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ABSTRACT

This report presents an experimental investigation into the tension and compression behaviour of a plate specimen with a angled elongated hole. This specimen type will be used for validation of three life management options on the F-111 wing pivot fitting (DADTA, cold expansion/interference fit plug and stress bridge). Two different brands of strain gauges were used to determine their suitability for use in regions of high plastic strains. The buckling load capability of the plate specimen was determined and found to be suitable for further validation tests.

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Executive Summary

AMRL has been tasked by the RAAF to investigate methods of improving the fatigue life of the F-111 airframe. An area of concern on the F-111 is the wing pivot fitting manufactured from D6ac steel in which there are a number of machined fuel flow vent holes. Under Cold Proof Load Test (CPLT), one of these holes (#13) experiences extensive plastic deformation and resulting residual stress. These residual stresses are detrimental, and coupled with the remote load sequence, contribute to crack initiation/growth from the effected area. There have bee numerous incidents of fatigue cracks at fuel flow vent hole #13 (FFVH13) in the wing pivot fitting in the RAAF's F-111 fleet, and the problem could compromise the structural integrity of the fleet out to the planned withdrawal date of 2020.

The methods being considered at AMRL for managing the life of this area of the F-111 airframe include (i) the accurate calculation of applied and residual stresses using a unified constitutive material model in finite element analysis for use in a DADTA[1], (ii) the implementation of the cold expansion of the non-circular hole, followed by the installation of an interference fit plug and (iii) the implementation of a "stress bridge". All these methods require validation on a simple geometry before implementation on a wing assembly.

This report presents the experimental investigation into the tension and compression behaviour of a plate specimen with an angled elongated hole. This specimen type will be used for validation of the three life management options on the F-111 wing pivot fitting (DADTA, cold expansion/interference fit plug and stress bridge). Two different brands of strain gauges were used to determine their suitability for use in regions of high plastic strains. The buckling load capability of the plate specimen was determined.

It was found that the plate specimen could develop the same levels of strain as applied to FFVH13 during the wing test, allowing this specimen to be used in experiments to represent FFVH13 under CPLT loading. The buckling load was slightly below that required to achieve the high compressive strains, but future tests which decrease the plate free length will eliminate this problem. The two gauge types - Kyowa and Micro-Measurement were found to work equally well over the extreme strain range tested of -17776 με to 12671 με.

[1] Durability and Damage Tolerance Analysis

Contents

1. Introduction

AMRL has been tasked by the RAAF to investigate methods of improving the fatigue life of the F-111 airframe. An area of major concern in the F-111 is the wing pivot fitting manufactured from D6ac steel in which there are a number of machined fuel flow vent holes (FFVH). Under Cold Proof Load Tests, one of these holes, number 13, Figure 1, experiences extensive plastic deformation in the lower inboard corner, resulting in tensile residual stresses. These residual stresses are detrimental and, coupled with the remote load sequence, contribute to crack initiation/growth from the affected area. There have been numerous incidents of fatigue cracking at FFVH13 in the wing pivot fitting in the RAAF's F-111 fleet, and the problem could compromise the structural integrity of the fleet out to the planned withdrawal date of 2020.

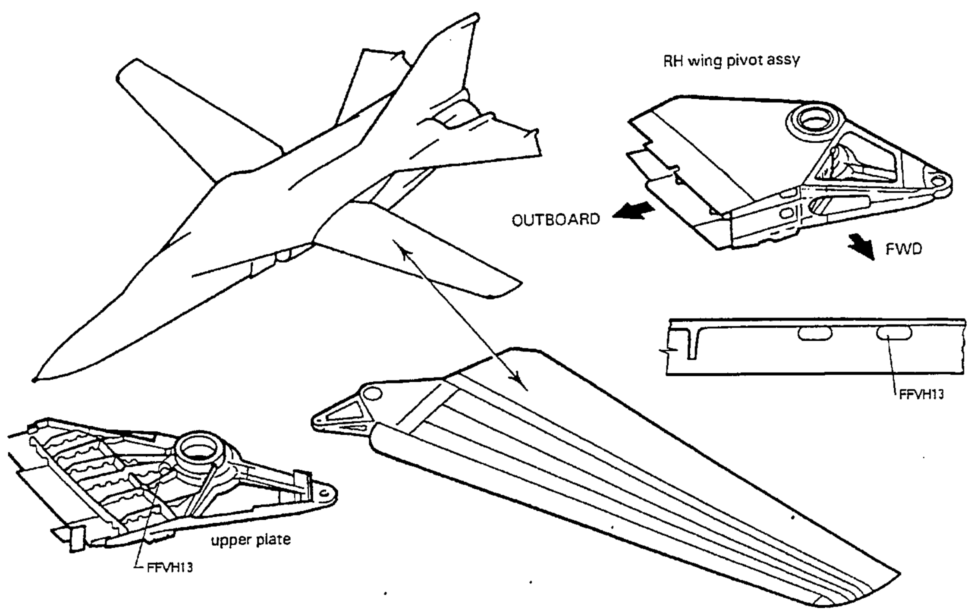

Figure 1: F-111 Aircraft & wing, showing location of critical hole, FFVH13

Currently, the problem is being managed by reworking the elongated fuel flow vent holes to a family of progressively larger shapes [1]. This process removes small cracks and corrosion as detected. The extent of the rework depends on the size of the detected crack. Unfortunately, the reworking does not completely eliminate further cracking, and at the current rate of crack growth and reworking, this method may not enable the aircraft to reach its desired service life. A Durability And Damage Tolerance Analysis (DADTA) is presently being used to certify the rework shapes as valid for managing this critical location. If the reworking procedure cannot allow the aircraft to reach life of type, an alternative method of life extension will need to be found to eliminate crack growth or significantly reduce the crack growth rate.

This report describes preliminary tests on a FFVH13 plate specimen to determine its strain versus load response and buckling strength. These tests were designed to mimic the stresses occurring at the critical point of FFVH13 so that studies into fatigue life improvement can be conducted. Those studies will include the following:

1. fatigue test of an open hole;
2. plasticity studies to validate a constitutive plasticity model for finite element usage in DADTA studies;
3. fatigue life improvement through the use of cold expansion and subsequent interference fit plugs; and
4. stress bridge life extension option.

2. Wing Test Results

A 1995 strain survey of an F-111 wing was reported by Lillingston [2]. Fuel flow vent hole #13 (FFVH13) in this test wing had been slightly ground out at some stage during its prior service. This means that the "baseline" strains determined from Reference 1 are not precisely applicable to a hole of original blueprint shape. This causes some correlation inaccuracy because the FFVH13 plate specimen had a hole of blueprint shape (but scaled up).

