THE IDENTIFICATION OF FATIGUE-CRITICAL REGIONS DURING FATIGUE TESTING OF MACCHI MB326H CENTRE SECTION LOWER BOOMS

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ABSTRACT

Early fatigue testing of the Royal Australian Air Force (RAAF) Macchi MB326H jet trainer aircraft indicated that the most fatigue-critical regions in the steel centre-section booms were bolt holes; the structural integrity of the centre-section has been managed, in part, on a safety-by-inspection basis focussed on specific highly-stressed bolt holes in the lower spar booms. Recently, tear-down of centre-sections as part of a fleet re-lifing program disclosed corrosion defects in screw holes in the booms, leading to concern that the corroded screw hole geometry might now be more critical than the bolt hole location. To resolve this problem, a series of component fatigue tests was conducted at AMRL, using lower boom samples which had seen extensive service, to determine the relative criticality of the screw holes and bolt holes. Fractographic analysis was performed on all significant cracking found.

Detailed analysis using a novel fractographic approach, identified a region in which the close proximity of several screw holes to bolt holes in the main body of the booms produced crack growth rates similar to the most severe bolt hole cracking, whilst cracking from isolated screw holes was significantly slower than the critical bolt holes. This result was predicted prior to the occurrence of a failure in this region. The existence of service-induced corrosion did not appear to significantly affect crack growth rate. The novel use of fractography to determine criticality has subsequently been used as an aid in interpreting early fatigue crack growth in components from other aircraft types.

KEYWORDS

Macchi MB326H, fatigue, crack growth initiation, crack growth, corrosion, quantitative fractography

INTRODUCTION

After loss of a Macchi MB326H jet trainer aircraft in 1990, the RAAF initiated a Macchi Recovery Program (MRP), part of which involved a re-assessment of the centre-section fatigue life. The centre-section lower boom is a fatigue critical component, thought to be second in criticality only to the wing main spar lower cap. Evidence supporting this level of criticality had been discovered during routine in-service inspections and tear-down inspections of service centre sections which disclosed that eight lower boom flange bolt holes contained small fatigue cracks (no cracking was found in the upper spar booms) and significant corrosion damage existed in the lower boom screw holes, two of which were found to exhibit associated fatigue cracking.

The spar booms examined in this teardown were of the 'O4C' geometry and material – a retrofit to the aircraft during a Life-Of-Type EXtension (LOTEX) program carried out during the early 1980s. This type of boom replaced the 'O4A' boom originally fitted to the aircraft during manufacture. Although the O4C boom had not been subjected to a full-scale fatigue test, it was considered to be more fatigue resistant than the O4A spar boom, and the critical holes (the holes from which the lead fatigue cracks would grow) were thought to be the same as those in the O4A spar boom for which extensive testing and service inspection data existed.

Although the RAAF uses a safe-life approach to managing Macchi boom structural integrity, the critical bolt holes are monitored in service by NDI as a precaution. However, the unexpectedly severe corrosion defects observed in the tear-down, combined with the unknown crack growth rates for fatigue cracking from such defects (and indeed for cracking in the O4C type booms) clearly demanded further investigation to determine the overall fatigue lives of the O4C booms relative to those of the O4A booms and more specifically the criticality of the corroded screw holes compared to the flange bolt holes. Fatigue testing of the lower boom was undertaken to address these matters.

A limited number of booms were available for testing. The O4C booms were obtained from service aircraft (writing off the airframe in the process), while only four of the pre-LOTEX O4A booms could be found in storage. To compensate for this limited specimen availability, complete post-test teardown of the O4C test articles was undertaken to acquire fatigue crack growth information from all boom details; all holes from the first four O4C test booms were examined destructively after failure. The extent of information obtained from these tear-down results considerably improved the confidence in the results of the testing and the understanding of the critical regions of the lower spar boom.

During the tests, further objectives were added to the test program. These were to determine:

a. the criticality of the screw holes relative to the fatigue performance of life-enhanced bolt holes (e.g after reaming and cold expanding bolt holes);
b. the criticality of regions in which screw holes intersect or come close to intersecting other holes in the boom.

