish the validity of (a) and also to accept that a distributed loading with a centre of pressure outside the sample is also a member of the sample. Thus any statistical forecast of the standard error of the estimate of such a distributed loading from the variances and covariances of the regression analysis would be dubious.

The justification for (b) requires the structure to conform with the principle of superposition and the mesh size of the calibration to provide satisfactory representations of the continuously distributed loadings encountered in flight and of the associated gauge responses. There is nothing in this argument however which justifies the acceptance of the standard error of the estimate which has been rejected above. Thus, whilst the regressions will cover a limitless range of centres of pressure, there is no statistical method of assessing the accuracy of its performance. In practice the accuracy of estimation of the unknown flight loading from the gauge responses can be assessed from the performance of the regression on similar distributed loadings assembled by superposition of the original calibration data.

It might be argued that the distributed loading data could be used for the sample, but there would still remain the difficulty of establishing that this sample is reasonably representative of the whole population and it is not practicable in this case to assume that any other loading is the summation of proportions of the particular members of the sample.

It is expedient therefore to include distributed loadings with the individual load sample and obtain a regression for the mixture of distributed and individual loads. The residual (actual load - estimated load) for each member can be obtained directly by the computer programme. The inclusion of distributed loadings also has the advantage of biassing the regressions towards the loadings expected in flight. However, it is not permissible to use statistical theory for the estimates of the accuracy of a general prediction because the members of the sample, through the inclusion of the distributed loadings, are no longer independent. The residuals of the distributed loadings can provide an indication of the accuracy of the regression for changes in the distributions.

The acceptance of similar accuracies for flight loadings demands a reasonable matching of the flight responses with the appropriate members of the sample.

3 DATA USED FOR LOAD ANALYSIS OF THE LIGHTNING FIN

3.1 Individual load sample

The calibration responses of the strain gauges, the positions of which are shown in Fig.1, are given in Tables 1 and 2 for the pre-flight and post-flight calibrations respectively, together with the associated bending moment (M), shear (V) and torque (T). Details of these calibrations are given in Appendix A. Bending moment values are referred to the strain gauge section axis and torque values are referred to an axis 85·25 in (2·165 m) forward of spar 5 in Tables 1-4. Zero values of M, V and T indicate that the loading pad was inboard of the gauge section.

3.2 Distributed load sample

As discussed in section 2 above, in order to provide a better estimate of flight loads, it is necessary to introduce a distributed load sample. Theoretical distributions of loads due to sideslip, rudder, gust and fishtail manoeuvres were used to provide the proportions of load on the calibration pads appropriate to these loadings. The total gauge responses were then assembled by superposition of the responses due to the load on each pad. These basic responses are shown in Figs.2 and 3. The individual pad loads were varied about their theoretical values in order to provide a range of loadings with different centres of pressure. These responses are given in Tables 3 and 4 together with the associated M, V and T values for the pre-flight and post-flight calibrations. The centres of pressure of these loads are shown in Fig.4 together with the estimated centres of pressure from the second calibration regressions (see section 3.4 and Table 5).

3.3 Mixed load sample

The single load sample and a selection from the distributed load sample were used as a mixed load sample from which regression equations for calculating the flight loads were obtained. The selected rows from the distributed load samples are shown in the first column of Tables 3 and 4 (Nos.1-15).

3.4 Regression equations

Equations for M, V and T were obtained by fitting regressions containing the twelve gauges to the sample matrices and successively discarding those gauges shown to be irrelevant or redundant. These equations are shown in tabular form in Table 5.

3.4.1 Choice of torque axis

Estimates of torque using regression equations based on the axis given in section 3.1 were of low accuracy and were improved by using regression equations based on an axis 28·75 in (0·73 m) aft of spar 5 for the individual load data and 5·25 in (0·133 m) forward of spar 5 for the mixed load data.

The bending moment axis is defined by the strain gauge positions. The torque axis cannot be so defined and a preliminary choice is an arbitrary one. Were it not for the loading points inboard of the strain gauge positions the choice would be comparatively simple: an arbitrary axis would be chosen, a regression equation found including a constant term, redundant or irrelevant gauges would be eliminated and the axis transferred to a position which reduced this constant to zero. With the introduction of inboard loading points in the data the above method has to be modified because, although, as before, as each gauge is eliminated from the regression equation the position of the torque axis is altered (as shown by the constant term), when the torque axis is translated to eliminate the constant term the redundancies or irrelevancies of the gauges change considerably.

There would appear to be no absolute choice of torque axis which could be found easily but the following method has been used with reasonable success for data including mixed loads. Regression equations containing all gauges are evaluated for a succession of torque axes, the constant being suppressed. The standard error of regression (σ) is then plotted against axis position and the regression equation found at the axis giving the minimum standard error. Redundant or irrelevant gauges are then eliminated from this regression.

4 DISTRIBUTED LOAD CALIBRATIONS

Two distributed loadings, as described in Appendix A, section A.2.2, were applied to the fin during the post-flight calibrations. The first distribution simulated a gust loading and the second applied a torque loading with a forward centre of pressure. The gauge responses are given in Tables 6 and 7 and can be compared with the responses obtained from the superposition of the individual load data. In general, there is very good agreement between the sets of responses and this confirmed that the principle of superposition could be applied to the structure. The responses due to the distributed loadings, after scaling to an applied load of 1335 lb (606 kg), are plotted in Figs.5 and 6 together with the spread in the responses of the members of the sample (Table 4) which have adjacent centres of pressure. There is reasonable agreement for the simulated gust loading but there are large differences in the corresponding responses of the shear gauges for the torque loading case. This could be expected from the relatively crude system (a total of 8 load positions) used in applying the distributed load to the fin compared with the 27 loads used to obtain the distributed load sample of Table 4.

Nevertheless, the regressions of Table 5 were used to estimate the shear, bending moment and torque from the measured responses and the corresponding centres of pressure; these are compared with the known loadings in Tables 6 and 7. The errors are presented both as percentages of shear, bending moment and torque and also, with more significance, as errors in the position of the centre of pressure. The large percentage error in the torque estimation for the simulated gust loading is associated with the small value of torque actually applied in this case and thus tends to be misleading.

The performance of the regressions on the members of the distributed load sample has been assessed from the residuals and the latter are expressed in Fig.7 as percentage errors in the basic parameters, M, V and T, and as errors in the positioning of the centre of pressure in Fig.8. The analysis of the two directly applied distributions tend to substantiate the conclusion that the regressions should estimate the flight loads on the Lightning fin to within ±5% or, alternatively, to within ±2 in (±0·05 m).

5 FLIGHT RECORDS

5.1 Range of tests

The flight conditions investigated were steady sideslips, rolls, passing manoeuvres with another Lightning aircraft and level flight in turbulence. This Report is concerned primarily with the technique of flight load measurement and the discussion is restricted to the interpretation of gauge responses in steady sideslip and roll conditions.

5.2 Analysis of flight records

The traces were read on Oscar trace readers which automatically converted the readings to digit values corresponding to the ground calibration recorder scale. The regression equations based on the post-flight calibration, Table 5, were used to obtain estimates of the flight loads and the appropriate corrections were made for acceleration errors on the galvanometers (see Appendix A, section A.2.4).

Typical examples of analysed flight records are given in Figs.9-16. Figs.9 and 10 show the gauge responses in steady sideslips to port and starboard together with the responses of distributed loads obtained by interpolation from the sample matrix for the same estimated centres of pressure. The large difference in response of gauge 9 (Fig.9) between the sample and the flight is reflected in the basic response for 1° sideslip shown in Fig.2. This is due to the very large response of the gauge to the calibration loading on pad 22 which provides about 16% of the total basic response. This effect could be lessened by a more extensive ground calibration and is mentioned below in section 6. Flight responses in steady sideslips to starboard are all characterised by a large response of gauge 9 associated with a reduced response of gauge 7. This effect is also noticed in sideslips to port but to a lesser extent.

Figs.11 and 12, and 15 and 16 show the time histories of the estimated shears and centres of pressure during rolls to port and starboard at $M = 0{\cdot}9$ and $M = 1{\cdot}7$ respectively. Figs.13 and 14 show the distributions of the gauge responses across the section for the maximum shears in each case. The sample used in the regression analysis did not include rolling cases and it is not possible to assess the accuracy of the estimation by interpolation. However the scaled responses in Figs.13 and 14 are not very different from those in typical gust loadings (Fig.5) and consequently it is reasonable to assume a similar accuracy.

6 COMPARISON OF PRE-FLIGHT AND POST-FLIGHT CALIBRATIONS

The Lightning fin is a 5 spar structure (Fig.1); the spars are mounted vertically from fuselage frames and ribs run horizontally between the front and rear shear walls which, with the skins, complete the main structure. A leading edge structure of skin and ribs normal to the front shear wall is attached to the front shear wall. The 5 spars transmit both shear and bending moments into the fuselage whereas the front and rear shear walls have only a shear attachment. The load positions were, in general, at the spar-rib intersections.

The gauge responses in the pre-flight and post-flight calibrations (Tables 1 and 2) are generally similar, but there are more responses whose differences between the two calibrations are significantly higher than a probability distribution calculation indicated. Sensitivity to small changes in pad position could be expected where there is a large change of response with position of the load as when the load is very close to the gauge station (e.g. pad 16, gauges 1 and 2). There are alternative load paths for the torque transfer into the fuselage and the discrepancies for the two calibrations at pads 65 and 66, which are maximum bending moment and maximum torque conditions, may be explained by a change in the stiffness of the fin-skin and fuselage attachment.

These differences could have been reduced by decreasing the mesh size in these areas and this would allow an averaging of responses when the distributed loads are assembled from superposed individual load data. It would be preferable to average the extra calibration data for inclusion in the individual load part of the sample as their separate inclusion would over-emphasise the local effects.

7 CONCLUSIONS

The accuracy with which flight loads can be estimated on a low aspect ratio multispar structure is poor for a regression based on a sample using only individual calibration loads. It is also difficult to justify the use of regression equations based entirely on a distributed load sample and better accuracy is obtained from regressions which have been fitted to a mixed sample of individual and distributed loads. Furthermore the performance of the regression equation on the distributed load items can be used in an interpolation method to assess the accuracy of the estimate of a flight loading. Although it is not demonstrated, it would appear that mesh size, particularly for loads near the gauges, and the make-up of the distributed loading could be important factors in the application of such a technique.

In the particular case of the Lightning fin it should be possible to estimate flight loads to within ±5% or to within ±2 in (±0·05 m) of the centre of pressure of the load. Both measures of accuracy should be used with caution when low values of load are involved.

Appendix A

GROUND CALIBRATION AND STRAIN GAUGE INSTALLATION

(See section 3.1)

A.1 Ground calibration equipment

A.1.1 Loading rig

Counterbalanced beams were placed, one either side of the fin and connected at each end. Load was applied to the fin through a rubber-faced pad attached to one beam and a cable led from the opposite beam to the side frame, passing round a pulley, to a deadweight equal to the maximum applied load. The weight was raised by a turnbuckle thus allowing incremental loading without exceeding the allowable load. The applied loads were reacted at the main undercarriage wheels which were restrained by brackets bolted to the floor. Side load on the nosewheel was reduced by mounting it on a plate supported by rollers.

A strain-gauged link was connected between the counterbalanced beam and the cable to measure the applied load and a calibrated C-link, fitted with a dial gauge, was mounted above the turnbuckle to indicate the incremental load applied. The loading rig is shown in Figs.17, 18 and 19 for a distributed load (see section 4).

A.1.2 Strain gauge installation

Strain gauges were bonded to the fin structure just outboard of rib 1 (Fig.1) consisting of six half bridges on each spar. Three half bridges bonded to the spar web were arranged to measure shear forces and three half bridges on the spar flanges were arranged to measure bending moments.

The connections to each of the half bridges were rewired for the flight tests to provide full bridges, leaving a spare half bridge available in the event of gauge unserviceability. The responses were recorded on galvanometer paper-trace recorders.

Responses were obtained from each of the three half bridges in the ground calibration. The responses from the two half bridges which formed the full bridges in the flight installation were summed and these responses are given in Tables 1 and 2.

A.2 Ground calibration

A.2.1 Pre-flight load calibration

Twenty-seven positions on the fin were chosen for the individual load calibration and are shown in Fig.1. Each position was loaded incrementally to a nominal 1000 lb (454 kg) and then unloaded. The Mercury computer was used to give a least-squares slope for each half bridge response against the strain-gauged link response. These slopes were expressed as responses for a 1000 digit link response representing a 1335 lb (606 kg) load.

On completion of the individual load calibration (loading to starboard) the side frame was transferred to the opposite side of the aircraft and the calibration was repeated. No significant changes were noted in the responses and those for the starboard loadings have been used to form the sample.

A.2.2 Post-flight load calibration

At the conclusion of the flying programme, the pre-flight calibration was repeated, omitting the calibration to port. The pre-flight calibration was made using a strain recorder which had a sensitivity of 2000 digits for 1% $\Delta R/R$. The post-flight calibration was made using a high speed digital recorder (the original recorder was no longer available) which had a sensitivity of 250 digits for 1% $\Delta R/R$ and all responses have been referred to the sensitivity of the pre-flight recorder.