The strain locations relevant to this report were for gauges 72 & 73 in Reference 2 (see Figures 2 & 4). Gauge 72 is the more critical of the two, being at the lower inboard corner of FFVH13, and its output was used as the target for the FFVH13 plate specimen of this report.

The relevant strain gauges used in the Reference 2 survey were Kyowa[1] brand, type KFG-1-120-D9-11N10C2, consisting of five elements each of 1mm length and 2mm pitch with gauge elements parallel to the strip.

The exact overall dimensions of the FFVH13 in the test wing were recorded in Reference 2 and are presented in Figure 3 compared with two possible blueprint original locations - "original 1" is considered to be the most likely position of the original hole. The nominal blueprint overall dimensions of the hole are 1.5 inch x 0.5 inch (38.1 mm x 12.7 mm). This would mean that a 10 mm long strip gauge would take up the complete quarter radius as shown in Figure 2 and Figure 4, from Reference 2.

[1] Kyowa denoted strain gauges manufactured by Kyowa Electronic Instruments, Tokyo, Japan.

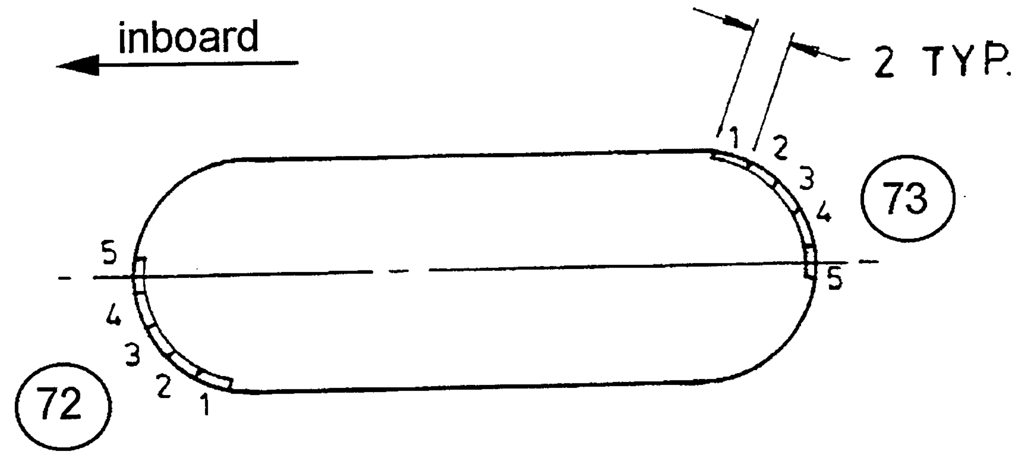

Figure 2: Location of Kyowa strip gauges number 72 & 73 on the bore of FFVH13.

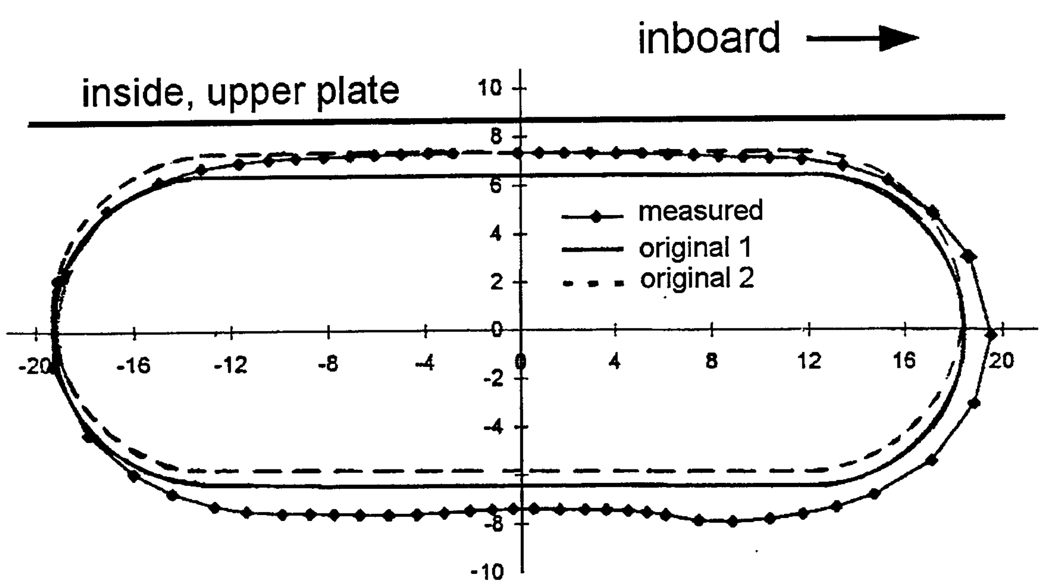

Figure 3: Measured shape of FFVH#13 compared with the original blueprint mousehole shape in two possible locations.

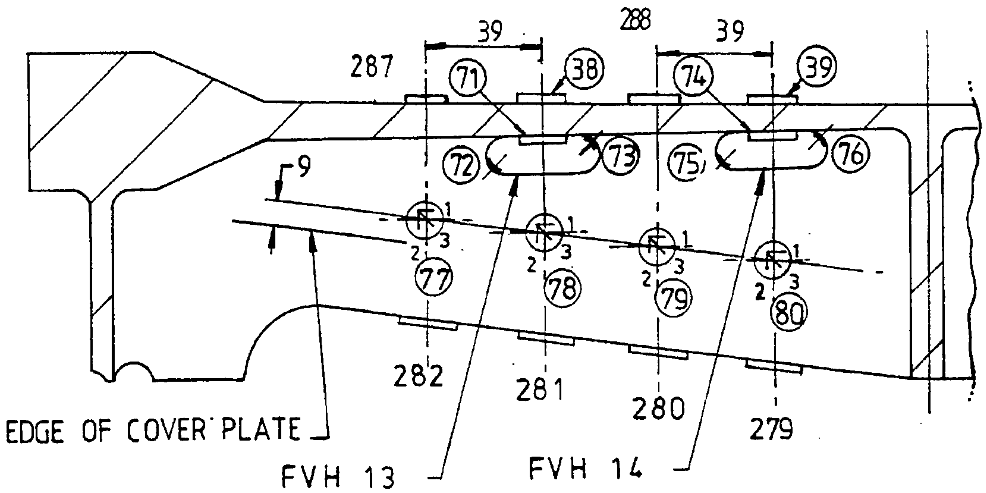

Figure 4: Location of FFVH13 in relationship to the surrounding structure and gauges [3]

The results for gauges 72 and 73 from the Reference 2 wing strain survey are tabulated below for maximum down load and maximum up load. Cases 15 and 16 corresponding to -2.4 g and 7.33 g respectively at 56° wing sweep.