Spar Boom Nomenclature

All holes in the lower spar boom were designated according to the schematic diagram in Fig. 1. Hole numbers without an alpha prefix are the critical flange bolt holes. Otherwise, the letters stand for; S:-Screw, WAHPF:-Wing Attachment Hole Port Forward, WAHSF:-Wing Attachment Hole Starboard Forward, SWAHPF:-Small Wing Attachment Hole Port Forward, SWAHSF:-Small Wing Attachment Hole Starboard Forward, VS:-Vertical Screw, VB:-Vertical Bolt, F:-Forward and A:-Aft. For example, S5F refers to the S5 screw hole in the forward face of the boom.

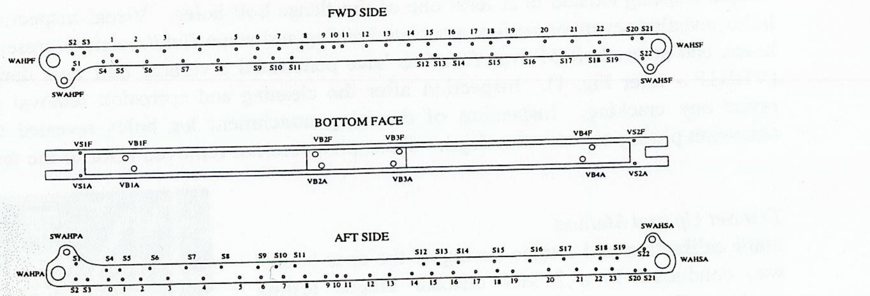

Fig. 1. Schematic drawing of the lower centre-section spar boom showing the hole numbering system used in AMRL investigations.

TESTING

Test Specimens

The spar booms were manufactured from AISI 4340 steel. All of the five O4C test booms except boom 084 conformed to this specification; boom 084 had a slightly high chromium content (0.92% vs a maximum of 0.90%). Hardness tests on the O4C booms indicated a UTS of 1110 - 1186 MPa, again with the exception of boom 084 which had an estimated UTS of 1380 MPa. The O4A spar booms were also AISI 4340 steel although specified to have a higher strength level than the O4C spar booms. Hardness tests indicated a UTS for the O4A booms of 1255 MPa.

The 084 spar boom appears to have been somewhat different to the other four O4C booms, in both composition and hardness, and further investigations revealed that the 084 boom was an O4C-geometry boom of particularly high hardness that was installed at original manufacture, not at LOTEX. This situation is unique, since all other fleet centre-sections were replaced at LOTEX. Therefore, the boom 084 was obtained from a material batch that was different to the remainder of the fleet, and this is associated with some interesting and unexpected results obtained on test.

The O4C type lower spar booms tested had accumulated considerable fatigue damage prior to the testing: -084: 268,530µf[1], -092: 293,640µf, -067: 257,640µf, -058: 231,800µf and -014: 101,520µf post-LOTEX. The lives of the O4A booms prior to the testing were unknown.

Condition of Test Articles

Screw holes were chemically cleaned of corrosion product followed by a borescopic inspection. Bolt holes were not cleaned physically since mechanical methods may have affected the fatigue characteristics of the test specimens. During each test the flange bolt holes were inspected using magnetic rubber and visual methods. Inspection of the lower spar boom 084 indicated that

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[1] A microfail (µf) is a measure of the fatigue damage experienced by the aircraft calculated using a fatigue damage model calibrated to the original full-scale fatigue test and data gained from the aircraft onboard fatigue meter. One µf equals 1 millionth of the life to failure of the original fatigue test. The fatigue damage for each specimen is the summation of the lower wing spar damage, pro-rata, for each set of wings fitted to the aircraft during its service life since LOTEX.

fatigue cracking existed in at least one of the flange bolt holes. Visual inspection of the screw holes revealed severe corrosion, associated pitting and some fluid/moisture presence within these holes, and screw hole 5F was found to have penetrated a vertical bolt hole during manufactur (VBH1F - refer Fig. 1). Inspection after the cleaning and corrosion removal process did no reveal any cracking. Inspection of the wing attachment lug holes revealed the presence o corrosion pitting of unknown depth—these pits were not removed prior to the test.