In addition to the above calibrations, two distributed loads were also applied to the fin. The first approximated to a gust loading and used five counterbalanced beams, loads being applied by either two or four pads on each beam. The correct proportion of the load on each beam was obtained by a lever system on the side frame (Fig.17). The second was in the form of a torque loading and used two pads per beam (four beams). Loads in one direction were applied to the rear shear wall and loads in the opposite direction were applied near the front shear wall.

A.2.3 Pre-flight and post-flight shunt calibrations

At the beginning and end of each flight record a shunt was introduced successively across each of the two strain gauges of each half bridge, thus providing positive and negative steps in the trace. These steps were also measured on each recorder used for the ground calibrations and provided conversions for the flight responses in terms of structural load.

A.2.4 Normal acceleration calibration

During the early flight tests it was found that many of the galvanometers in the flight recorders were unduly sensitive to normal acceleration. The recorders were therefore mounted in a centrifuge and the galvanometer deflections were obtained for accelerations between -4 g and +4 g.

A.3 Accuracy of calibration

The strain-gauged link was calibrated against load on both recorders and a slight change in sensitivity was observed. The gauge slopes (gauge response/link response) for the second calibration were corrected and the resulting slopes for both calibrations were then referred to the sensitivity of the first recorder; thus the slopes × 1000 represented responses for 1335 lb (606 kg) applied load.

The scaled responses from the second calibration have produced rounding errors in addition to the basic errors of the data. An estimate of the overall error between the first and second calibration gave a standard deviation of ±14 digits for the difference between the two calibrations, whereas estimates of the differences between four successive calibrations of one pad on the second calibration gave standard deviations of about ±8 digits.

An analysis of variance using the F-ratio test showed that differences between the first and second data due to possible change of gauge sensitivity or structural response were not significant; however this test is not entirely conclusive since the two sets of data were obtained with recorders of different sensitivity.

Table 1

PRE-FLIGHT CALIBRATION - STRAIN GAUGE RESPONSES FOR 1335 lb (606 kg) AT LOADING PAD

Pad	M		V		T		1	2	3	4	5	6	7	8	9	10	11	12
	lb in	kgm	lb	kg	lb in	kgm												
01	0	0	0	0	0	0	9	0	-7	14	-17	21	-33	14	-97	5	116	-192
02	0	0	0	0	0	0	8	3	-10	12	-26	12	-21	7	138	-53	-26	-13
03	0	0	0	0	0	0	-6	0	-17	5	-27	0	77	-63	0	15	-40	14
04	0	0	0	0	0	0	-9	0	-15	-5	95	-64	-17	0	-10	18	-24	5
05	0	0	0	0	0	0	-5	-26	103	-63	-16	0	-9	25	-10	13	-17	0
06	0	0	0	0	0	0	221	-93	-17	-42	-28	0	-21	8	9	-8	0	15
13	7076	81.5	1335	606	73099	842.1	-5	0	-50	43	-67	33	-775	75	-20	29	-70	25
14	7076	81.5	1335	606	93658	1078.9	-40	6	-64	18	-732	-35	-57	47	-24	43	-42	28
15	7076	81.5	1335	606	113817	1311.2	-76	-16	-619	-20	-71	18	-38	51	-17	36	-25	33
16	7076	81.5	1335	606	142119	1637.2	-1282	-253	-98	-21	-63	29	-17	28	-3	14	5	39
22	23630	272.2	1335	606	44664	514.5	29	9	-65	62	-93	73	-133	76	-554	153	-312	2
23	24698	284.5	1335	606	73099	842.1	-18	17	-93	73	-166	90	-498	176	-88	92	-109	42
24	24698	284.5	1335	606	93658	1078.9	-77	2	-155	75	-508	122	-133	107	-58	77	-67	43
25	24698	284.5	1335	606	113817	1311.2	-199	7	-473	126	-170	103	-67	95	-38	65	-38	55
26	24698	284.5	1335	606	146124	1683.3	-848	51	-244	62	-98	86	-26	70	-9	38	4	65
32	43788	504.4	1335	606	68827	792.9	12	24	-124	123	-179	161	-250	200	-190	182	-144	80
34	43922	506.0	1335	606	93658	1078.9	-69	32	-186	137	-319	193	-139	167	-87	117	-82	79
35	47927	552.1	1335	606	113817	1311.2	-224	45	-288	181	-182	201	-86	163	-52	106	-50	96
36	47927	552.1	1335	606	149328	1720.3	-581	85	-249	159	-119	182	-22	123	-7	63	12	113
43	61544	709.0	1335	606	89253	1028.2	-41	58	-204	218	-237	280	-152	259	-118	178	-107	116
44	78365	902.8	1335	606	109945	1266.6	-102	87	-202	271	-167	328	-94	256	-71	164	-76	145
45	71156	819.7	1335	606	115285	1328.1	-168	81	-218	250	-167	296	-88	230	-63	145	-61	135
46	71823	827.4	1335	606	156136	1798.7	-474	118	-219	242	-109	277	-18	179	-9	93	13	150
54	88511	1019.6	1335	606	121827	1403.4	-144	114	-194	309	-142	365	-72	266	-59	166	-58	165
56	83571	962.7	1335	606	156270	1800.2	-416	136	-199	287	-101	327	-15	217	0	115	6	172
65	115478	1330.3	1335	606	154400	1778.7	-235	198	-170	437	-93	480	-26	313	-30	179	-14	224
66	112541	1296.5	1335	606	165081	1901.7	-349	202	-178	421	-77	456	0	290	-8	161	7	225

Table 2

POST-FLIGHT CALIBRATION - STRAIN GAUGE RESPONSES FOR 1335 lb (606 kg) AT LOADING PAD

Pad	M		V		T		1	2	3	4	5	6	7	8	9	10	11	12
	lb in	kgm	lb	kg	lb in	kgm												
01	0	0	0	0	0	0	0	0	-19	16	-31	19	-31	4	-109	0	136	-163
02	0	0	0	0	0	0	0	0	-30	16	-31	24	-32	0	129	-54	-38	-8
03	0	0	0	0	0	0	-2	0	-29	24	-12	8	79	-58	14	11	-47	-5
04	0	0	0	0	0	0	-15	0	-18	0	97	-61	-19	9	-5	23	-27	14
05	0	0	0	0	0	0	-6	-8	104	-61	-12	4	-15	20	-7	31	-15	12
06	0	0	0	0	0	0	212	-78	-29	-41	-42	0	0	27	-17	14	8	26
13	7076	81.5	1335	606	73099	842.1	-14	11	-51	42	-73	35	-774	86	-22	36	-74	14
14	7076	81.5	1335	606	93658	1078.9	-44	0	-65	26	-760	-32	-56	40	-31	48	-44	24
15	7076	81.5	1335	606	113817	1311.2	-76	-20	-627	-22	-65	25	-38	49	-21	37	-28	33
16	7076	81.5	1335	606	142119	1637.2	-1428	-301	-110	-20	-66	33	-5	23	10	15	7	46
22	23630	272.2	1335	606	44664	514.5	28	10	-65	65	-98	90	-132	82	-541	174	-346	19
23	24698	284.5	1335	606	73099	842.1	0	20	-94	78	-171	105	-500	166	-88	93	-110	48
24	24698	284.5	1335	606	93658	1078.9	-62	21	-151	76	-502	128	-141	106	-56	83	-72	62
25	24698	284.5	1335	606	113817	1311.2	-198	0	-468	121	-176	97	-69	92	-41	65	-37	58
26	24698	284.5	1335	606	146124	1683.3	-847	38	-232	57	-105	83	-26	66	-3	43	0	71
32	43788	504.4	1335	606	68827	792.9	0	26	-128	127	-190	173	-255	204	-188	180	-164	86
34	43922	506.0	1335	606	93658	1078.9	-79	30	-192	136	-325	198	-136	172	-89	122	-87	81
35	47927	552.1	1335	606	113817	1311.2	-224	40	-292	195	-190	214	-91	168	-63	112	-63	106
36	47927	552.1	1335	606	149328	1720.3	-582	83	-246	159	-118	192	-10	120	-17	70	0	113
43	61544	709.0	1335	606	89253	1028.2	-17	42	-190	199	-227	267	-156	253	-113	177	-107	107
44	78365	902.8	1335	606	109945	1266.6	-90	83	-194	272	-163	330	-105	266	-81	168	-81	145
45	71156	819.7	1335	606	115285	1328.1	-158	76	-218	248	-171	306	-92	236	-75	150	-70	137
46	71823	827.4	1335	606	156136	1798.7	-465	117	-205	248	-101	281	0	161	-10	105	6	162
54	88511	1019.6	1335	606	121827	1403.4	-128	107	-197	321	-160	370	-82	267	-65	176	-63	168
56	83571	962.7	1335	606	156270	1800.2	-433	135	-193	292	-89	327	-5	215	-17	119	8	177
65	115478	1330.3	1335	606	154400	1778.7	-190	182	-149	388	-82	443	-18	287	-32	174	-28	219
66	112541	1296.5	1335	606	165081	1901.7	-293	178	-157	382	-78	434	-12	269	-21	161	0	215

Table 3

PRE-FLIGHT CALIBRATION - STRAIN GAUGE RESPONSES FOR DISTRIBUTED LOAD OF 1335 lb (606 kg) FOR VARIATIONS OF SIDESLIP AND GUST LOADS

No.	M		V		T		1	2	3	4	5	6	7	8	9	10	11	12
	lb in	kgm	lb	kg	lb in	kgm												
	80012	921.7	1335	606	21948	252.8	590	113	-7	325	-180	352	-187	261	-467	247	-206	-17
1	75296	867.4	1335	606	43094	496.4	398	104	-47	298	-171	327	-162	242	-388	218	-171	6
2	70711	814.6	1335	606	63662	733.4	212	96	-85	271	-162	303	-137	224	-311	190	-137	28
3	68465	788.7	1335	606	73736	849.4	120	92	-105	258	-157	291	-124	215	-273	177	-120	39
4	66248	763.2	1335	606	83670	963.9	30	89	-123	245	-153	279	-112	206	-236	163	-104	50
	65899	759.2	1335	606	18184	209.5	537	75	-33	259	-204	292	-213	243	-437	235	-211	-21
5	63972	737.0	1335	606	37305	429.8	377	73	-64	245	-193	279	-187	229	-373	212	-180	0
6	61996	714.2	1335	606	56911	655.6	214	72	-96	231	-180	266	-159	215	-306	188	-147	21
7	60989	702.6	1335	606	66903	770.7	130	71	-112	224	-174	260	-146	208	-273	176	-131	32
8	59968	690.8	1335	606	77022	887.3	45	71	-128	217	-168	253	-132	201	-238	164	-114	43
	55394	638.1	1335	606	15384	177.2	498	47	-53	210	-223	247	-233	229	-415	227	-215	-24
9	55144	635.3	1335	606	32796	377.8	361	49	-78	205	-210	242	-206	219	-361	207	-187	-6
10	54870	632.1	1335	606	51394	592.1	215	52	-104	199	-196	237	-178	208	-303	186	-156	15
11	54725	630.4	1335	606	61178	704.8	138	54	-118	196	-188	234	-163	202	-272	175	-140	26
12	54577	628.7	1335	606	71314	821.5	59	55	-133	193	-180	231	-148	196	-240	164	-124	37
	66700	768.4	1335	606	113290	1305.1	-175	88	-182	236	-158	274	-114	211	-109	138	-69	103
13	68516	789.3	1335	606	115276	1328.0	-179	93	-181	243	-154	281	-111	213	-107	138	-66	107
14	58676	675.9	1335	606	105636	1216.9	-156	73	-173	205	-164	238	-137	193	-136	135	-87	93
15	60637	698.5	1335	606	110303	1270.7	-187	79	-178	212	-155	246	-122	193	-127	132	-80	97
	57583	663.4	1335	606	107236	1235.4	-181	73	-176	200	-158	233	-127	186	-137	130	-87	91
	59044	680.2	1335	606	107351	1236.7	-170	74	-177	206	-159	239	-126	191	-138	134	-85	91

Table 4

POST-FLIGHT CALIBRATION - STRAIN GAUGE RESPONSES FOR DISTRIBUTED LOAD OF 1335 lb (606 kg) FOR VARIATIONS OF SIDESLIP AND GUST LOADS

