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MELBOURNE, VICTORIA

STRUCTURES TECHNICAL MEMORANDUM 394

A SURVEY OF AERONAUTICAL  
STRUCTURAL RESEARCH IN AUSTRALIA

by

F.H. HOOKE

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A SURVEY OF AERONAUTICAL  
 STRUCTURAL RESEARCH IN AUSTRALIA \*

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SUMMARY

A survey of Aeronautical structural research in Australia has spanned over more than 40 years, from the establishment of the C.S.I.R. Division of Aeronautics in 1939. Industry, civil aviation and the armed services have benefited from the expertise of Structures Division in problem solving, as well as from ad-hoc research and, perhaps less immediately, from basic research. Not every avenue has been able to be explored. A major subject of research, structural fatigue, arose from an accident in 1945, and each new development in design and materials has brought new problems.

Standards of safety and risk have been explored. New technology of fibre composites permits better tailoring of strength and stiffness to requirements: this and the introduction to aircraft of active controls offer benefits and problems for the future.

*Additional keywords:*  
 Aeronautical Laboratories; aerospace engineering;  
 aircraft structures; metal fatigue

\* The paper is a slight abridgement for publication of the eleventh L.P. Coombes Lecture to the Victoria Division of the Institution of Engineers Australia, Aeronautical Branch.

*ultra high strength steels;  
 structural analysis*



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POSTAL ADDRESS: Director, Aeronautical Research Laboratories,  
 P.O. Box 4331, Melbourne, Victoria, 3001, Australia.

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1. THE BIRTH OF AERONAUTICAL STRUCTURAL RESEARCH

Every saga has its beginning. The saga of aeronautical structural research in Australia begins with the birth in 1939 of the Aeronautical Research Laboratory of the Council for Scientific and Industrial Research, conceived in 1937 as part of a plan put by the C.S.I.R. to the Government of Australia by which Australia's secondary industries might be stimulated and developed.

A first task of Dr. L.P. Coombes, O.B.E., (then Mr. Coombes), first Officer in Charge of the Laboratory and shortly after Chief of the renamed Division of Aeronautics of C.S.I.R., was to define its functions, activities and staffing. The work was envisaged to fall into four main areas; aerodynamics, structures and materials, engines and fuels, and aircraft instruments. The work of the Structures and Materials Section was envisaged to cover "design of the structure to withstand aerodynamic and inertia loads, its strength, elasticity and dynamical characteristics, structural materials, metallic and non-metallic."

Work on structures and materials began with the appointment in September 1939 as Officer in Charge, of Mr. H.A. Wills, B.E., University of Western Australia, an aeronautical engineer with experience in Great Britain and in Australia. (Mr. Wills was later to become Chief Defence Scientist, and was awarded the O.B.E. for his work). It is interesting that his budget for equipment totalled Pounds Sterling 1350, about twice the annual salary of a Research Officer.

By 1941 the nucleus of staff had been recruited and work had begun both in immediate support for local industry in its development and manufacturing problems, and also in forward-looking basic research.

Methods of analytical structural analysis were researched. A typical example was the new "relaxation method" which facilitated the numerical solution of multiple redundancies in the days before digital computers were available. This was a fore-runner of today's "finite element analysis" and was applicable to other than structural problems. F.S. Shaw and G.K. Bachelor collaborated in the use of these methods in the design of wind tunnel contractions<sup>1</sup>, while Shaw himself applied them to analysis of structural elements.

In view of an imminent shortage of aluminium, research was begun (in association with the Division of Forest Products) on the use of timber and improved wood in all aspects of aeroplane construction. Typical of the basic research was a mathematical study by R.C.I. Smith of buckling of orthotropic plates,<sup>2</sup> applicable to plywood panels of wing skins, fuselages and spar webs.

Structural analysis is the study of stress and strain. Stress is not measurable, but strain is. Not only were instruments acquired to measure extension, but research was started to develop the new concept of electric resistance strain gauges - tiny zig-zags of resistance wire, usually cemented to a fine paper backing, the resistance of which varied according to the strain.

In September 1942 the Section was called upon by industry for assistance in the third phase of its expertise, namely, elasticity and dynamics. The question was to determine by calculation the safe diving speed, for avoidance of flutter, of the C.A.C. CA-12 interceptor. Over the next 40 years this expertise was to be developed and repeatedly called upon to assist design, safe operation and accident investigations.