Test Set Up and Method

Static calibration and fatigue testing of the spar booms was conducted in a 2 MN uniaxial fatigue testing machine. Figure 2 shows the test arrangement. Load was applied using a "flight-by-flight" loading sequence consisting of a modified FALSTAFF 32 load level sequence of 35966 turning points, designed to simulate 220 flight hours of aircraft use, applied at a cyclic rate of approximately 3Hz; the load sequence was tailored to reflect RAAF usage over the period 1987 to 1990 inclusive. After the first O4A test, the sequence was modified, bringing the two highest loads closer together to help identify the sequence repeats for quantitative fractography of the cracking. No significant effect from the closer placement of the two highest loads in the sequence was envisaged, or detected.

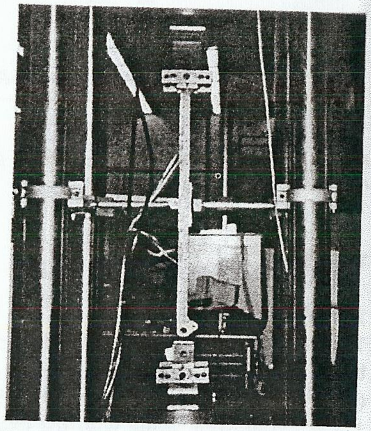

Fig. 2. The AMRL 2MN fatigue tes machine showing the test arrangeme

In order to generate loads which were representative of service loads in the main body of the spa booms ie. all the screw and flange bolt holes, it was necessary to increase the loading on the wing attachment lugs to approximately 110% of the relevant service loads. The lugs were believed t have a fatigue life only slightly lower than the critical O4A flange bolt holes, and it was predicte that the lugs might fail in these tests prior to a flange bolt hole. However, the first two O4A tria spar booms tested failed from the desired location so no fatigue enhancement methods were applied to the first O4C boom's wing attachment lugs.

DETAILS OF SPAR BOOM TESTING

Table 1 summarises the testing and investigations carried out on the Macchi centre-section lowe booms. Not all aspects of the testing and analysis are included in this paper.

O4A Lower Boom Tests. The first two O4A booms tested were used to confirm that the test se up was working satisfactorily, and that the loading sequence could be read fractographically.

O4C Lower Boom 084. Failure occurred in the port wing attachment lug at severe corrosio pitting in the lug hole. The boom also had a substantial crack at bolt hole 3F.

O4C Lower Boom 092. After the lug failure in the 084 boom from a large corrosion flaw specimen 092 was also found to have corrosion pits in the lug holes, so the lug holes of all subsequent test articles had their lug holes bored and honed to the maximum allowable oversize.

Table 1 Summary of test results

	Specimen	Failed at	Failure Area	Full quantitative fractography	MRI during test/ crack growth correlation	Fractographic growth estimates
1	O4A U/K	program 15	Bolt hole 19F fwd.	-	-	-
2	O4A -053 Pre LOTEX	program 18	Bolt hole 3F.	3F (depth and area).	-	-
3	O4C -084 Post LOTEX	program 17	Lug hole port forward.	hole 3F.	Flange bolt holes / some holes.	-
4	O4C -092 Post LOTEX	program 31	Lug end face port aft.	hole 3F.	Flange bolt holes / All cracked bolt holes.	All significantly cracked holes.
5	O4C -067 post LOTEX	program 41	16F and lug hole stbd fwd.	3F, 4F, 5F, 19F, 20F & 5A, 6A, 7A, 16, 20A.	Flange bolt holes.	All significantly cracked holes.
6	O4A -081 Pre LOTEX	program 17	4F	4F.	-	-
7	O4A U/K	program 16	20A.	20A.	-	-
8	O4C -058 Post LOTEX	program 36	19A	19F and 19A.	Flange bolt holes /All cracked bolt holes.	All significantly cracked holes.
9	O4C -014 Post LOTEX	program 46	S18F/VBH4F.	S5F/VBH1F (depth and area), S18F/VBH4F.	Flange bolt holes.	Two VBH/S cracks.