No.	M		V		T		1	2	3	4	5	6	7	8	9	10	11	12
	lb in	kgm	lb	kg	lb in	kgm												
	80012	921.7	1335	606	21948	252.8	624	107	-14	313	-185	346	-196	257	-464	245	-223	-17
1	75296	867.4	1335	606	43094	496.4	427	99	-51	287	-175	322	-168	238	-386	218	-186	8
2	70711	814.6	1335	606	63662	733.4	235	91	-88	262	-165	298	-140	219	-311	192	-150	32
3	68465	788.7	1335	606	73736	849.4	141	87	-105	250	-161	287	-127	210	-273	180	-132	43
4	66248	763.2	1335	606	83670	963.9	48	83	-123	238	-156	276	-114	201	-237	167	-115	55
	65899	759.2	1335	606	18184	209.5	560	71	-42	256	-211	294	-224	246	-435	235	-225	-21
5	63972	737.0	1335	606	37305	429.8	397	69	-70	242	-197	281	-195	230	-371	213	-193	2
6	61996	714.2	1335	606	56911	655.6	230	68	-99	228	-185	268	-165	215	-306	191	-159	24
7	60989	702.6	1335	606	66903	770.7	145	67	-114	221	-178	261	-150	207	-272	180	-142	36
8	59968	690.8	1335	606	77022	887.3	59	66	-129	214	-172	254	-135	199	-239	168	-125	47
	55394	638.1	1335	606	15384	177.2	512	44	-62	214	-228	255	-245	237	-413	228	-228	-23
9	55144	635.3	1335	606	32796	377.8	374	46	-85	208	-215	249	-217	225	-359	209	-198	-3
10	54870	632.1	1335	606	51394	592.1	226	49	-109	201	-201	243	-186	211	-302	190	-167	18
11	54725	630.4	1335	606	61178	704.8	149	50	-121	197	-193	239	-169	205	-272	180	-150	30
12	54577	628.7	1335	606	71314	821.5	68	52	-134	194	-185	236	-153	197	-240	169	-133	41
	66700	768.4	1335	606	113290	1305.1	-163	81	-179	229	-161	273	-117	205	-115	142	-78	109
13	68516	789.3	1335	606	115276	1328.0	-167	86	-178	236	-157	279	-113	207	-113	142	-75	113
14	58676	675.9	1335	606	105636	1216.9	-145	67	-169	198	-167	238	-139	188	-139	140	-97	98
15	60637	698.5	1335	606	110303	1270.7	-176	73	-174	206	-158	245	-124	188	-130	137	-89	102
	57583	663.4	1335	606	107236	1235.4	-171	67	-173	195	-161	234	-129	182	-139	136	-97	97
	59044	680.2	1335	606	107351	1236.7	-160	68	-174	200	-162	239	-127	186	-140	139	-94	98

Table 5

REGRESSION COEFFICIENTS FOR INDIVIDUAL AND MIXED LOAD CALIBRATIONS - PRE-FLIGHT AND POST-FLIGHT

Bending moment - individual loads				
Calib.	Pre-flight		Post-flight	
Gauge	Coef. lb in	Coef. kgm	Coef. lb in	Coef. kgm
1				
2				
3				
4	82·10	0·9457	97·47	1·1229
5				
6	89·60	1·0321	95·23	1·0971
7				
8	55·12	0·6350		
9	-40·71	-0·4690	-23·92	-0·2764
10			57·84	0·6663
11	53·08	0·6114	51·76	0·5962
12	89·09	1·0264	93·68	1·0792
Mean	37677	434·04	37677	434·04
σ	±3404	±39·21	±3240	±37·32

Shear - individual loads				
Calib.	Pre-flight		Post-flight	
Gauge	Coef. lb	Coef. kg	Coef. lb	Coef. kg
1	-0·769	-0·349	-0·755	-0·343
2			0·381	0·173
3	-1·526	-0·692	-1·512	-0·686
4				
5	-1·326	-0·601	-1·288	-0·584
6	0·412	0·187	0·484	0·220
7	-1·319	-0·598	-1·359	-0·616
8	0·527	0·239		
9	-1·502	-0·681	-1·551	-0·703
10				
11				
12	1·441	0·653	1·983	0·899
Mean	1038	470·8	1038	470·8
σ	±70	±38·9	±56	±25·4

Torque - individual loads				
Calib.	Pre-flight		Post-flight	
Gauge	Coef. lb in	Coef. kgm	Coef. lb in	Coef. kgm
1	-4·30	-0·0496		
2	42·40	0·4885	32·09	0·3697
3	37·77	0·4351	36·32	0·4184
4				
5	51·61	0·5946	50·18	0·5781
6	25·79	0·2970	47·78	0·5504
7	74·32	0·8562	65·98	0·7601
8			-84·41	-0·9723
9				
10	-180·54	-2·0798	-128·15	-1·4762
11	212·35	-2·4462	205·75	2·3702
12	117·93	1·3586	166·57	1·9188
Axis	114 in	2·90 m	114 in	2·90 m
Mean	-29930	-344·79	-29930	-344·79
σ	±3301	±38·03	±3333	±38·40

Bending moment - mixed loads				
Calib.	Pre-flight		Post-flight	
Gauge	Coef. lb in	Coef. kgm	Coef. lb in	Coef. kgm
1	-2·51	-0·0289	-2·97	-0·0342
2			14·65	0·1688
3			4·43	0·0511
4	94·53	1·0890	92·33	1·0636
5				
6	77·13	0·8886	99·26	1·1435
7	6·99	0·0806		
8	70·42	0·8113		
9	-31·37	-0·3614	-19·24	-0·2217
10			72·15	0·8312
11	33·90	0·3906	45·40	0·5230
12	67·96	0·7829	74·50	0·8582
Mean	46478	535·43	46478	535·43
σ	±2537	±29·23	±2559	±29·48

Shear - mixed loads				
Calib.	Pre-flight		Post-flight	
Gauge	Coef. lb	Coef. kg	Coef. lb	Coef. kg
1	-0·782	-0·355	-0·716	-0·325
2				
3	-1·531	-0·694	-1·485	-0·674
4			0·981	0·445
5	-1·344	-0·610	-1·234	-0·560
6	1·455	0·660		
7	-1·281	-0·581	-1·297	-0·588
8				
9	-1·147	-0·520	-1·477	-0·670
10			0·933	0·423
11	-0·960	-0·436		
12			0·982	0·445
Mean	1144	518·9	1144	518·9
σ	±71	±32·0	±69	±31·1

Torque - mixed loads				
Calib.	Pre-flight		Post-flight	
Gauge	Coef. lb in	Coef. kgm	Coef. lb in	Coef. kgm
1	-32·82	-0·3780	-30·81	-0·3549
2	51·19	0·5897	63·96	0·7369
3	-16·47	-0·1897	-14·88	-0·1714
4				
5	5·07	0·0584	8·02	0·0924
6	32·88	0·3787	40·37	0·4650
7	25·42	0·2928	19·52	0·2249
8			-86·70	-0·9988
9	-48·65	-0·5605	-33·66	-0·3878
10	-200·20	-2·3063	-102·36	-1·1792
11	213·18	2·4559	196·62	2·2650
12	205·85	2·3714	245·02	2·8227
Axis	80 in	2·03 m	80 in	2·03 m
Mean	-9684	-111·56	-9684	-111·56
σ	±4520	±52·07	±4029	±46·41

Table 6

ANALYSIS OF SIMULATED GUST LOADING APPLIED TO FIN (POST-FLIGHT REGRESSIONS)

Gauge	1	2	3	4	5	6	7	8	9	10	11	12
(1) From direct application	-384	200	-480	592	-568	712	-424	584	-192	328	-136	248
(2) From superposition	-408	210	-504	592	-584	729	-425	566	-184	347	-147	269

	Units	Applied load	Centre of pressure	Estimate from (1)	Percentage error	Centre of pressure error
Shear	lb	3682		3652	-0·1	
	kg	1670		1657		
Bending moment at section	lb in	171480	46·6 in	166931	-1·7	-0·9 in
	kgm	1975·4	1·18 m	1923		-0·02 m
Torque about axis at	lb in	17980	4·9 in	3953	-78·0	-3·8 in
5·25 in (0·133 m) fwd of spar 5	kgm	207·1	0·12 m	45·5		-0·10 m

Table 7

ANALYSIS OF TORQUE LOADING APPLIED TO FIN (POST-FLIGHT REGRESSIONS)

Gauge	1	2	3	4	5	6	7	8	9	10	11	12
(1) From direct application	748	104	-336	588	-710	708	-908	732	-337	458	-380	252
(2) From superposition	754	114	-312	534	-703	698	-915	712	-332	451	-381	255

	Units	Applied load	Centre of pressure	Estimate from (1)	Percentage error	Centre of pressure error
Shear	lb	3497		3740	6·9	
	kg	1586		1696		
Bending moment at section	lb in	160014	45·8 in	163431	2·1	-2·1 in
	kgm	1843·4	1·16 m	1882·7		-0·05 m
Torque about axis at	lb in	-111247	-31·8 in	-118205	6·3	-0·2 in
5·25 in (0·133 m) fwd of spar 5	kgm	-1282·6	-0·81 m	-1361·7		0 m

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No.	Author	Title, etc.
1	T.H. Skopinski W.S. Aiken, Jnr. W.B. Huston	Calibration of strain gauge installations in aircraft structures for the measurement of flight loads. NACA Report 1178 (1954)
2	P.B. Hovell D.A. Webber T.A. Roberts	The interpretation of strain measurements for flight load determination. A.R.C. C.P. No.839 (1964)