Table 1: Strains during loading to maximum CPLT[2] DOWN loading, -2.4 g.

	Gauge I.D.				
Load	72-1	72-2	72-3	72-4	72-5
%CPLT	με	με	με	με	με
0	482	727	953	229	-34
20	1192	1527	1854	994	376
40	1906	2331	2755	1745	770
60	2621	3147	3679	2504	1161
80	3378	4039	4688	3274	1531
100	4314	5345	5998	3979	1761
80	3583	4525	5067	3180	1331
50	2486	3293	3693	2037	740
20	1424	2102	2369	940	174
0	734	1327	1509	229	-194

[2] CPLT stands for Cold Proof Load Test and 100% CPLT is the maximum load applied in the strain survey of Reference 1.

Table 2: Strains during loading to maximum CPLT UP loading,+7.33 g.

	Gauge I.D.				
Load	72-1	72-2	72-3	72-4	72-5
%CPLT	με	με	με	με	με
0	645	757	708	347	295
20	-2003	-2250	-2724	-2593	-1343
40	-4681	-5340	-6318	-5727	-3165
60	-7418	-8530	-10060	-8878	-4950
80	-10176	-11933	-14264	-12151	-6548
100	-13180	-16353	-21549	-17316	-7047
80	-10590	-13425	-18201	-14364	-5322
50	-6531	-8732	-12676	-9536	-2573
20	-2359	-3618	-6288	-4412	-113
0	559	215	-1373	-930	1125

The strain gauge values in Tables 1 and 2 become the "target" values for the specimen test on the FFVH13 plate specimen, ie testing was to be done with the tension load being applied until a maximum strain of 5998 με was seen, then compression to -21549 με.

Figure 5 presents the wing strain results from Reference 2 for gauge 72 for the two load cases under consideration - CPLT UP (compressive strain) and CPLT DOWN (tension strain). Of interest is that the strains remain all of the same sign for a given load case - something that proved different to the test specimen (Section 6).

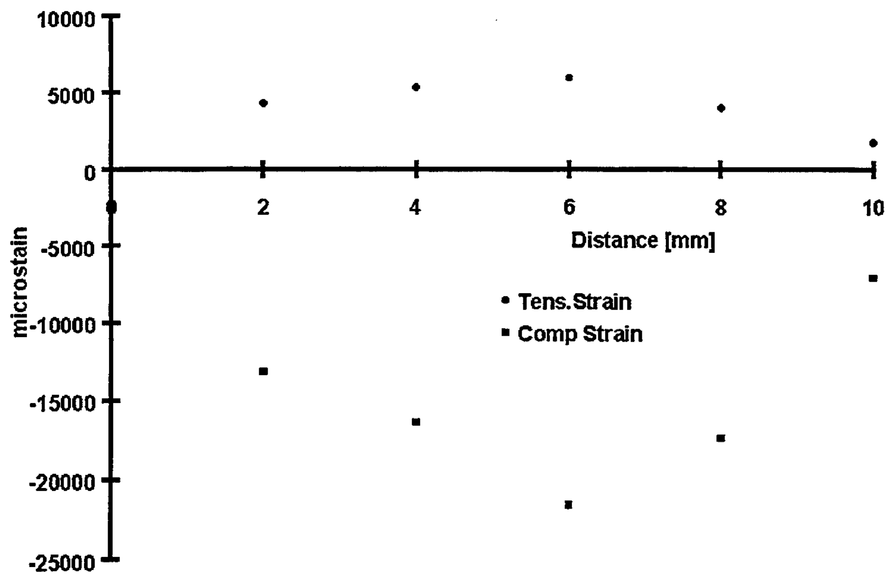

Figure 5: Strains around FFVH13 as a function of distance along strip gauge

3. Test Specimen

A test specimen design existed from prior analysis. Figure 6 gives the dimensions of the specimen. The design was such that it would:

1. represent the stresses existing in the FFVH13 (see Reference 4); and
2. represent a plug size that would cover the majority of the current F-111 fleet size and shape configurations of FFVH13.

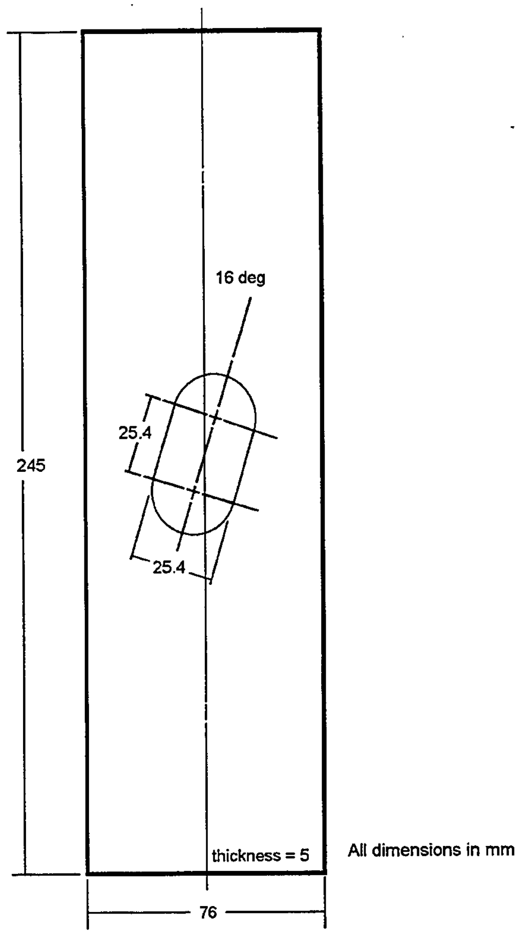

Figure 6: Geometry of test specimen

Strain gauges were fitted to the test specimen as shown in Figure 7. A Kyowa strip gauge is shown in the top left radius of the hole, numbered "strip_1" through to "strip_5". A Micro-Measurements[3] strip gauge is shown in the bottom right radius, numbered "s2_1" through to "S2_10". Gauge elements s2_1, s2_3 & s2_6 were inoperative through the test. Elements s2_3 & s2_6 were damaged during installation (Micro-Measurements strip gauges do not come pre-wired and are therefore more susceptible to damage), and s2_2 failed prior to test for an unknown reason. This meant there was no gauge at the critical point in the hole for the MM strip gauge.