Soon after the Structures Wing Testing Laboratory was completed it was put into use for testing wing structures as part of investigations of flight failures. One such test of an Oxford wing<sup>3</sup> is illustrated in Fig. 1. The wing was mounted to a strong frame at its root in an inverted position. The desired highly accurate test loads were applied by a series of levers, pulleys and jacks to wooden frames surrounding the wing - by methods now regarded as primitive, slow and labour intensive.

Later, under W.W. Johnstone, head of the Structures Experiment Group, tests were made on other aeroplane wings, including the de Havilland "Mosquito"<sup>4</sup>, a wooden aeroplane built in Australia. Here the test rig was more advanced and mechanised (Fig. 2).

In 1942 there was set up, with the Prime Minister's approval, an Advisory Committee for Aeronautics (A.C.A.) comprising representatives of C.S.I.R., the Dept. of Civil Aviation, the R.A.A.F., Sydney University Dept. of Aeronautics, and Industry. As well as performing a very useful function of overseeing the aims and achievements of research, it established a series for the publication of the cream of Australian aeronautical research papers (the A.C.A. Series) for circulation world-wide.

## 2. METAL FATIGUE - AN EMERGENT PROBLEM

In January 1945 there occurred an event which was to influence a major redirection of structures research; it was the crash of the Stinson airliner VH-UYU at Spring Plains in Victoria, with the loss of ten lives. Examination of the wreckage<sup>5</sup> showed that the cause was fatigue failure in a welded steel joint of the main wing structure. The aircraft was eight years old and had flown 13768 hours or an average of 4.7 hours per day.