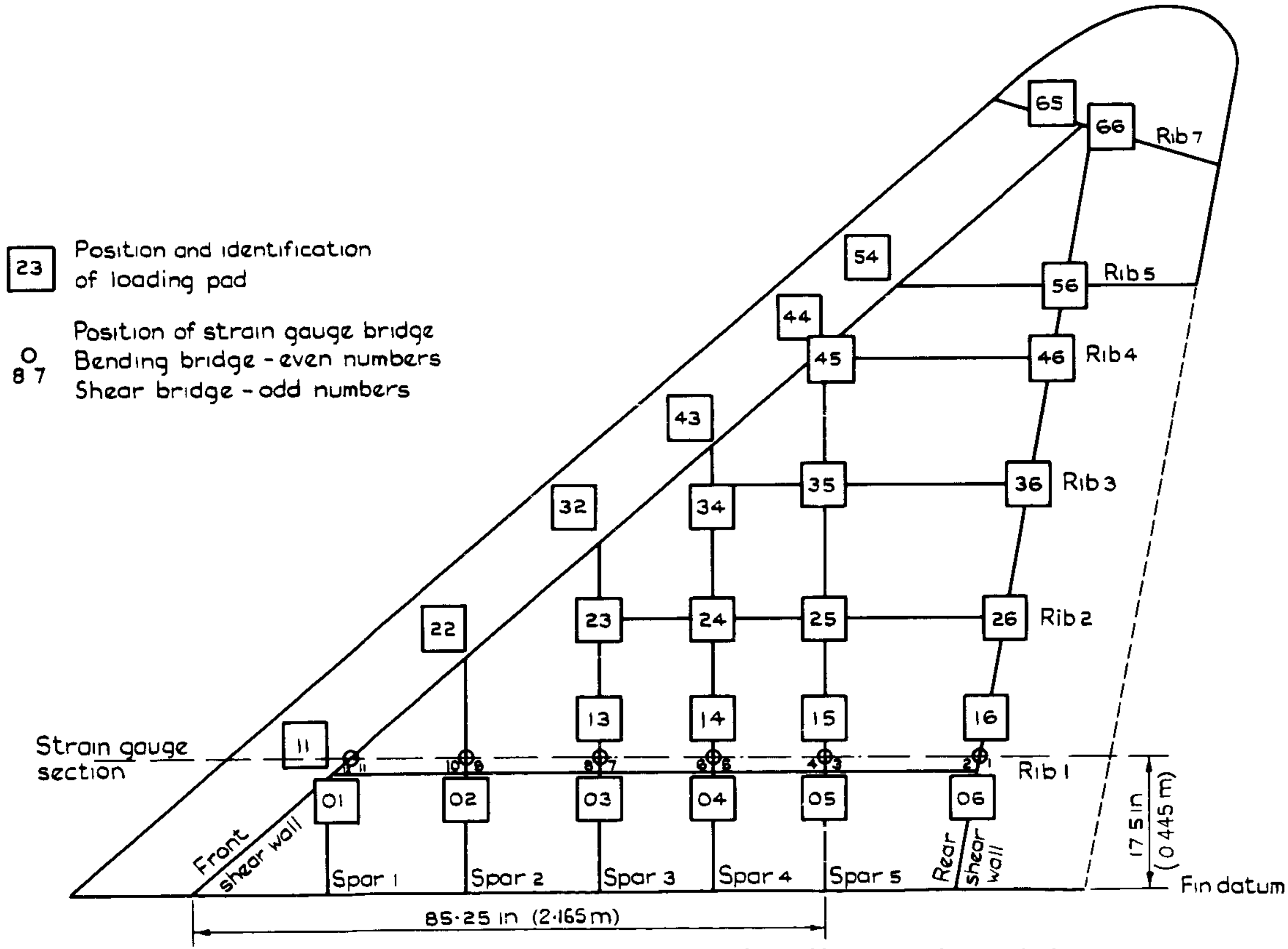


Fig. 1 Strain gauge bridge and loading pad positions

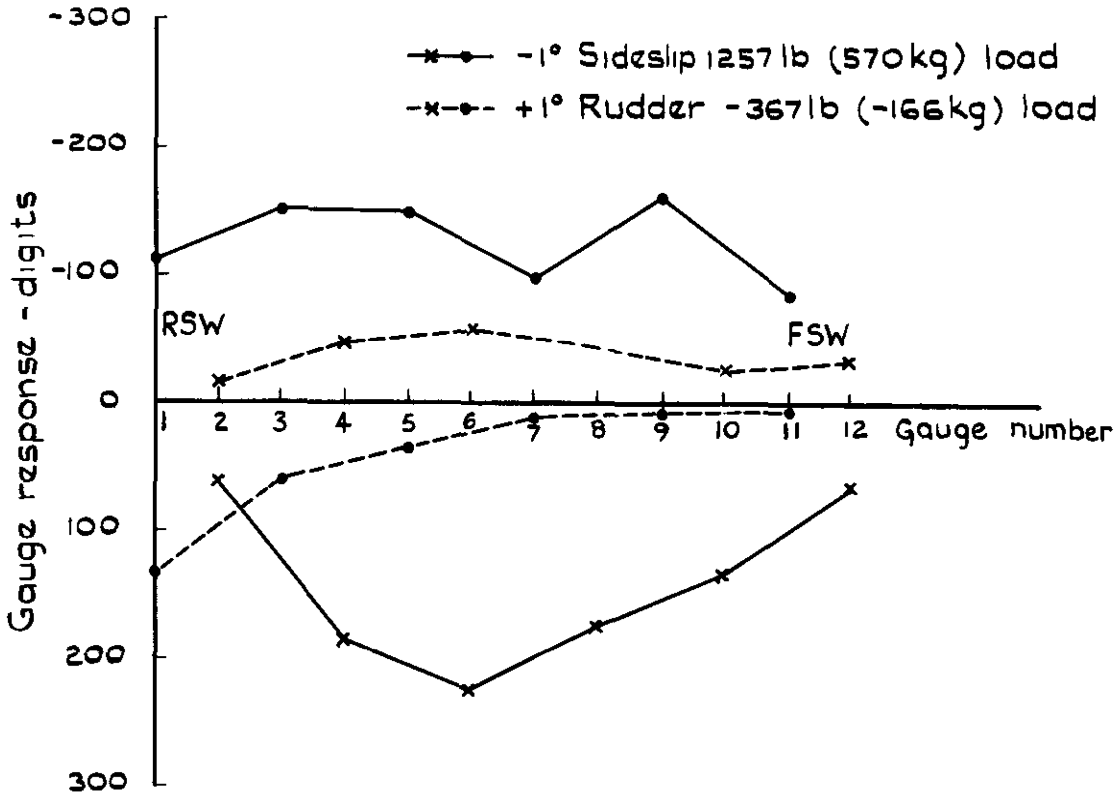


Fig. 2 Basic gauge responses for simulated sideslip and rudder loads

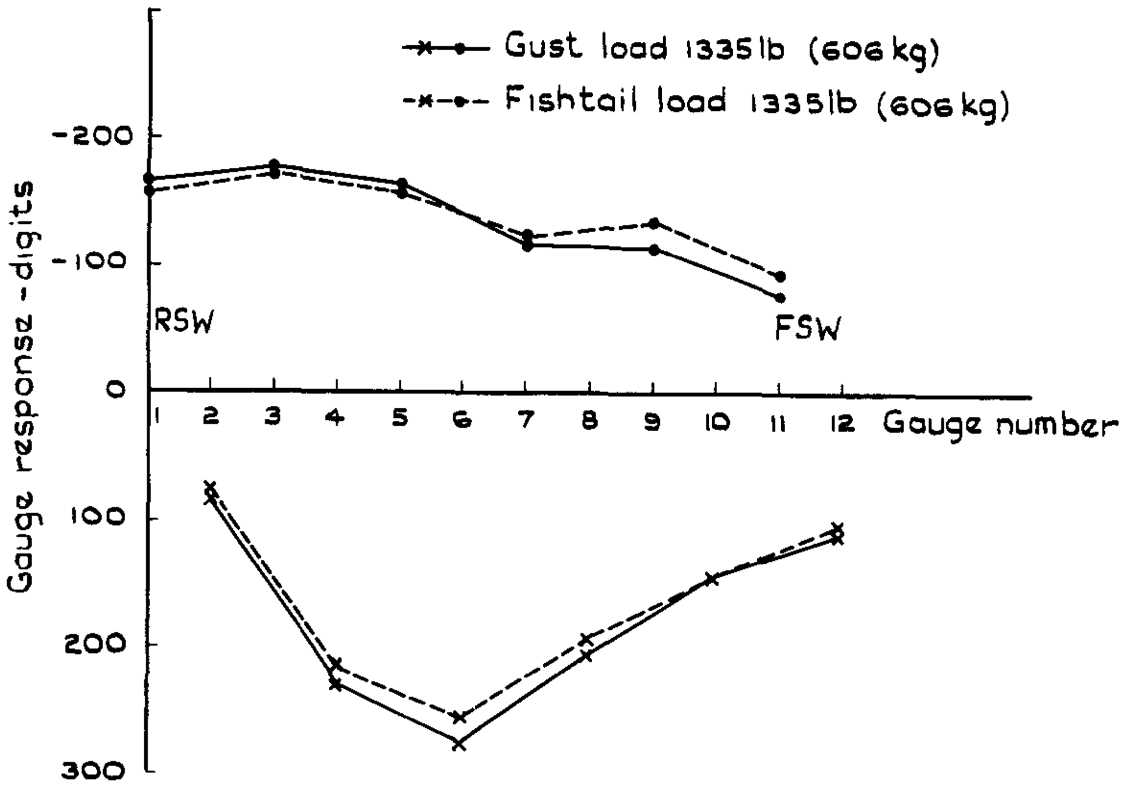


Fig. 3 Basic gauge responses for simulated gust and fishtail loads

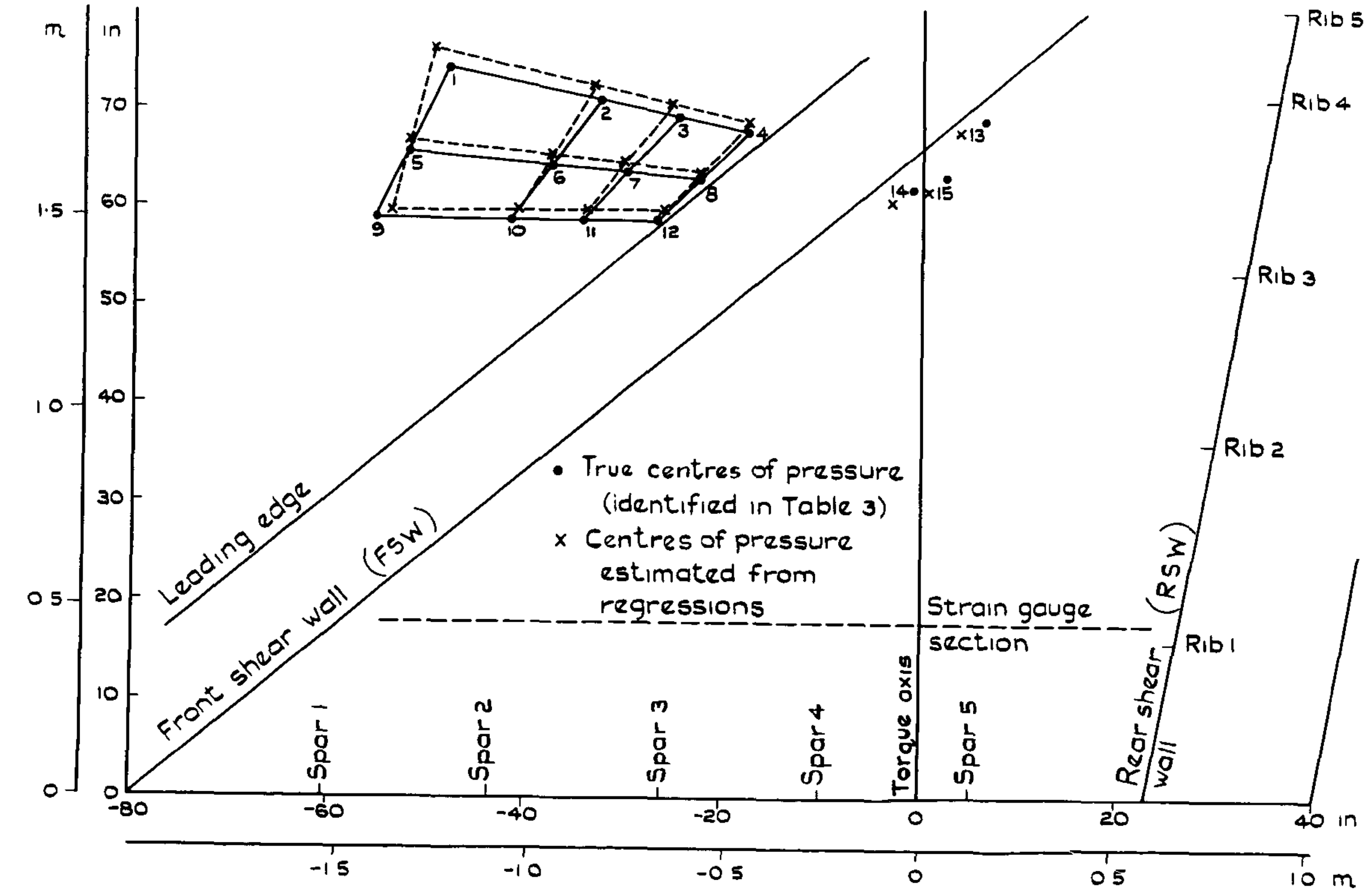


Fig. 4 Centres of pressure of distributed load sample

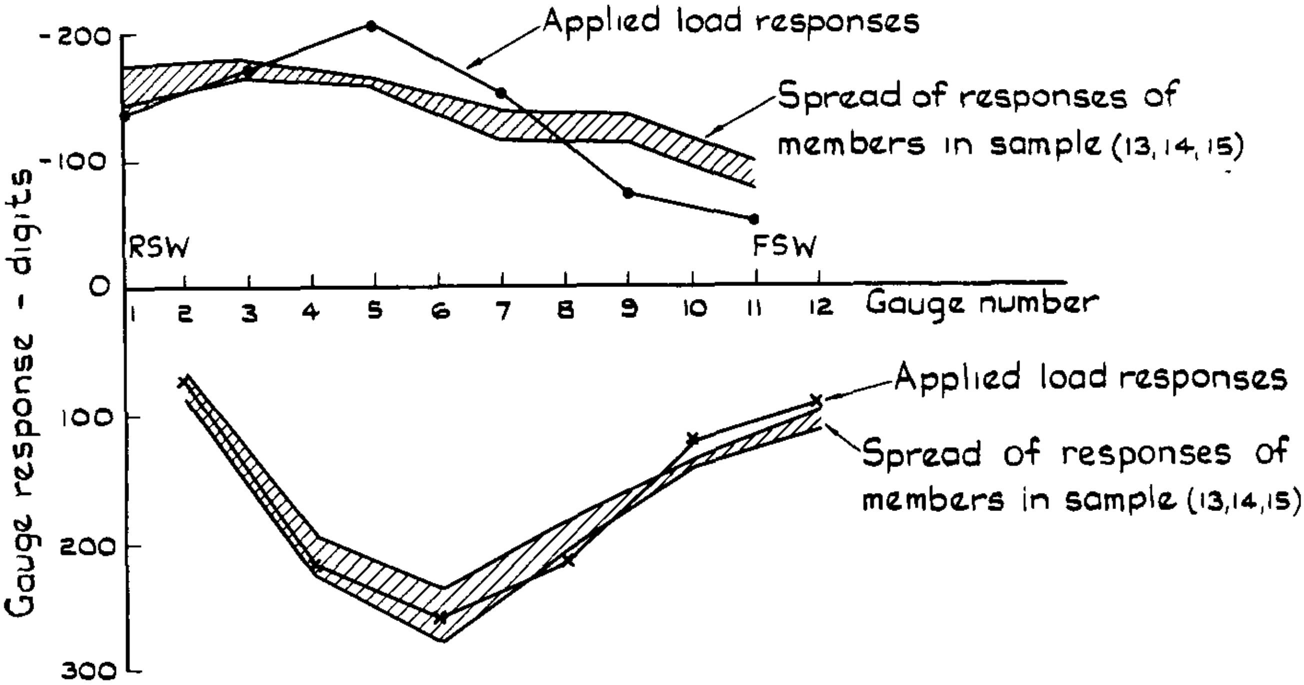


Fig. 5 Comparison of responses with sample members
Gust simulated loading - scaled to shear of 1335 lb (606 kg)