[3] Micro-Measurements denotes gauges manufactured by the Micro-Measurements Group of Measurements Group Inc, North Carolina, U.S.A.

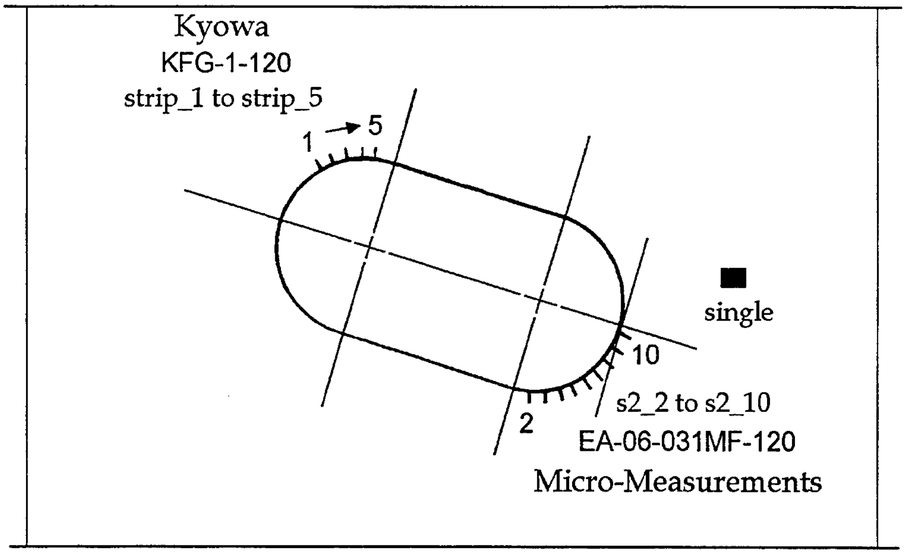

Figure 7: Strain gauge locations on specimen

4. Test Loading

Test loading was intended to simulate the CPLT loading of the wing, however the exact value of this loading was not known in advance. Strain gauges were monitored so that the load required to achieve CPLT measured wing strains could be determined.

Maximum loads were set for testing machine operation as 190kN in tension and 310kN in compression. It was expected that the maximum strains, equivalent to those in the wing test would be achieved well before these values

Tensile loading was done in steps as follows: 0 kN, 49 kN, 99 kN, 123 kN, 150 kN, 174 kN, 188 kN. Unloading was to be done in steps as follows: .163 kN, 149 kN, 126 kN, 101 kN, 52 kN, 0 kN.

During the tension loading, strain gauges were monitored and were found to show significantly lower strains than those predicted. It was decided that the test should continue until the tension load sequence was completed before trying to rectify the anomaly. This decision was made on the basis that the loading sequence selected would not cause any damage to the specimen that would effect its compressive buckling capacity - the primary reason for the test.

The reason for the anomalous results was that the set-up software had an erroneous entry, causing strains to be out by a factor of 10. The results in Section 5 are corrected data.

Compressive loading was done in steps as follows: 0 kN, -52 kN, -100 kN, -125 kN, -151 kN, -175 kN, -200 kN, -226 kN. Buckling then occurred at approximately -245 kN to -249 kN, and the component was unloaded with the steps as follows: 204 kN, -148 kN, -100 kN, -52 kN, 0 kN.

5. Test Results

The results for all strain gauges during the tension cycle of the loading are shown in Figure 8.

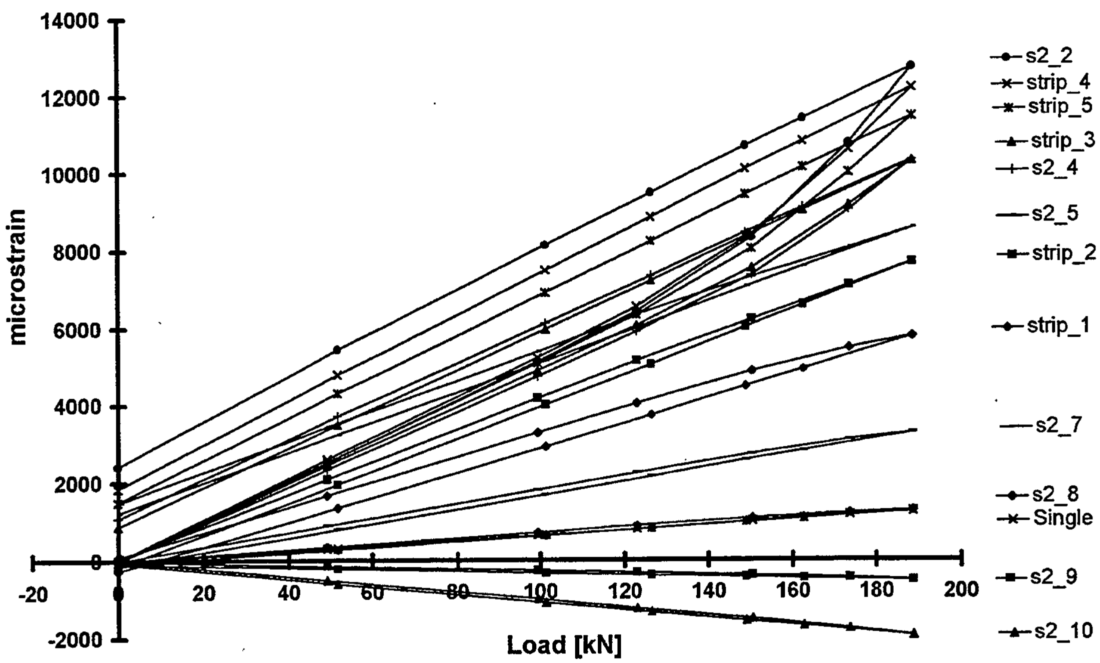

Figure 8: Strain vs load results for all strain gauges during tension loading. Strip_i denoted Kyowa gauges. s2_i denotes Micro-Measurements gauges. The single gauge is a Micro Measurements gauge.

The Kyowa gauge "strip_4" and the Micro-Measurements gauge "s2_2" gave the highest gauge readings at each location, though these values are unlikely to be the maximum value experienced on the hole radius. The full set of strain data from the tension and compression tests is given in Tables 3 and 4. For the tension data in Table 3 the response of these gauges are compared in Figure 9 to the maximum of 5045 με (= 5998 με - 953 με) seen during the static test of the wing in CPLT DOWN loading case.