Boom 092 failed at the port aft wing attachment lug. Whereas the lug from boom 084 cracked from the bore of the hole, cracking in 092 initiated from the outside surface of the lug. The crack initiation points were deep pits in the outside surface of the lug, associated with the presence of manganese sulphide inclusions (stringers) in the material. The boom also had substantial crack growth at bolt hole 3F.

O4C Lower Boom 067. The lug surfaces in all booms tested after this time were glass bead peened to 18 Almen N. The 067 boom failed through bolt hole 16 however on removing the two parts of the test article from the machine the forward starboard wing attachment lug was found to have failed. Prior to the termination of the test (16A failure), the aft lug was taking virtually the entire load making the 16A crack growth data suspect. Lug cracking had initiated sub-surface from a very large surface-breaking group of 'blocky' particles of aluminium oxide, 250 µm wide (across the lug) by 13 mm long (in the axis of the boom).

Fig. 3 Boom 058; fracture surface holes 19F and 19A.

O4C Lower Boom 058. Since all the previously tested O4C booms had failed in at least one of the wing attachment lugs (while the main failure in 067 was from a bolt hole, the effect of the lug failure on the bolt hole failure was not clear), the primary goal of this boom test was to produce a single failure from a bolt or screw hole. The boom was prepared in the same manner as the 067 boom and it was hoped that no large inclusions of the type observed in the lug failure of 067 would exist in the lugs. The boom failed satisfactorily through the 19F and 19A bolt holes. The fracture surface is shown in Fig. 3.

O4C Lower Boom 014. The boom was prepared in the same manner as the 058 boom. In addition, after initial magnetic rubber inspection of all bolt holes, all bolt holes were reamed oversize to the nearest 0.5 mm on diameter above their present size to remove any machine tears, corrosion and other minor defects.

During the test several bolt holes were found to have cracked. The test was continued after these holes were reamed to the maximum oversize and cold expanded. The boom failed through the complex near-intersection of screw hole 18 forward (S18F) with vertical bolt hole VBH4F, through VBH4A and flange bolt hole 1A. No fatigue cracking was detected in flange bolt hole 1A. The fatigue cracking that caused failure had grown from the top and bottom of hole S18F and the aft side of the VBH4F, as shown in Fig. 4.

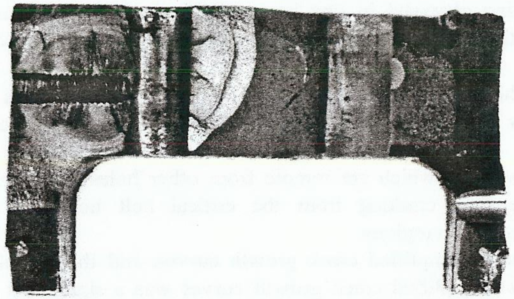

Fig. 4. Boom 014; fracture surface, holes S18F and VBH4F.

Inspection of the VBH1F hole revealed similar cracking to the crack that caused failure. The port end of the boom was loaded to establish the residual strength of the cracked VBH1F/S5F configuration, as an aid to assessing the life of the region. The boom failed (through S5F/VBH1F and VBH1A, similar to the STBD end) at a load of 1195 kN. This failure revealed fatigue cracking had grown from the top and bottom side of hole S5F and the aft side of the VBH1F (small fatigue cracks were detected in the VBH1A). The fracture surface appeared similar to the main (STBD end) failure although the fatigue areas were considerably smaller.