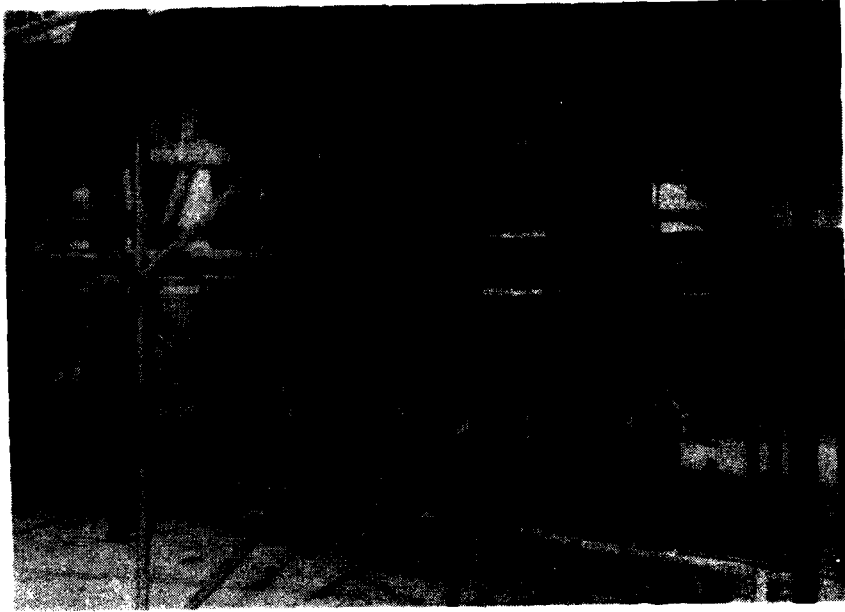


FIG. 1 STATIC TEST OF OXFORD WING

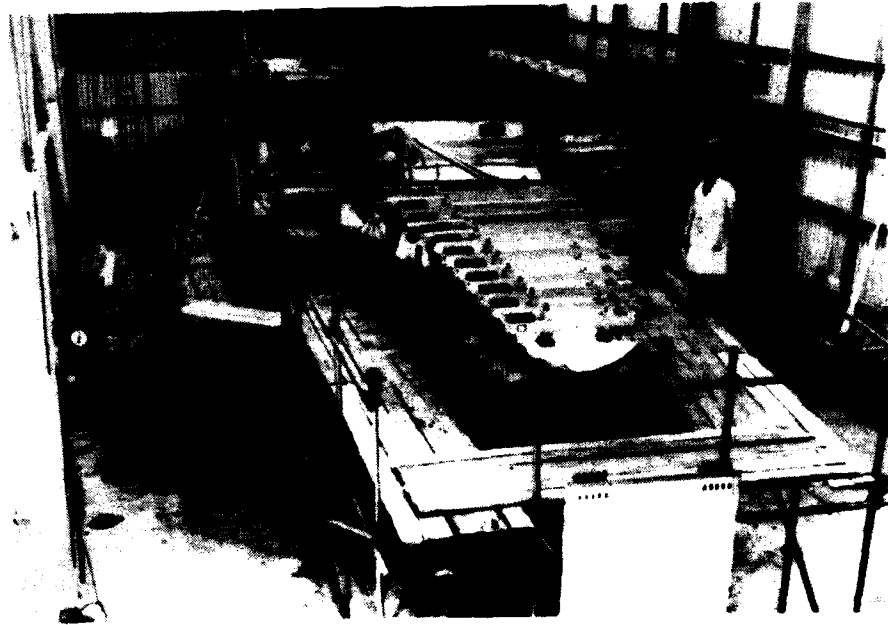


FIG. 2 STATIC TEST OF MOSQUITO WING

This accident drew attention to fatigue as no longer a negligible risk to civil aircraft and it raised the question of the effect of age and other factors on the airworthiness of aircraft.

Fatigue failure of metals was by no means new in mechanical engineering - fatigue failure in railway axles of the Austrian State Railways had been studied by Wöhler, a German Engineer, in the 1860's - and since then avoidance had become part of the expertise of mechanical engineers in the design of machines, transport vehicles, and the like. The ultimate test of good design for long life was either laboratory testing or user-testing after purchase. In structural engineering long endurance was normally ensured by the use of a strength factor of safety on the maximum expected load in service. In the case of the Stinson aircraft the steel structure had been heat treated to a strength of 80,000 pounds per square inch, and the stress in level flight was only one tenth of that. The use of a safety factor on static strength was inadequate.

All credit must be given to Mr. Wills for his foresight that fatigue was a potentially growing problem, which, for its solution demanded acquisition of data on fatigue behaviour of structures and the loading actions occurring in service, with analytical procedures to relate the two.

In December 1946 a symposium on "The Failure of Metals by Fatigue", the first ever in an English speaking country, was organised by Melbourne University, attracting 30 papers<sup>o</sup>, including 6 from Great Britain, 3 from the U.S.A. and 6 from A.R.L. In retrospect the Symposium proved most valuable in bringing together experts from all over the world, and assembling and exposing the state of the art, nevertheless it is not too harsh a criticism to say that it revealed more areas of ignorance than of knowledge, since it revealed that current design methods were inadequate to deal with the very simplest fatigue problems.

### 3. THE LIFE OF AIRCRAFT STRUCTURES - AUSTRALIA'S ATTACK ON THE PROBLEM

Meanwhile, under Mr. Wills' direction a two-pronged study of the fatigue problem had been begun. Firstly laboratory testing with constant amplitude loading was planned and begun on complete structures, components and small material specimens, and secondly, research was begun in flight to measure the operational loadings caused by manoeuvres and gusts, and the geographical and vertical distribution of atmospheric turbulence, while theoretical studies were begun on the response of aircraft to atmospheric turbulence.

Experiments on the fatigue strength of structures under fluctuating load were begun by automating the "Mosquito" test rig to load and unload between chosen upper and lower levels. One such wing withstood 5000 repetitions of load to 90% of design ultimate load, and then withstood 102% of design ultimate load before collapse. Experiments on metal wings showed their endurance to be much less than that of representative component specimens.

At the end of the war there were many surplus aeroplanes, and A.R.L. began to harvest surplus "Mustang" aeroplanes from wherever they could be found. A hydraulic test rig was built to accommodate these wings, and a test programme was planned with the aim of testing at a variety of mean loads and alternating load ranges. These test results were thus regarded as not specific to "Mustangs", but generically representative of all 24 ST aluminium alloy structures.

Endurance testing is time consuming and the replications under the various alternating and mean loads took years to complete. The results were first published by W.W. Johnstone and A.O. Payne in 1956<sup>7</sup>, while Fig. 3 shows the plots of accumulated results at a later stage, plotted as stress and representative of 24 ST structures, from a paper by Dr. Payne<sup>8</sup>. The test series, comprising more than 200 Mustang wings, was the most comprehensive test series on complete structures ever undertaken: the reports were to establish the name of A.R.L. in every aeronautical laboratory, airworthiness center and with every aircraft manufacturer throughout the world.