Gauge element s2_5 had a large zero offset from the beginning of the test. The reason for this is unknown. If this data were corrected for the zero offset, the results would be consistent with the gauge elements s2_4 and s2_7 (the two closest gauge elements). Corrected data is not presented as it was not needed for this study.

Table 3: Strain gauge results - CPLT DOWN

Load	strip_1	strip_2	strip_3	strip_4	strip_5	s2_2	s2_4	s2_5	s2_7	s2_8	s2_9	s2_10	Single
kN	με												
-0.035	61	10	14	14	17	15	18	1559	-5	-23	-39	-23	1
-0.035	64	11	89	4	6	8	14	1560	1	-17	-37	-25	-5
-0.035	57	4	5	4	9	9	15	1551	-2	-18	-35	-24	-3
0.2463	108	57	41	40	19	10	21	1499	7	-3	-21	-8	-10
49.251	1671	2084	2441	2600	2513	2519	2337	3433	901	352	-143	-504	320
99.341	3278	4165	4886	5220	5081	5114	4730	5378	1807	720	-254	-1000	650
122.83	4021	5141	6041	6523	6316	6398	5884	6309	2244	891	-313	-1237	802
150.49	4861	6195	7508	8377	8005	8288	7331	7279	2713	1075	-378	-1506	999
173.66	5456	7067	9122	10560	9964	10720	8998	8025	3075	1215	-452	-1762	1161
188.48	5758	7653	10268	12150	11416	12671	10270	8541	3267	1281	-515	-1933	1249
162.62	4905	6564	8989	10779	10100	11358	9059	7547	2800	1086	-462	-1684	1082
149.01	4470	5999	8316	10053	9398	10651	8418	7029	2565	996	-430	-1560	985
126.36	3727	5031	7188	8829	8208	9444	7308	6121	2143	823	-379	-1333	827
101.16	2920	3991	5943	7471	6893	8112	6098	5142	1683	637	-322	-1085	653
51.7	1354	1944	3483	4788	4307	5438	3708	3233	800	280	-211	-603	311
-0.168	-260	-154	881	1853	1493	2410	1091	1222	-136	-97	-82	-69	-14

Table 4: Strain gauge results - CPLT UP

Load	strip_1	strip_2	strip_3	strip_4	strip_5	s2_2	s2_4	s2_5	s2_7	s2_8	s2_9	s2_10	Single
kN	με												
-0.037	7	8	7.0809	3.1659	-1.7	-2	-5	-2	-6	-1	3	5.9	4
-2.490	-93	-110	-123	-126	-124	-123	-120	-92	-59	-29.5	1	28	73
-51.68	-1646	-2105.7	-2456	-2648	-2583	-2628	-2439	-2025	-945	-374	123	512	-227
-100.3	-3090	-3992	-4862	-5403	-5198	-5561	-4912	-3866	-1775	-691	252	997	-544
-125.3	-3765	-4902	-6175	-7029	-6725	-7447	-6340	-4781	-2180	-840	332	1256	-699
-151.1	-4407	-5796	-7562	-8798	-8359	-9489	-7855	-5700	-2570	-974	425	1532	-853
-175.1	-4971	-6652	-8968	-10664	-10064	-11660	-9402	-6567	-2921	-1092	517	1793	-1004
-200.3	-5487	-7578	-10615	-12903	-12164	-14303	-11207	-7501	-3255	-1192	627	2077	-1158
-226.0	-5924	-8608	-12649	-15779	-14874	-17776	-13415	-8493	-3480	-1213	798	2404	-1377
post buckling με													
-204.0	-5082.5	-8530.2	-14493	-20185	-20853	-27823	-15973	-8555	-2778.	-727.1	1085.9	2560.1	-4051
-148.6	-3150.4	-6151.5	-11883	-17644	-18644	-24781	-13046	-6120	-1670.	-267.9	987.43	2017.8	-2266
-100.3	-1581	-4107	-9447	-15032	-16167	-21913	-10499	-4113	-803.8	55.691	846.16	1512.2	-1416
-50.22	-63.758	-2018.5	-6774.4	-12064	-13242	-18621	-7770.	-2073	40.818	353.56	673.94	971.51	-803
1.0654	1379	148.83	-3761	-8490.8	-9776	-14564	-4613	4.6	848.09	632.1	479.46	401.63	-283

The validity of the data can be checked against the theoretical stress concentration as follows:

At an applied load of 99.341 kN the plate is still elastic and the following average strain can be calculated.

$$\begin{aligned}\varepsilon &= \frac{\sigma}{E} \\ &= \frac{99.341}{75\times 5}\times\frac{1}{209{,}000} \\ &= 0.0012675 \\ &= 1267\,\mu\varepsilon\end{aligned}$$

This is compared with the far-field gauge "single" which gives 649.5 $\mu\varepsilon$ and the maximum strain of 5114 $\mu\varepsilon$ - a stress concentration of 4 on the average stress. This K_t=4 is consistent with finite element calculations , indicating that the "single" gauge is not measuring far-field strain.

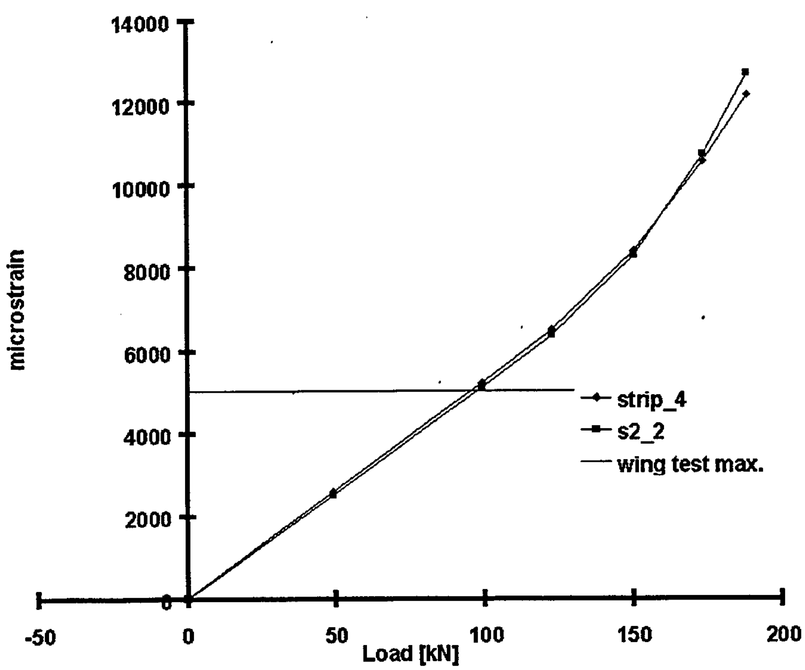

Figure 9: Response of gauges s2_2 and strip_4 during tension loading compared to the maximum seen during wing test in Figure 7.