QUANTITATIVE FRACTOGRAPHY

After completion of the fatigue test on boom A7-092, the boom was torn down to reveal all the locations of fatigue cracking and the major fatigue cracks were examined using a novel rapid crack growth estimation method to indicate fatigue-critical areas. This method relies on use of log/linear fatigue crack growth curves; it is based on wide experience with crack growth determinations which indicate that crack growth tends to follow a straight line when plotted on a log/linear scale [2,3]. Such exponential behaviour is expected in the constant-amplitude loading case where crack growth per cycle is a function of $(\Delta K)^2$. The authors have observed, however, that many cases of variable-amplitude loading result in crack growth which aligns closely with this type of behaviour (see Fig 5 below). Fractography on the centre-section booms also showed that growth of major cracks began from the initial flaw during the first applied program i.e. the initiation phase of fatigue was not present. Combining these two observations, then if the initial flaw size and the final crack depth are known, a simplistic crack growth curve may be assumed from these two data points. Crack growth curves were produced by this means and plotted as log crack depth *vs* linear program number (or life). In this representation, the starting crack size is simply the initial flaw size, and the slope of the log/linear curve provides a measure of the severity of the stressing and materials parameters controlling crack growth from that flaw.

The determination of the initial flaw size was based on identifying a particular flaw in the region of crack initiation. This may have been a score mark, a pit or an intermetallic particle, in which case the size was taken to be the ellipse which fits around the boundaries. Where the flaw was long in comparison with its depth, the maximum depth was taken as the effective flaw size i.e. an edge crack configuration was assumed. Once the crack starts growing from the initial flaw, there is an anomalous crack growth regime [3], where various factors can influence crack growth:

(i) the influence of the initial flaw geometry on the local stress field
(ii) short crack growth conditions; differences in crack closure for long and short cracks at the same nominal stress intensity factor results in different crack growth rates
(iii) metallurgical and environmental influences on early crack growth.

Note that the initial effective flaw size here is a <u>measured</u> size, to distinguish it from the term "equivalent flaw size", which is a <u>notional</u> initial flaw which if allowed to grow according to some chosen growth law, will, later in life, duplicate the actual long crack sizes found in service.

In practical terms, the straight line representing exponential crack growth can be plotted based on the initial effective crack size and final crack depth. This approach permits crack growth to be estimated rapidly in situations where full fractographic analysis would be too time-consuming, or where crack sizes are too small to allow for extraction of fractographic growth information.

The approach described above is clearly based on several important assumptions; these assumptions, particularly the assumption of exponential behaviour, are currently the subject of further research and the results obtained using this approach must therefore be treated with appropriate caution. The estimation of initial defect size is itself particularly difficult; for example, which dimension of the defect is the critical one?

In the present case, the severity of the cracking was extracted by fitting an exponential curve with the general form:

$$(\text{crack depth}) = A \exp[B * (\text{programs})]$$

where B defines the slope of the log crack depth *vs* programs curve (see example in Fig 5), and therefore indicates the stressing severity (and indirectly the growth rate), and A is the initial flaw size.

RESULTS

Criticality Comparison, O4A vs O4C Booms.

Comparison of the crack growth from the O4A booms and the O4C boom major bolt hole cracks was based on the data shown in Fig. 5. Generally, the O4C cracks are slower than those in O4A booms, with one exception. This exception is the cracking from 084, which displayed a growth rate similar to the O4A booms, despite being of O4C geometry. This apparent anomaly is believed to be associated with the fact that the 084 boom is, surprisingly, manufactured from material very similar to the O4A material. Note that in Fig 5, crack growth from hole 3FWD upper on 092 initiated at a defect substantially smaller than the initiating defects for other geometrical features, highlighting the statistical nature of the crack growth process.

Criticality Comparison, Bolt and Screw Holes.
To determine the relative criticality of screw and bolt holes, the 'B' constants were calculated for the screw holes and bolt holes of boom 092 (and later boom 067), and were used to indicate whether the screw hole stressing was significantly different from that of the various bolt holes. The data from boom 092 are presented in Fig. 6. The value of B determined in each case is an estimate based on judging the initial defect size and final defect size, or by fitting a straight line through fractographically determined growth information.

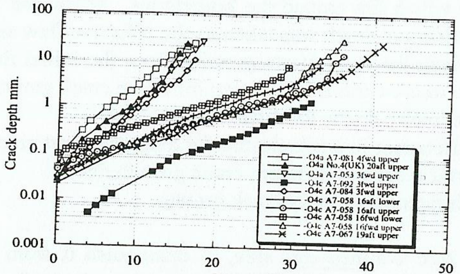

Fig. 5. Crack depth (on a log. scale) vs. No. of programs for the O4A and O4C boom tests.