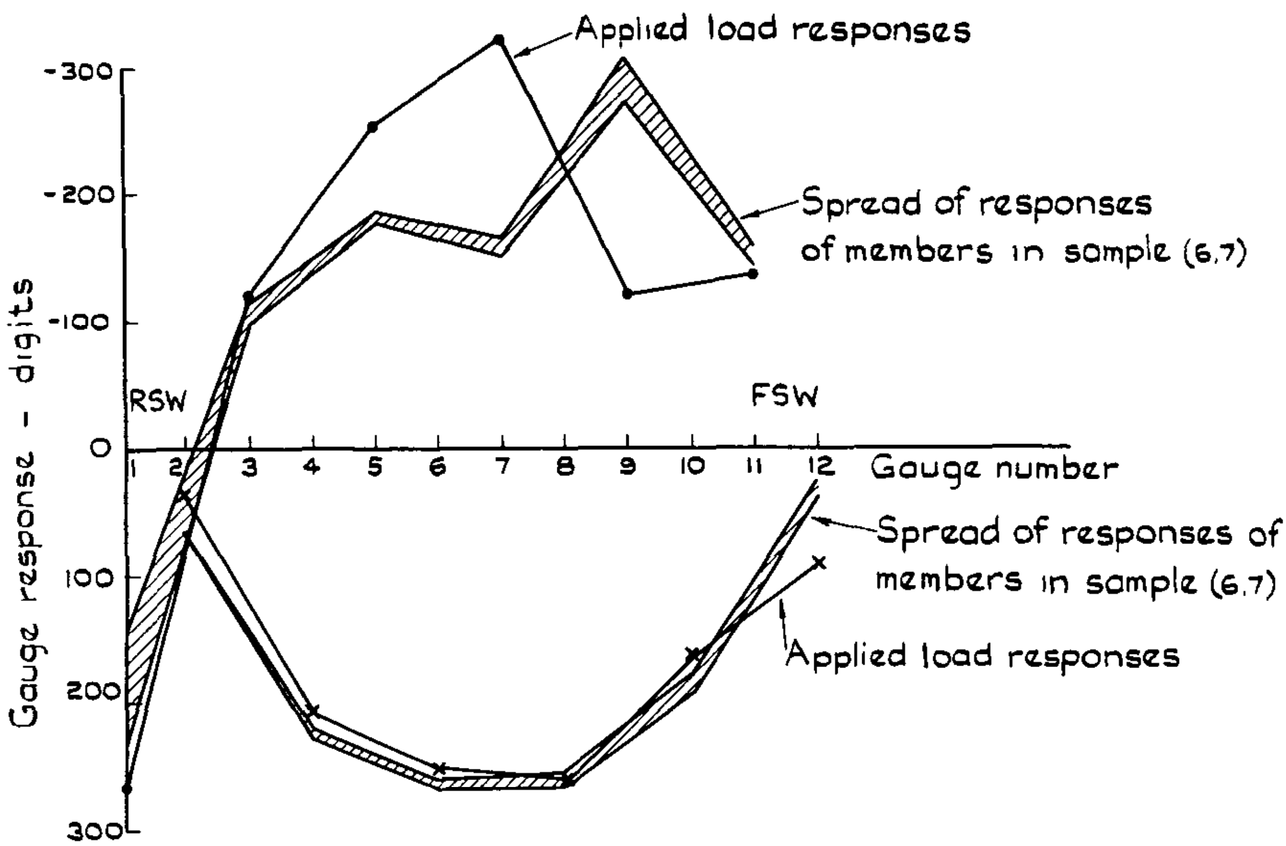


Fig. 6 Comparison of responses with sample members
Torque loading - scaled to shear of 1335 lb (606 kg)

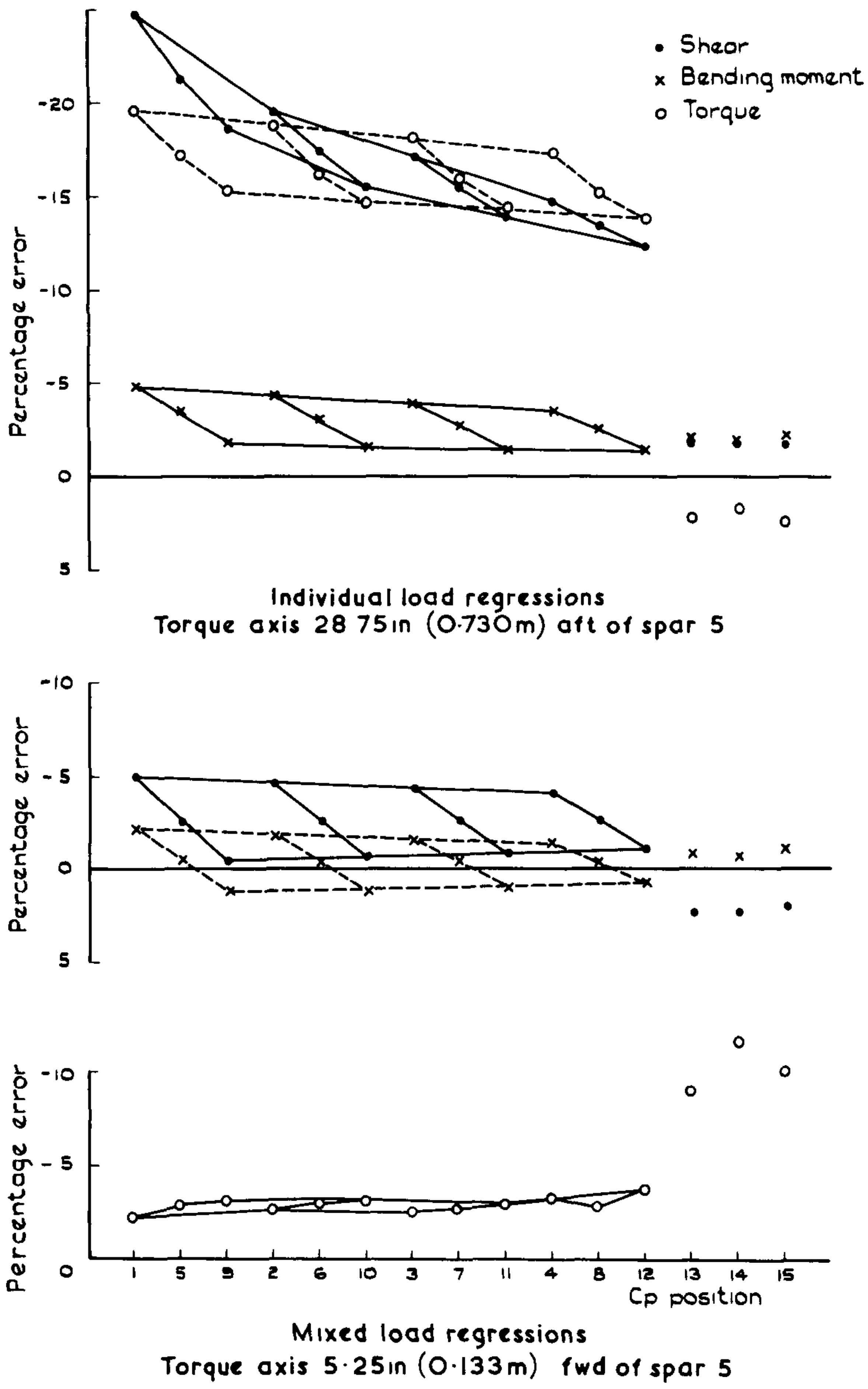


Fig.7 Percentage errors of estimates of sample distributed loads

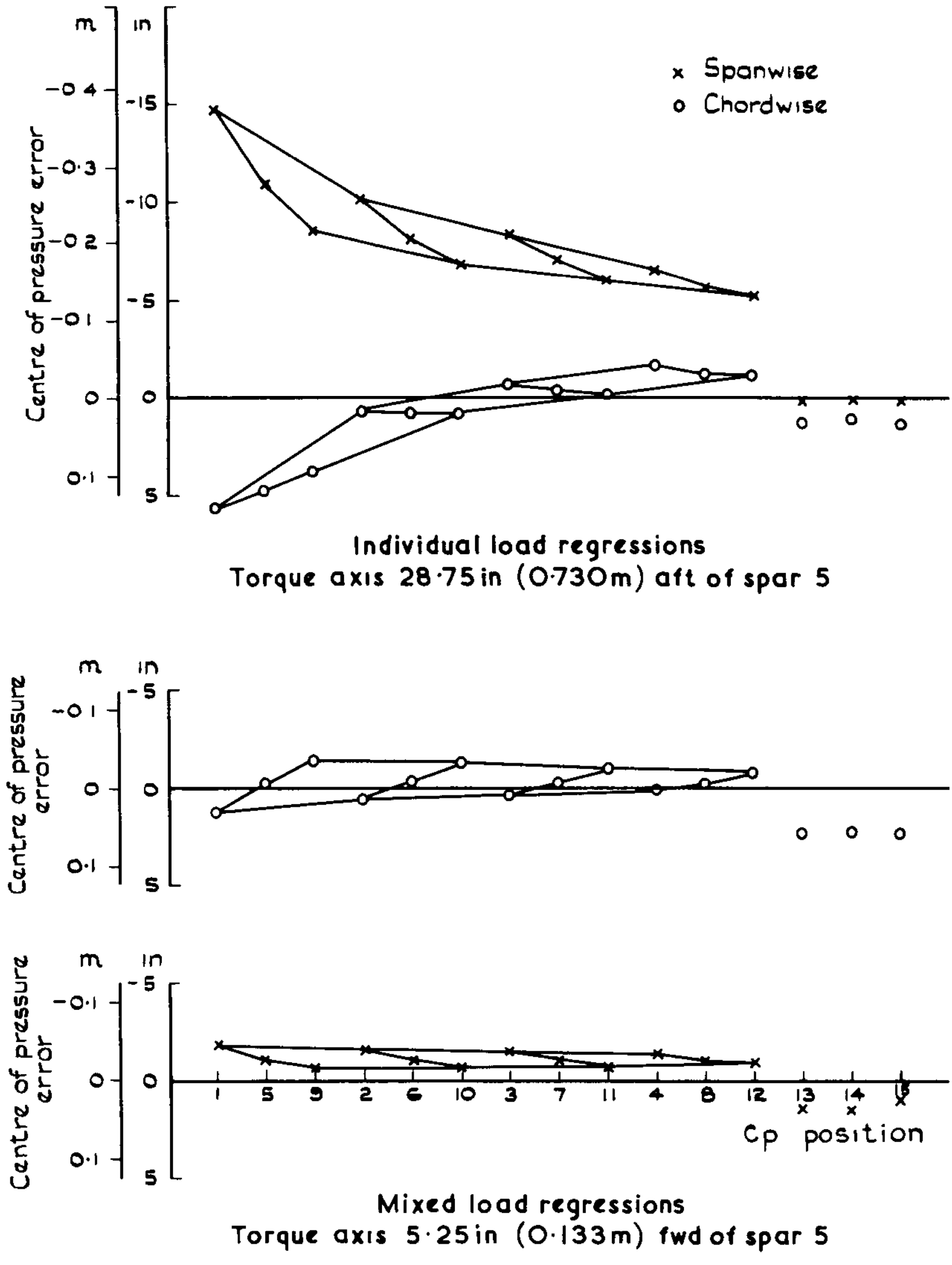
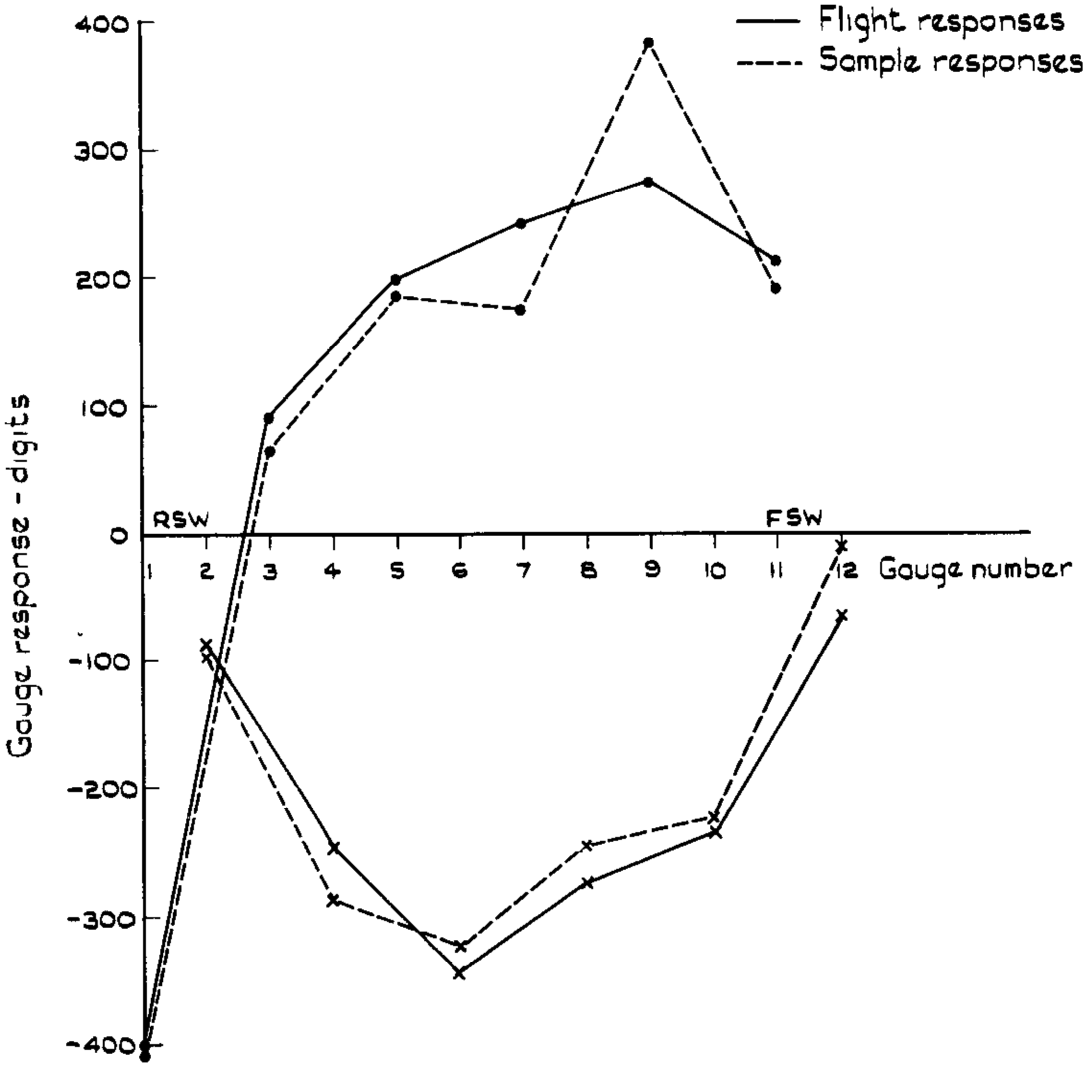