Concurrent with the beginning of laboratory fatigue testing was the study of loading actions in flight, firstly with the N.A.S.A. V-g recorder, recording the highest accelerations and speeds during each flight, and later using improved instrumentation. With the co-operation of the Dept. of Civil Aviation, Australian National Airways, Ansett Airlines, T.A.A., MacRobertson Miller Airlines, the R.A.A.F. and Qantas, data were acquired all over the Australian continent, and from Australia to Japan and Australia to Great Britain<sup>9,10</sup> (Fig. 4).

Continuous recording is inefficient and laborious to analyse: this led to the concept of a strain range counter<sup>11</sup> for sensing the numbers of large and small extensions of the structure. Fig. 5 is a diagram of Mark II of this instrument, designed and tested by the author. Both it and Mark I worked exceptionally well in the laboratory: neither worked reliably in the air, in the presence of inertia effects, engine vibration and other disturbances. After several years intensive effort the idea was abandoned, only to be taken up twenty years later, in an improved form by Ford and Patterson, and achieving production development ten years subsequently as the "Aircraft Fatigue Data Analysis System" (AFDAS). The Royal Aircraft Establishment, Farnborough, had more success in counting peaks of vertical acceleration with its Counting Accelerometer, and its later miniaturised "Fatigue Meter", and these were acquired for the Australian programme. Typical results from a Dove

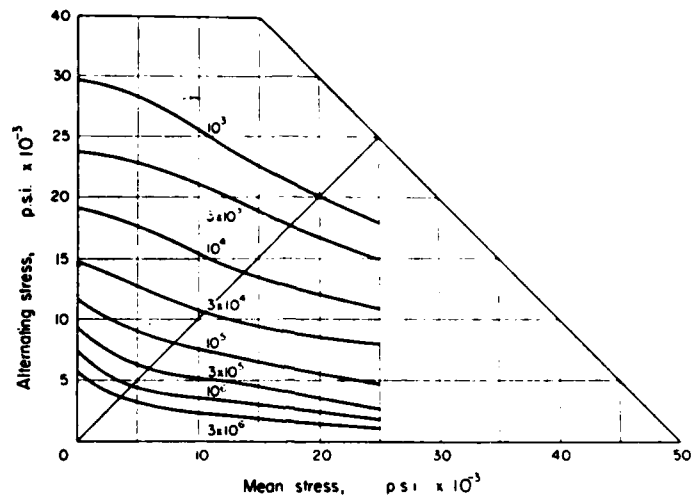
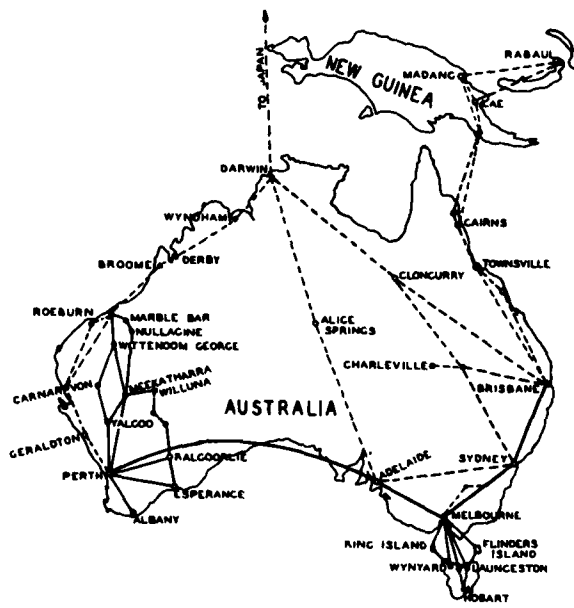


FIG. 3 TYPICAL FATIGUE DIAGRAM FOR 24ST STRUCTURES



ACCELERATIONS DUE TO GUSTS WERE MEASURED ON THESE ROUTES USING.

V-g RECORDERS .....  
 COUNTING ACCELEROMETERS ———

FIG. 4 FLIGHT LOAD DATA ACQUISITION ROUTES

aircraft are shown in Fig. 7, in which the accelerations have been converted to gust velocity. Small disturbances occurred many times; larger peaks of 30 f.p.s. were met once in the recording period: these are to be compared with the design gust velocity of 50 f.p.s.

Detailed continuous recordings of strain taken in severe weather revealed the response to be a random process approximately to a "Normal" or "Gaussian Distribution". This randomness was soon to have repercussions into fatigue testing, as being more representative than constant amplitude testing.

Concurrently, theoretical studies were made of the aeroplane's reaction to turbulence. Radok and Styles<sup>12</sup>, expressed the equations of motion as complex integral equations virtually insoluble before digital computers. A somewhat simplified analysis<sup>13</sup> was more tractable, nevertheless requiring some weeks assistance of Sydney University's staff and differential analyser to evaluate solutions.