From Figure 9, it can be seen that some plasticity exists after about 100kN load, which also corresponds to the point where the wing strain is reached.

At the load levels of 150.5kN and 173.6kN, the strain distributions around the hole radii were as shown in Figure 10. This indicates that the Kyowa and Micro-Measurements gauges were giving good correlation to points above yield onset. It also indicates that the strain distribution around the specimen hole goes negative - something that does not occur with the wing strain gauge (compare to Figure 4).
Note : the wing strain gauge is the same length as the Kyowa gauge, but the wing hole is of smaller radius.

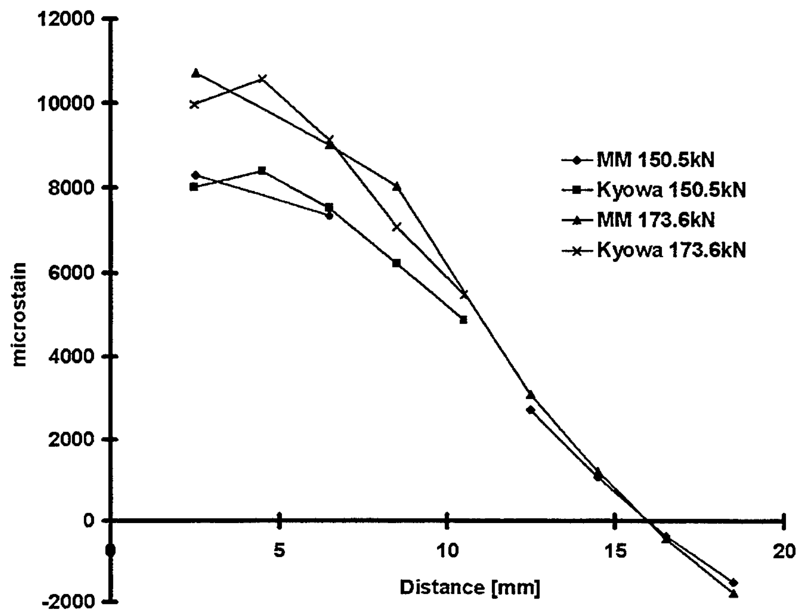

Figure 10: Tension strain versus gauge distance from tangent point - Kyowa & Micro - Measurements strain gauges. Loads 150.5kN & 173.6kN

After yielding and at the maximum tensile strain point, the results are shown in Figure 11. This shows that one end of the hole is experiencing higher strains - possibly due to slightly different material properties influencing a different yield onset.

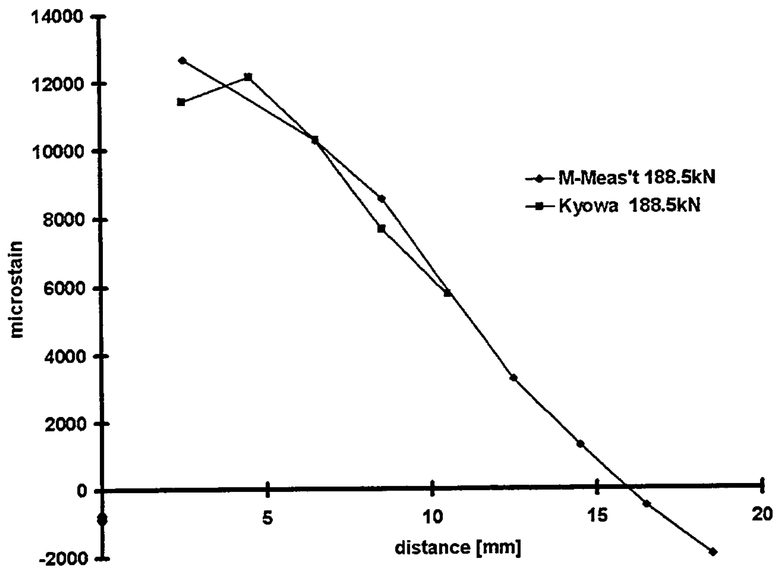

Figure 11: Maximum tension strain versus gauge distance from tangent point - Kyowa & Micro - Measurements strain gauges.

The reason for using both Kyowa and Micro-Measurements gauges in the same, but opposite locations was to determine the differing (if any) responses of the gauges after removal of the load. Figure 12 plots the gauge offset after removal of the tensile loading. There is no reason to suspect any difference between Kyowa and Micro-Measurements gauges based on this limited information. The compressive cycle is more severe, and could show a difference.

Complete data would include the same information for the compressive side of the loading, but since the specimen buckled, these data are not available.

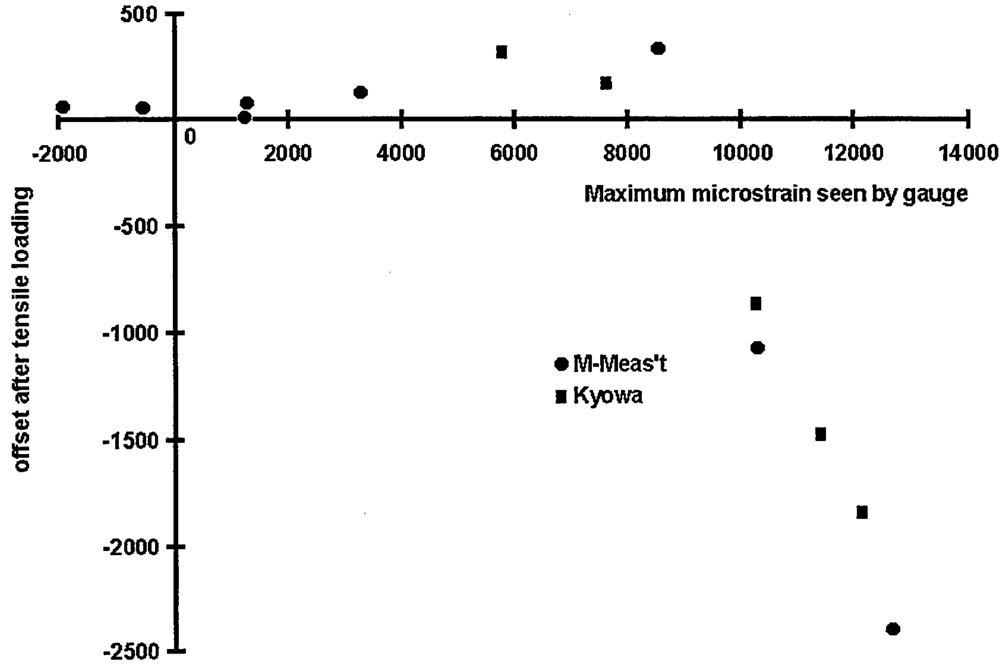

Figure 12: Gauge offset versus maximum strain seen by gauge during tension loading

Gauges were zeroed at the beginning of the compression cycle as the data acquisition system needed to be re-calibrated because of the aforementioned error. Results cannot be looked at in isolation - all gauges having a degree of offset indicated in Figure 8 and Figure 12. Figure 13 presents the strain results during the compressive cycle, with Figure 14 presenting the same data of strains occurring up to buckling.