Fig. 8 Errors of estimated centres of pressure of sample distributed loads



M = 0 9 Alt = 25 000ft (6350m) Indicated SS = 4 5° Normal accel = 2·1g

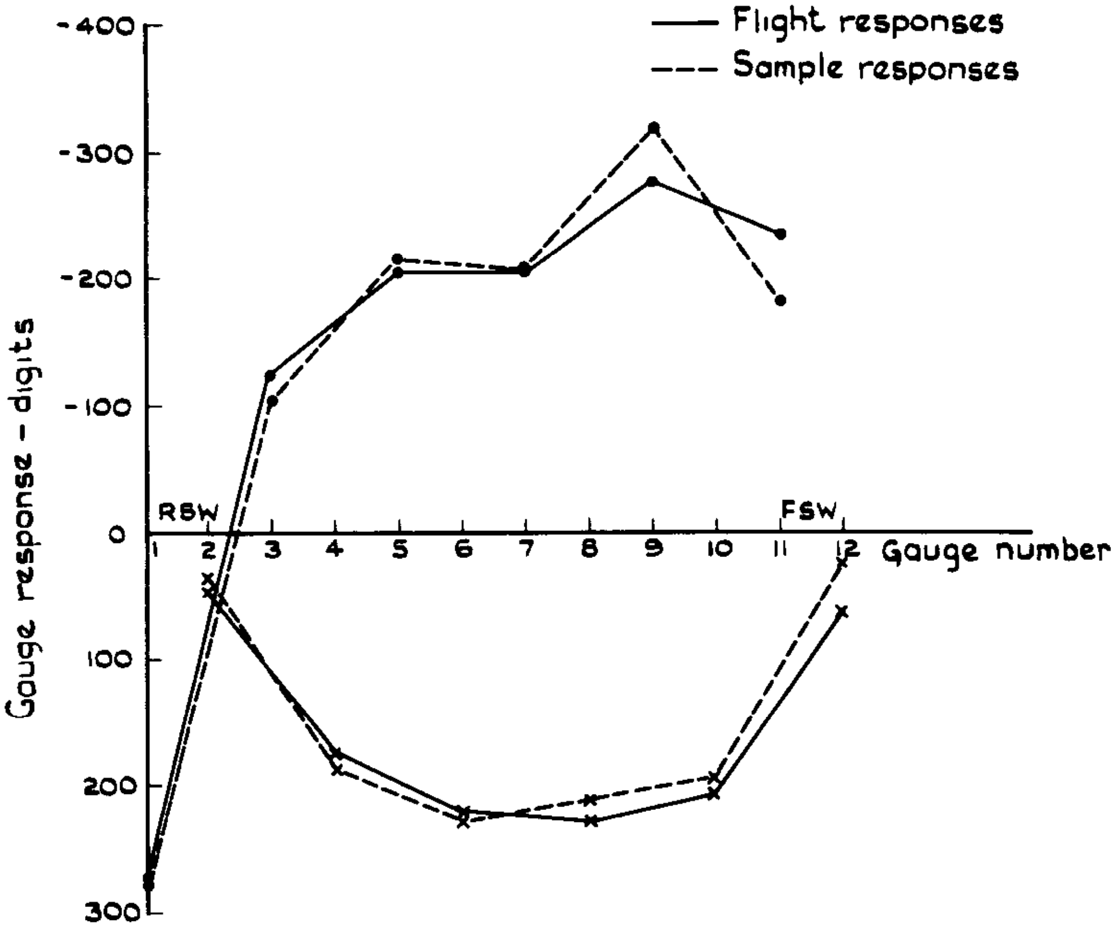
Centre of pressure of sample load Spanwise = 71·7 in (1 82m) Chordwise = -46 0 in (-1 17m)

Estimated centre of pressure of sample load Spanwise = 73 2 in (1 86m) Chordwise = -47 2 in (-1 20m)

Estimated centre of pressure of flight load Spanwise = 73·1 in (1·86m) Chordwise = -47·2 in (-1 20m)

Flight load shear estimate = -2224 lb (-1009 kg)

Fig.9 Comparison of responses of flight load with sample load
Sideslip to port - responses scaled to
estimated shear of 1335 lb (606kg)



M = 0·9 Alt = 25 000ft (6350 m) Indicated SS = -3·75° Normal accel = 2·1g

Centre of pressure of sample load Spanwise = 55·5in (1·41m) Chordwise = -49·3in (-1·25m)

Estimated centre of pressure of sample load Spanwise = 56·3in (1·43m) Chordwise = -47·1in (-1·20m)

Estimated centre of pressure of flight load Spanwise = 56·1in (1·42m) Chordwise = -47·4in (-1·20m)

Flight load shear estimate = 2600 lb (1179 kg)

Fig.10 Comparison of responses of flight load with sample load
Sideslip to starboard - responses scaled
to estimated shear of 1335lb (606kg)