Despite the inaccuracies inherent in the estimation of the initial flaw size, Fig. 6 indicates a clear trend to higher 'B' values in the regions believed to be highly stressed (the flange bolt holes from 3 to 7 and 15 to 20). The screw holes featured slightly lower B values, indicating that they are therefore less fatigue-critical than the bolt holes. The 'B' constants for the bolt and screw holes from the A7-067 boom test also showed that the flange bolt holes from 3 to 7 and 15 to 20 were more critical than the screw holes.

Identification of Other Critical Areas using Fractographic Analysis
A most important finding was that the B values were also high for regions where screw holes near-intersect other bolt holes (eg the VBH4F/S18F intersect in Fig. 6), identifying the potential fatigue criticality of the intersect region. This result led to the fatigue program being extended to examine that result further by testing the screw hole/bolt hole intersect region in boom 014 to failure. In this test, the quantitative fractographic analysis of the cracking that grew from the VBH1F, VBH4F, S5F and S18F intersect regions gave 'B' constant values between 0.09 and 0.13. Analysis of the 'B' constant exponents indicated that, assuming a uniform distribution of initial flaws in the boom, the following holes, with 'B' values above 0.12, could be considered to be in the group regarded as most critical to the structural integrity of the boom: bolt holes 3 to 7, 15 to 20 forward and aft along with VBH1F/S5F and VBH4F/S18F.

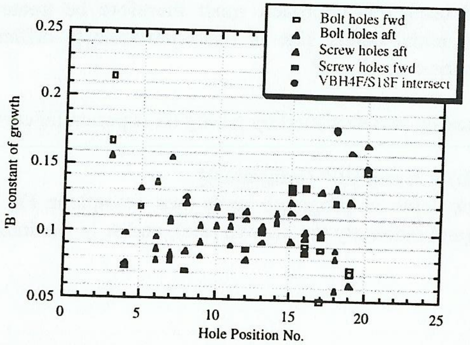

Fig. 6 'B' constants, representing severity of stressing, estimated for the A7-092 centre section boom cracked bolt and screw holes and the near-intersecting hole region.

CONCLUSIONS

The results of the testing and fractographic analysis of fatigue cracks produced in Macchi O4A and O4C centre-section booms indicated the following:

a. The wing attachment lugs on the O4C booms tested were the most highly stressed part of the boom in this test configuration. The tests showed that the wing attachment lug region of the boom is highly susceptible to the presence of defects. Pitting in the bore of the lug holes leads to rapid fatigue cracking, and the presence of deep pitting on the outboard end of the lugs or the presence of any large metallurgical defects (such as a large array of inclusions) will also be detrimental to the fatigue life.

b. An examination of the crack growth rates of the flange bolt holes indicated that there is a significant difference between the O4C booms and the O4A booms. An exception to this appears to be the cracking observed in one boom which could be attributed to the significant material variations noted for this boom when compared to the other O4C booms.

c. The tests showed that the screw hole/vertical bolt hole intersection was a source of fatigue cracking that grew at much the same rate as the most severe known critical bolt hole cracking.

d. Crack growth from screw holes which are remote from other holes was generally at a significantly slower rate than cracking from the critical bolt holes or the screw hole/vertical bolt hole intersection regions.

e. The development and use of simplified crack growth curves, and the calculation of a growth exponent for these simplified crack growth curves was a significant aid to the interpretation of crack growth in these tests. These curves were used to identify the "next most critical" area of the boom.

f. The final O4C boom test (014) showed that reaming combined with cold working, can retard fatigue crack growth in bolt holes in the O4C booms. Use of these life enhancement methods caused the failure location in this boom test specimen to move to a screw hole/vertical bolt hole intersection, unfortunately with little gain in life, due to the high stress at the screw hole/vertical bolt hole intersection locations.

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