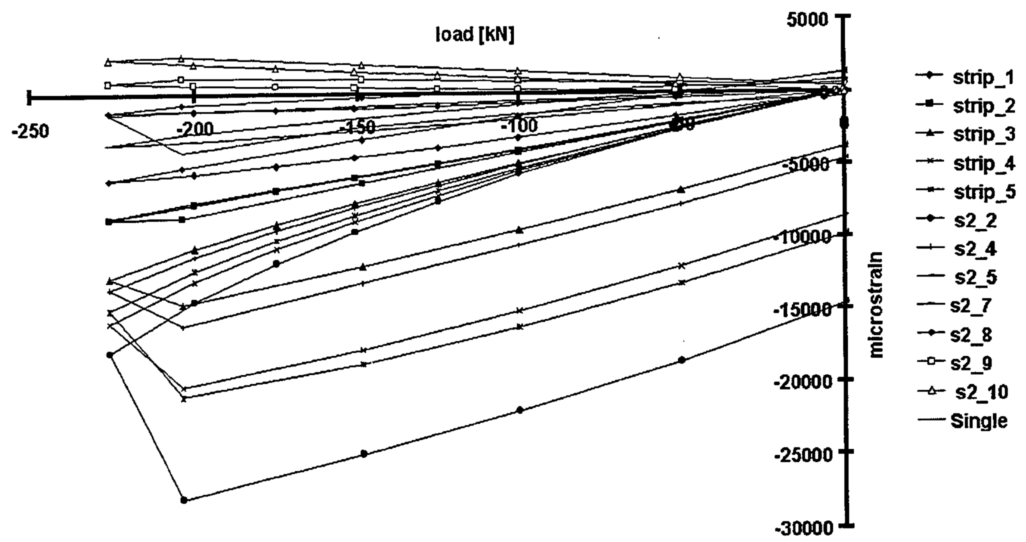

Figure 13: Strain vs load results for all strain gauges during compression loading. Strip_x denotes Kyowa gauges. s2_z denotes Micro-Measurements gauges. The single gauge was a Micro-Measurements gauge.

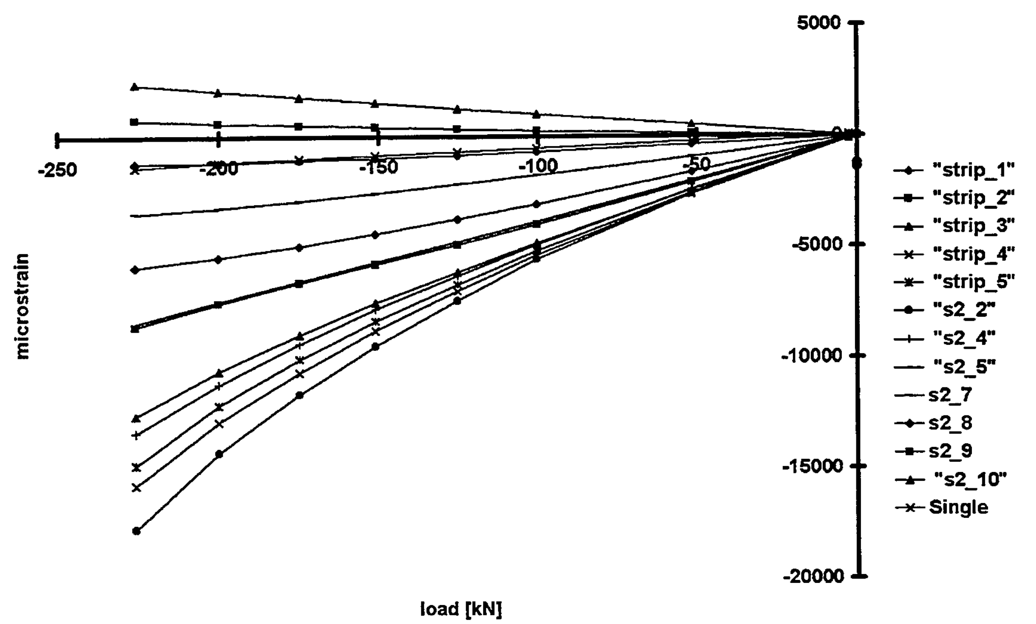

Figure 14: Strain vs load results for all strain gauges during compression loading up to point of buckling. Strip_x denoted Kyowa gauges. s2_z denotes Micro-Measurements gauges. The single gauge is a Micro-Measurements gauge.

The strip gauge element s2_2 reached a strain of -17776 με at -226 kN - the last measurement before buckling at approximately 248 kN. As the gauges had been zeroed, an additional strain equal to the gauge offset at the end of the tension loading should be added. This additional value is 2410 με.

The test specimen reached a load of 248 kN. This was a lot lower than the value predicted, so it came as a surprise. Figure 15 shows the out of plane deflection versus load during the compressive cycle.

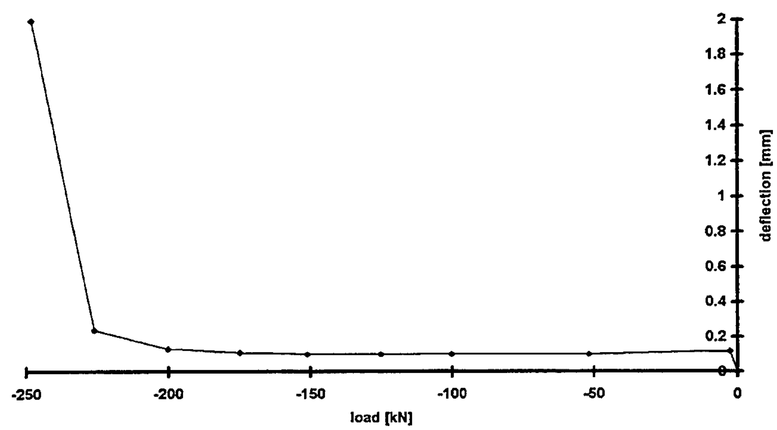

Figure 15: Load vs out of plane deflection showing onset of buckling

The response of gauge element s2_2 is given in Figure 16 with the line extrapolated out to 250kN. It is easy to see that the specimen was very close to reaching the target 21549με.