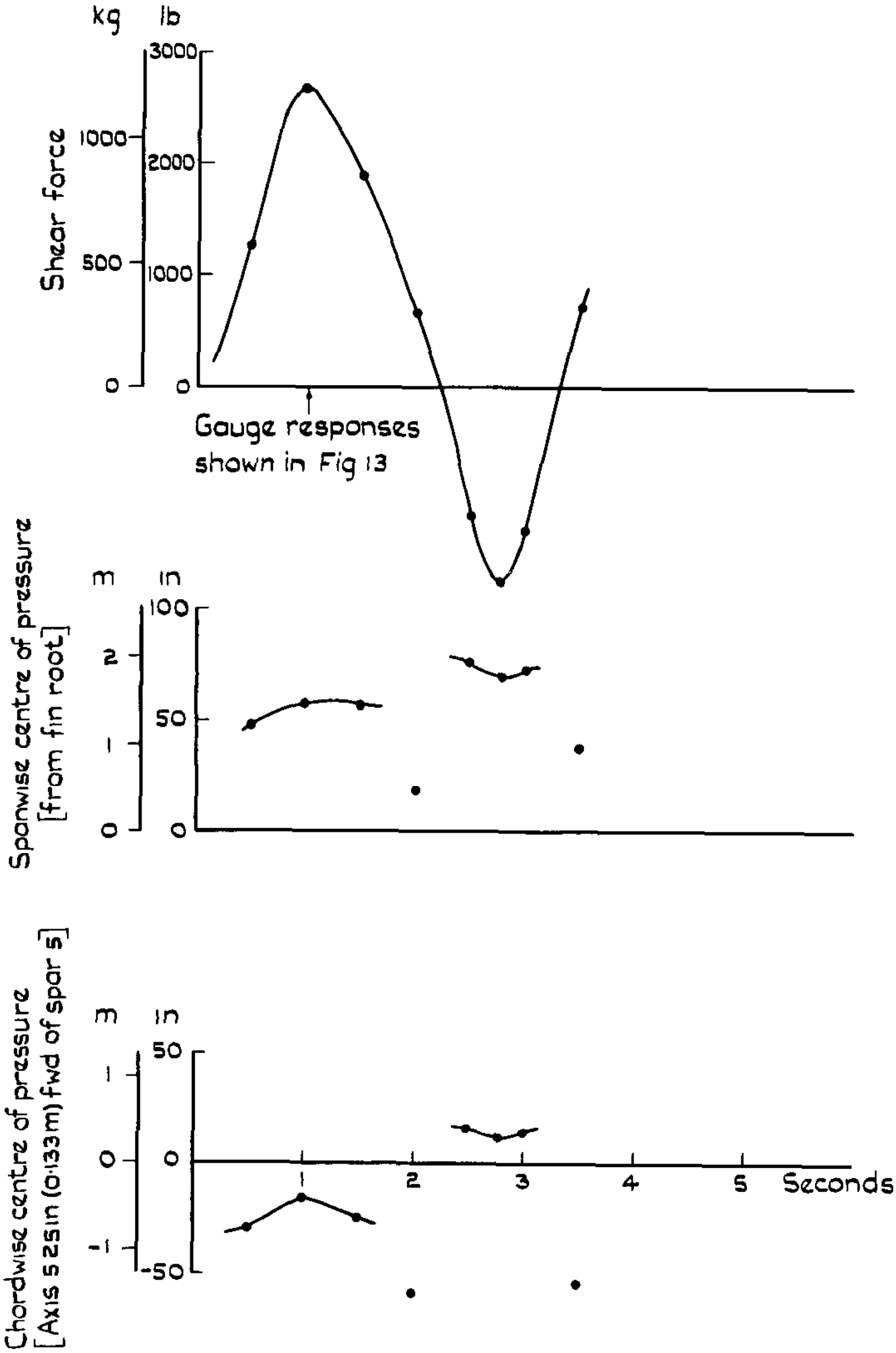


Fig. 11 Roll to port
M = 0·9 Alt = 30 000 ft (7620 m) Normal accel = 2·5g

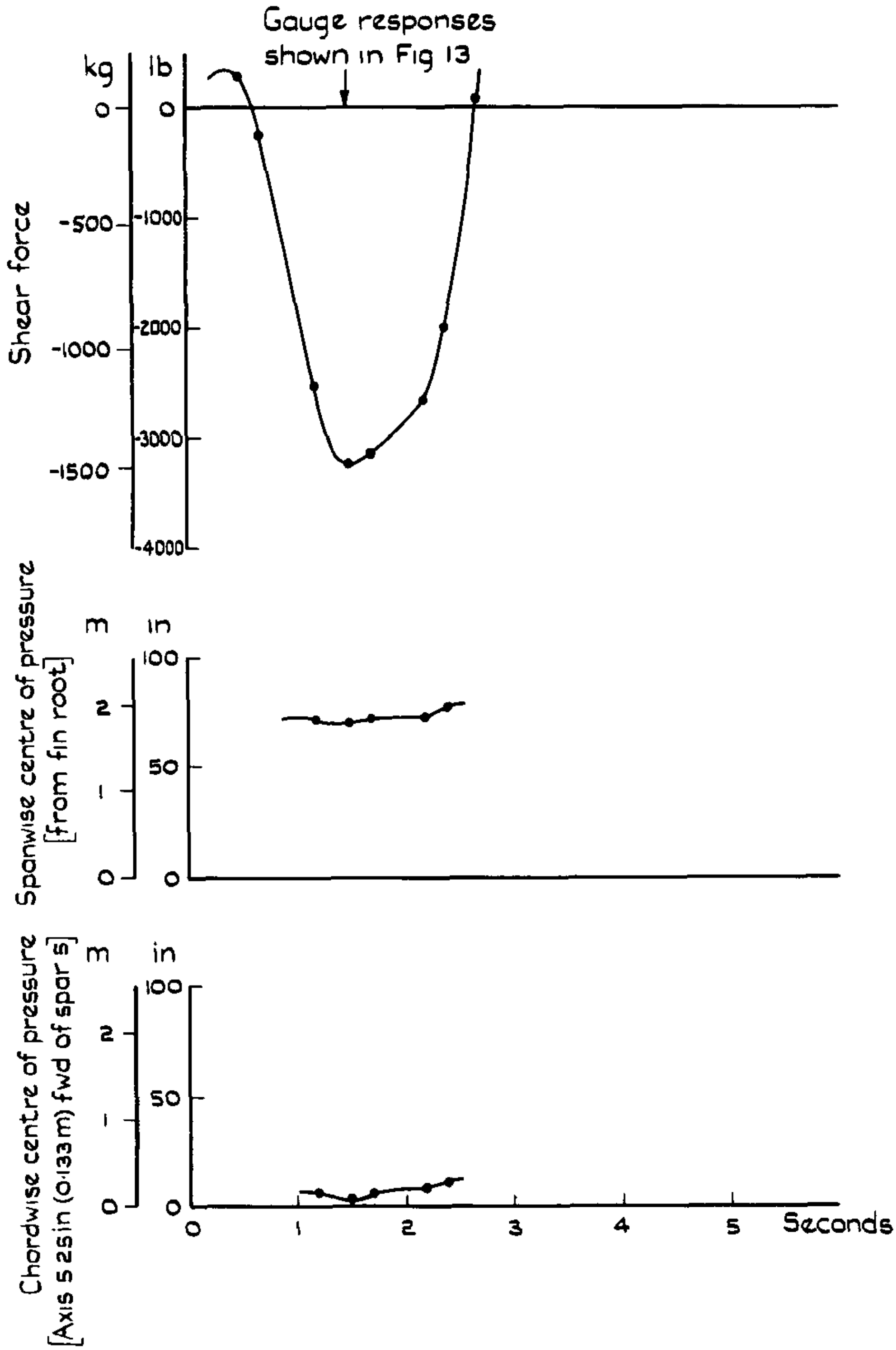


Fig. 12 Roll to starboard
M = 0·9 Alt = 31 000 ft (7874 m) Normal accel = 2·5g

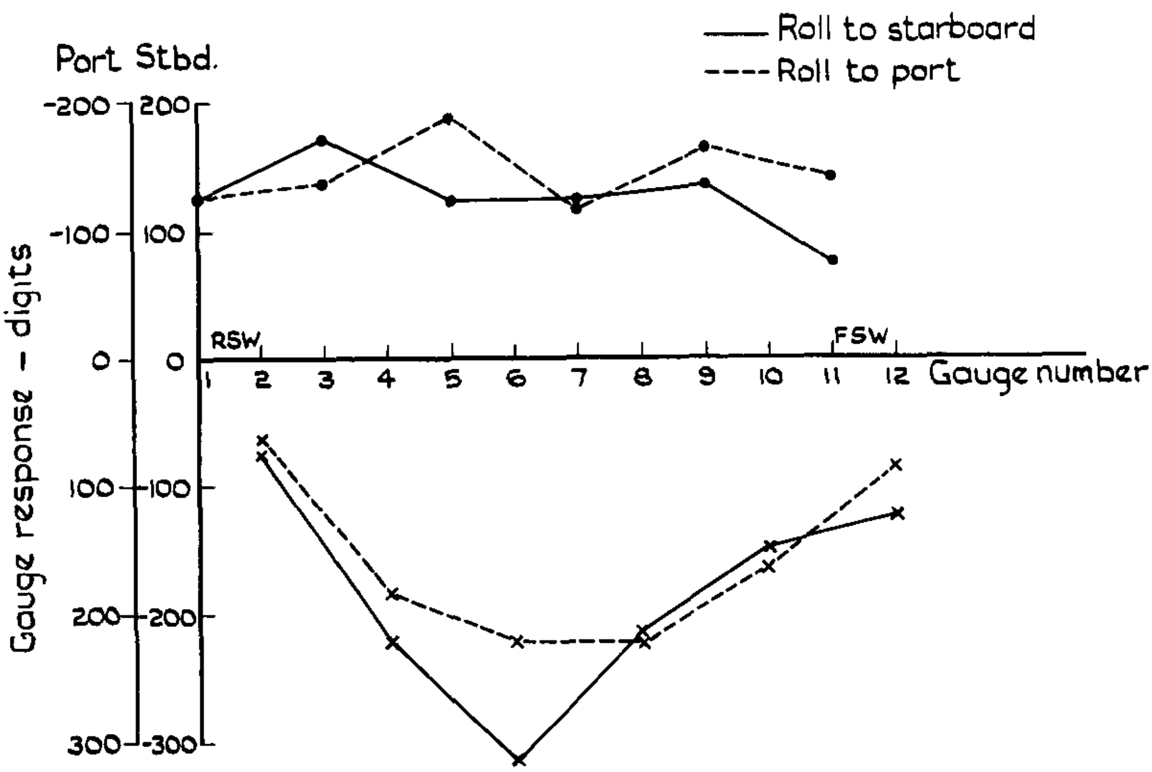


Fig. 13 Responses due to rolls at M=0·9
Responses scaled to estimated shear of 1335lb (606 kg)

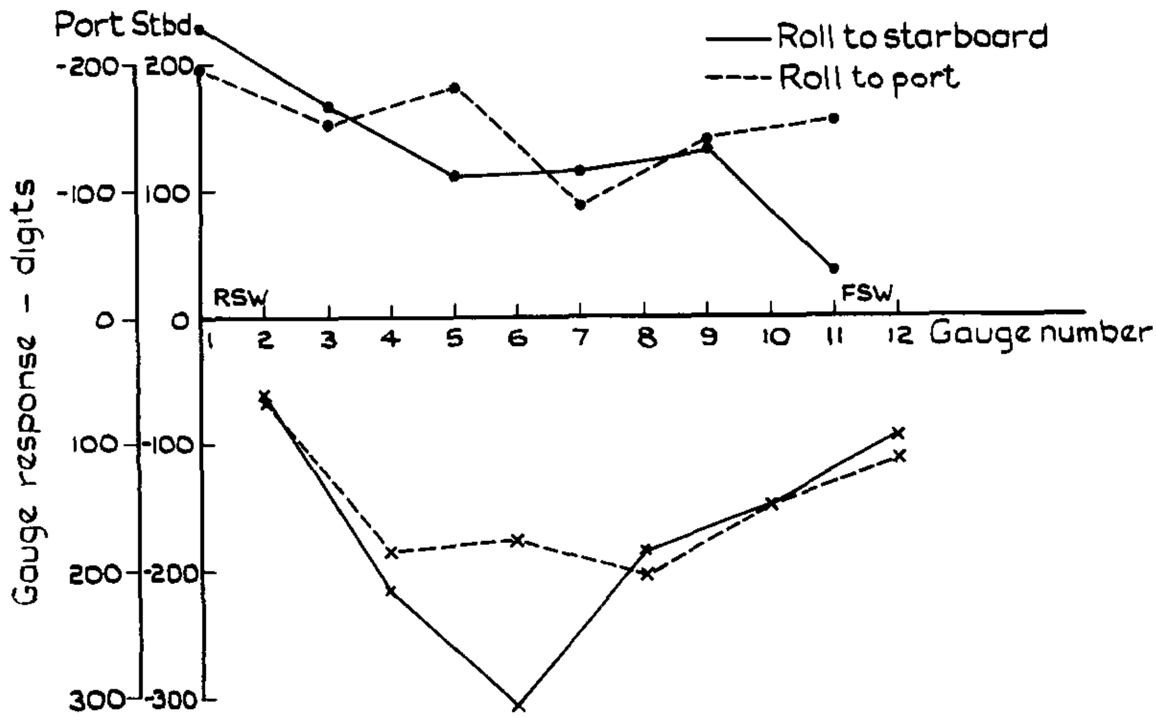


Fig. 14 Responses due to rolls at M=1·7
Responses scaled to estimated shear of 1335lb (606kg)

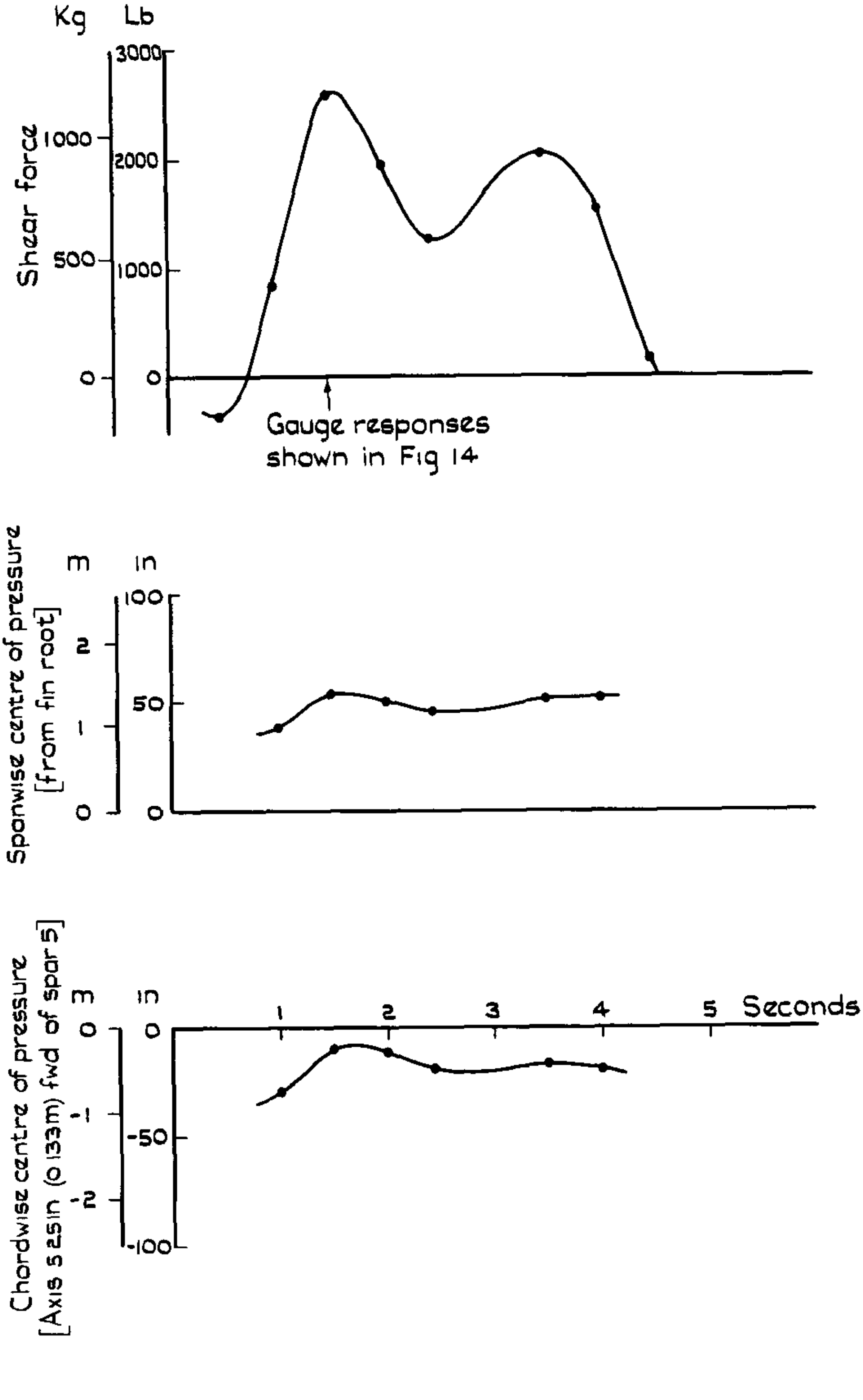


Fig.15 Roll to port
M = 1·7 Alt = 40 000ft (10160m) Normal accel = 3·75g

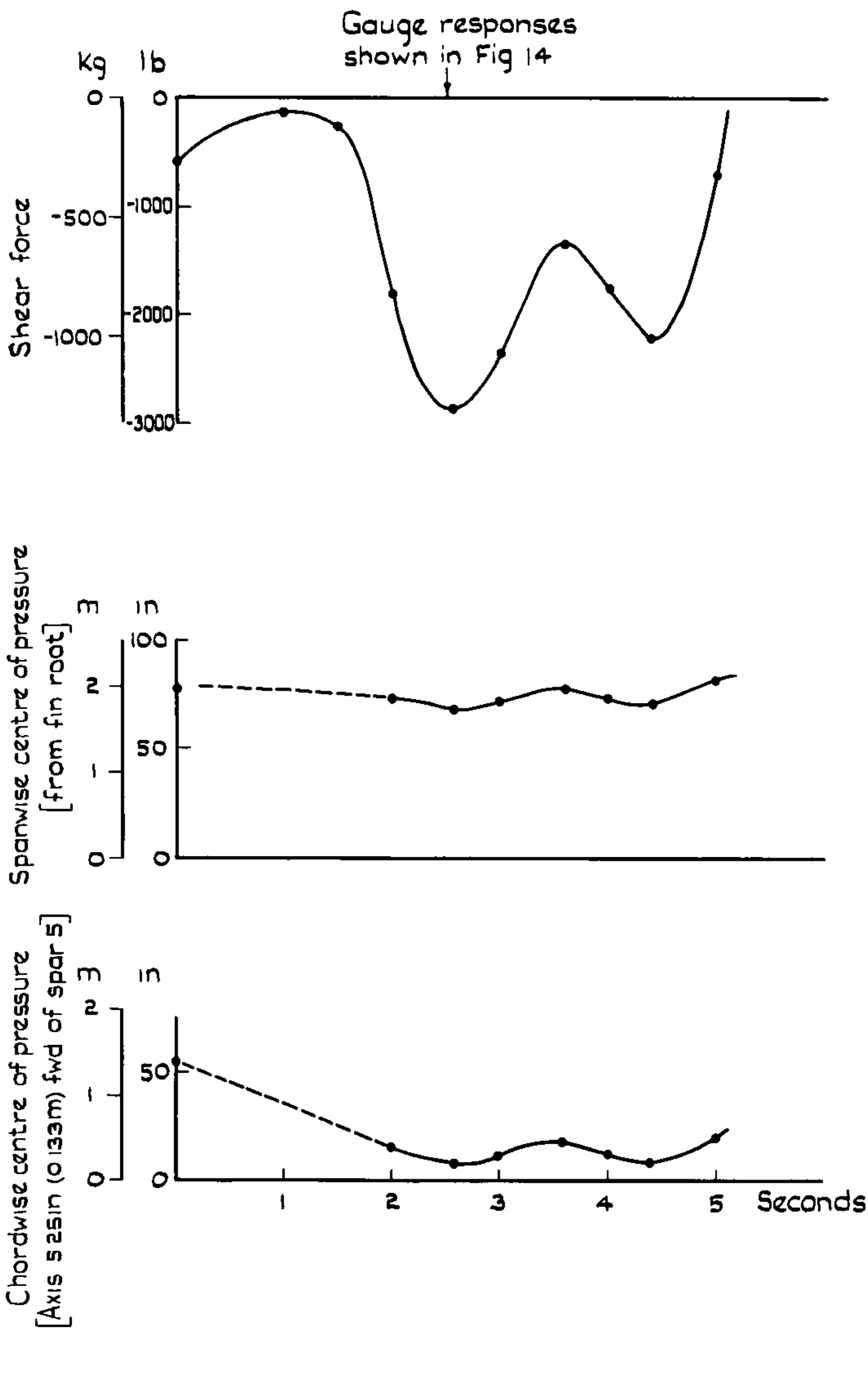


Fig.16 Roll to starboard
M = 1·7 Alt = 39500 ft (10033 m) Normal accel = 3g (nominal)