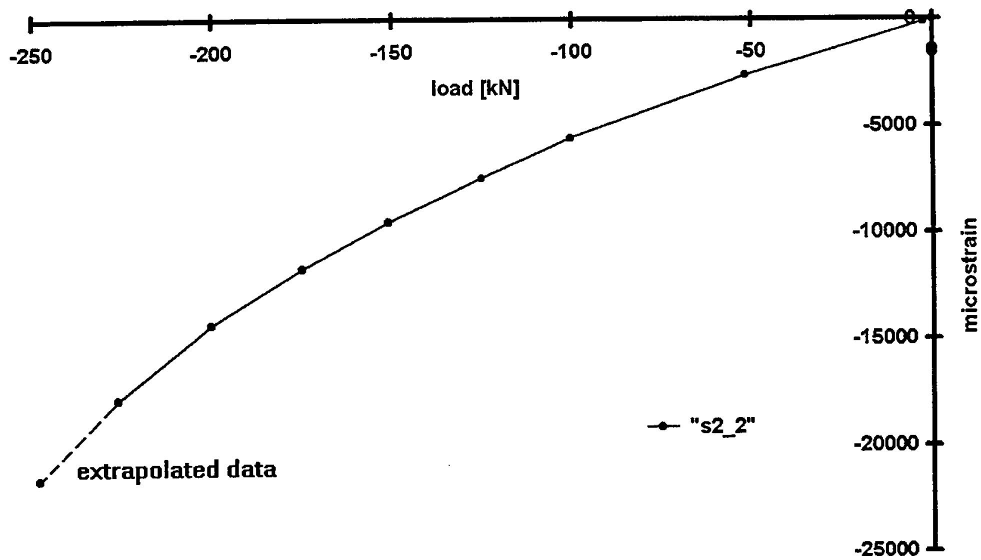

Figure 16: Load vs strain at gauge element s2_2 showing extrapolated data (if no buckling had occurred)

The response of the Kyowa and Micro-Measurements gauges can be compared side-by-side as shown in Figure 17 at different load values. Values are plotted around the radius with the zero being the tangent between the radius and the flat side of the hole.

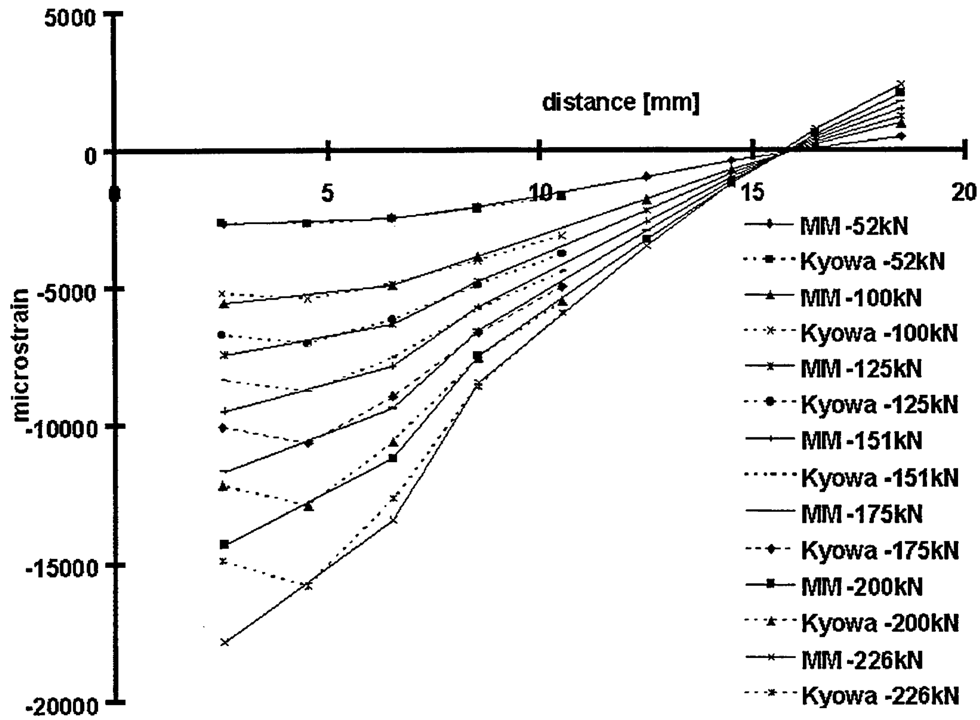

Figure 17: Strain gauge comparison between Kyowa and Micro-Measurements gauges at different load steps.

6. Conclusions

This report has produced strain results for a plate specimen with an angled elongated hole under tension and compression. These results form the basis for further testing and analysis of life extension methods for the F-111 by determining loading of the plate specimen for: (i) testing cold expansion and interference fit plugs, (ii) testing the "stress bridge" concept and (iii) validating the unified constitutive model implemented in PAFEC level 8.

This experimental stress analysis has shown that the plate specimen can produce the required strain levels within the capacity of a 300kN testing machine. The -2.4 g condition is achieved by a specimen load of just over 100 kN. The load required to achieve the +7.33 g condition needs to be established from another test with premature buckling prevented, but could be of the order of -250 kN.

Results indicate that both Kyowa and Micro-Measurements gauges operated similarly through the range of loading tested and there is no reason to prefer one to the other.

Note: the Kyowa gauges have been used in the F-111 testing [2] because they come pre-wired which is an advantage in the confines of the F-111 wing.

All gauge elements in the critical location need to be operational before the test commences. Insufficient data at or near the critical point makes correlations harder.

The gripping of the specimen should not give a test length greater than 120mm. This should **preferably be less than 110mm** to maximise the buckling load in future tests.

7. Acknowledgments

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Robert B. Allan

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19. ABSTRACT

This report presents an experimental investigation into the tension and compression behaviour of a plate specimen with a angled elongated hole. This specimen type will be used for validation of three life management options on the F-111 wing pivot fitting (DADTA, cold expansion/interference fit plug and stress bridge). Two different brands of strain gauges were used to determine their suitability for use in regions of high plastic strains. The buckling load capability of the plate specimen was determined and found to be suitable for further validation tests.

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