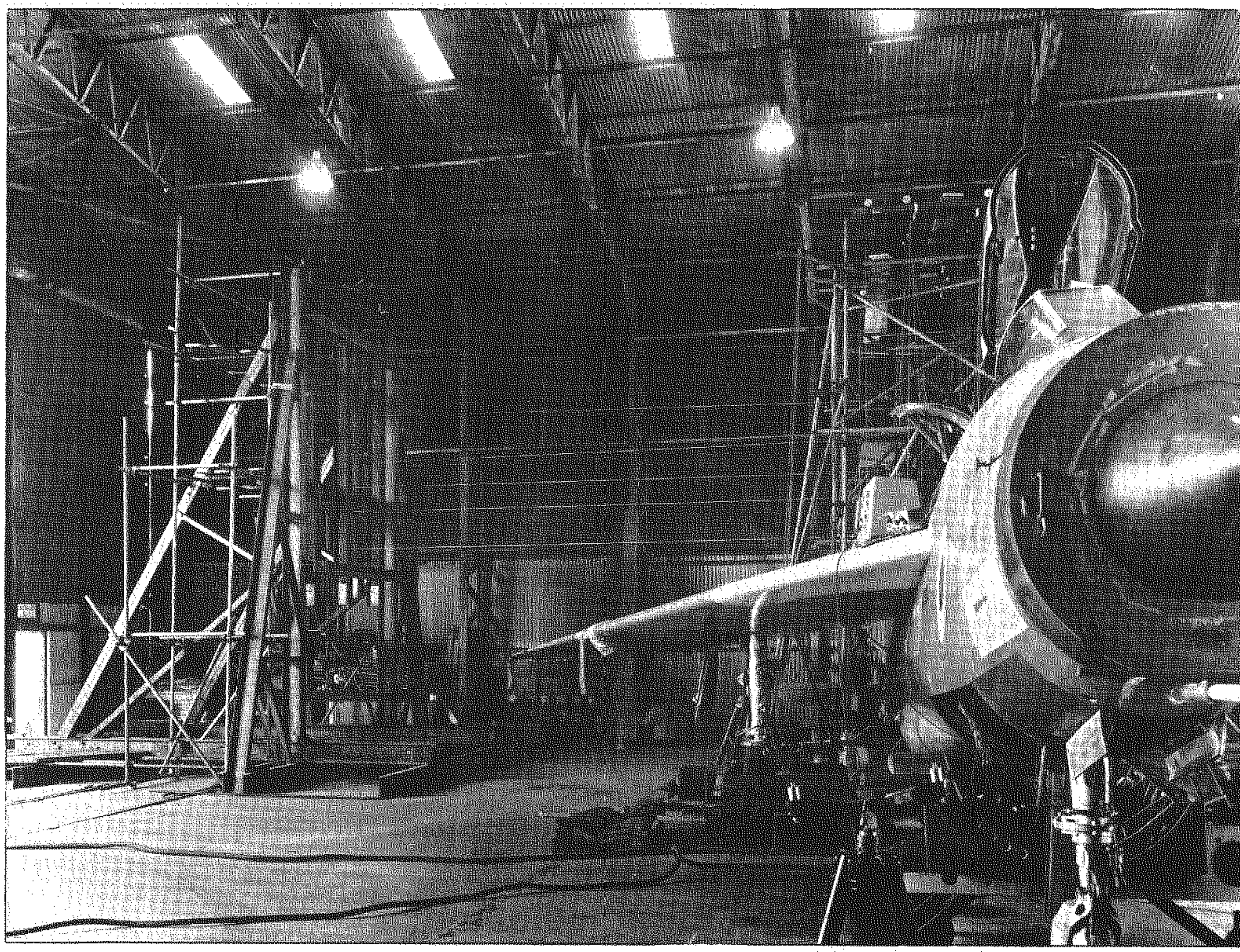


Fig.17. General view of loading rig for distributed load

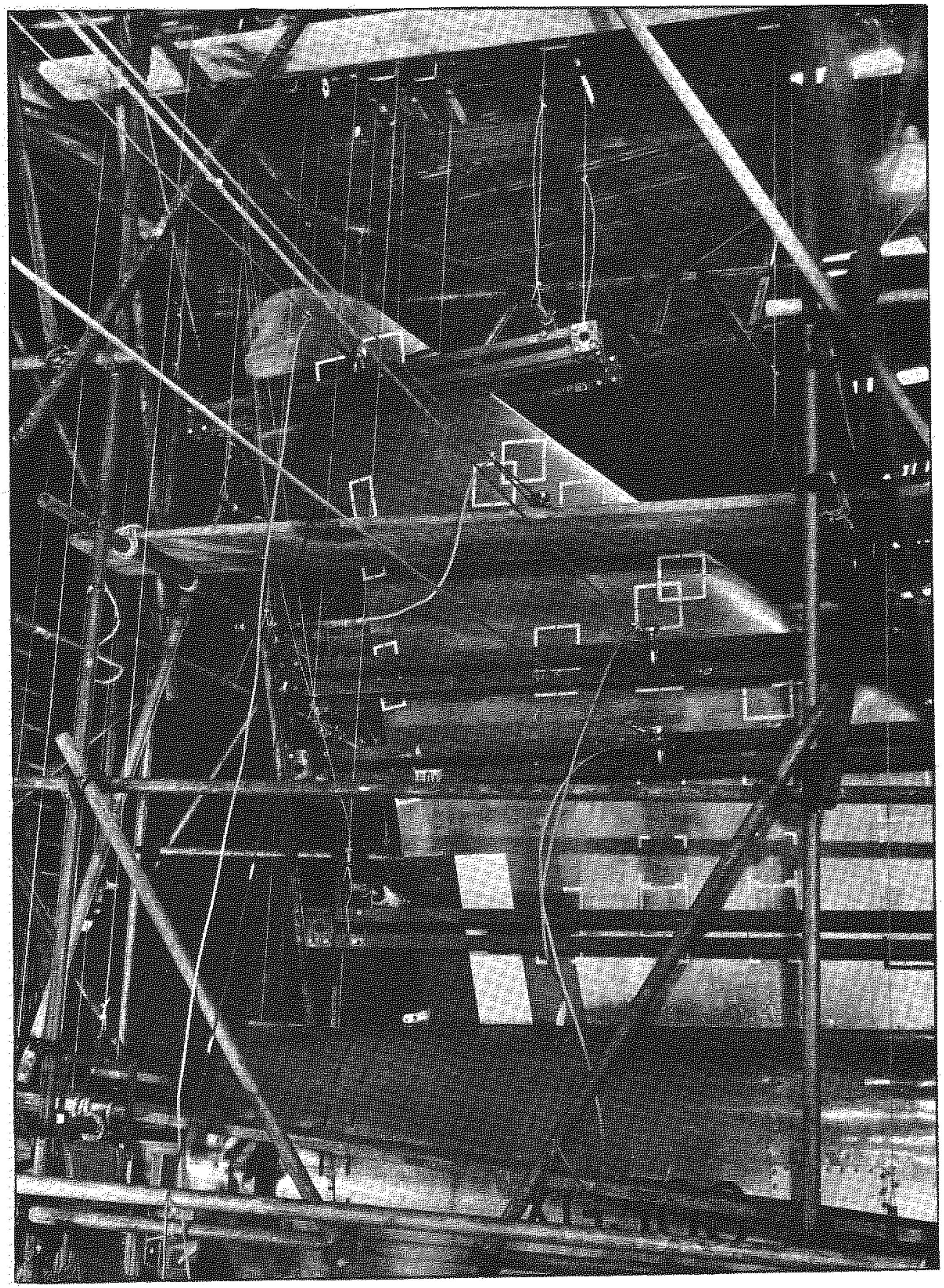


Fig.18. Loading beam system for distributed load (starboard view)

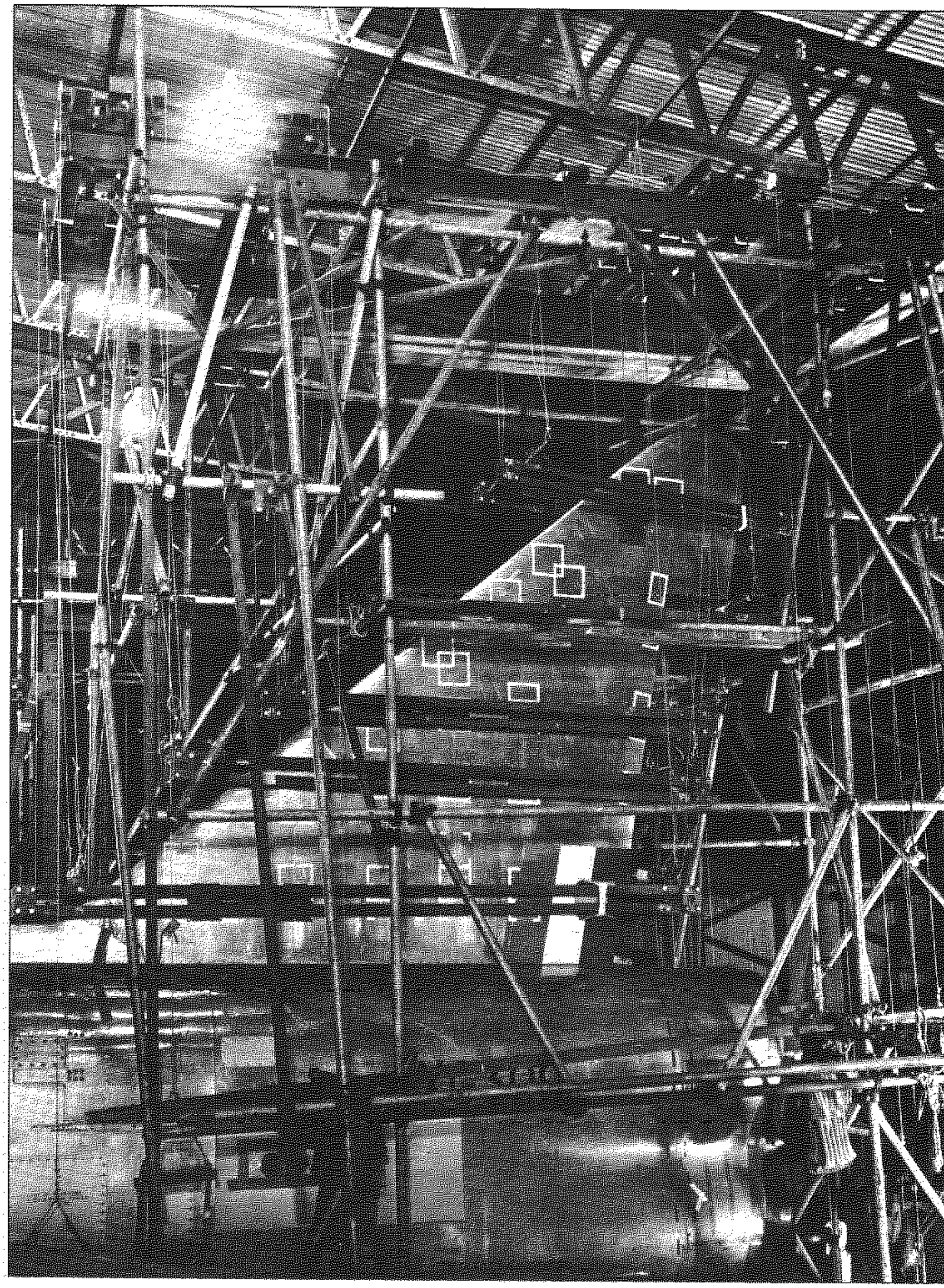


Fig.19. Loading beam system for distributed load (port view)

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Roberts, T.A.

THE USE OF CALIBRATED STRAIN GAUGES FOR FLIGHT LOAD DETERMINATION

An American statistical technique was evolved for the measurement of flight loads, but is of restricted use when applied to low aspect ratio multispar structures. This Report describes a modification in which a mixture of distributed loads (assembled by superposition of individual loads) and individual loads together with their corresponding strain gauge responses is used as a regression sample. This method is demonstrated on test results from a flight programme to measure fin loads on a Lightning aircraft.

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