Returning for the moment to the period of 1946-47, thought was being given to what were the relevant factors, and how, given relevant data, they would be evaluated to establish safe operating lives<sup>14</sup>, and during 1948 Wills lectured to the Institution of Engineers Australia on the subject.

In 1949 Wills was to present a historic paper to the Second International Aeronautical Conference in New York and London on "The Life of Aircraft Structures"<sup>15</sup>: it was epoch making in that, for the first time, the author defined factors which would make fatigue failure progressively more likely, and, with factual data, was able to illustrate with a numerical example, the calculation of safe life. There followed research on metallurgical aspects of fatigue, the effects of manufacturing variables and surface treatments<sup>16</sup>, while Head<sup>17</sup> devised a theoretical model for fatigue, highlighting the role of the exhaustion of plastic strain at the migrating crack tip in crack propagation. A decade or more later Paris in the U.S.A. was to introduce stress intensity at the crack tip as most relevant, and this has been followed in most subsequent analyses.

#### 4. NEW MATERIALS AND NEW DEVELOPMENTS

In 1951 an unhurried, if not complacent, approach to fatigue was shaken by the fatal crash at Kalgoorlie, Western Australia, of a Dove aircraft VH-AQO belonging to MacRobertson Miller Airlines. The aircraft had flown 9000 hours and the failure occurred in the centre section main spar, which appeared well designed, and carried no apparently high nominal stress. No Dove elsewhere in the world had exceeded 3000 flying hours at the time.

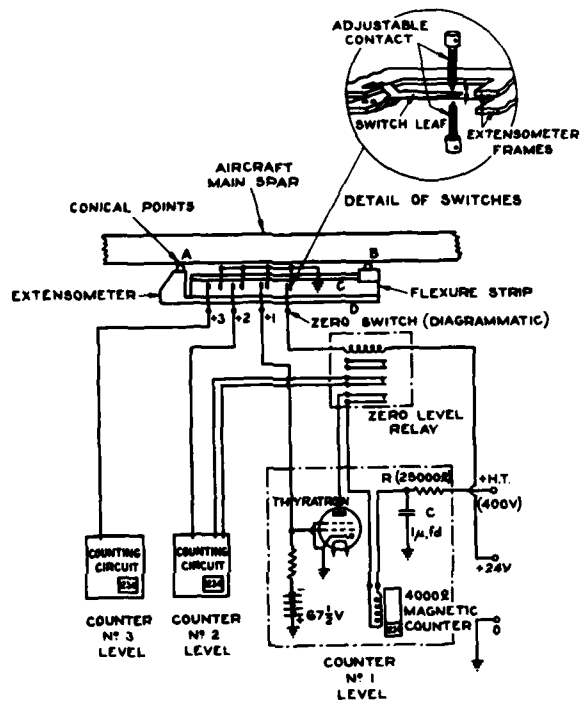


FIG. 5 DIAGRAM OF STRAIN COUNTER

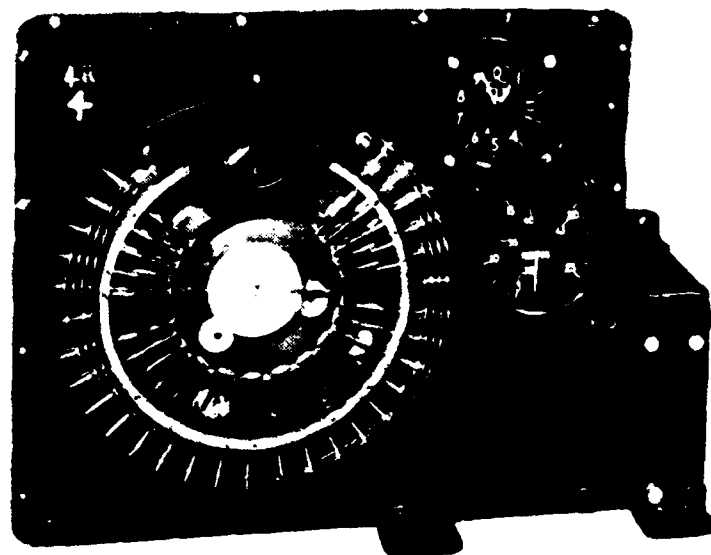


FIG. 6 R.A.E. COUNTING ACCELEROMETER

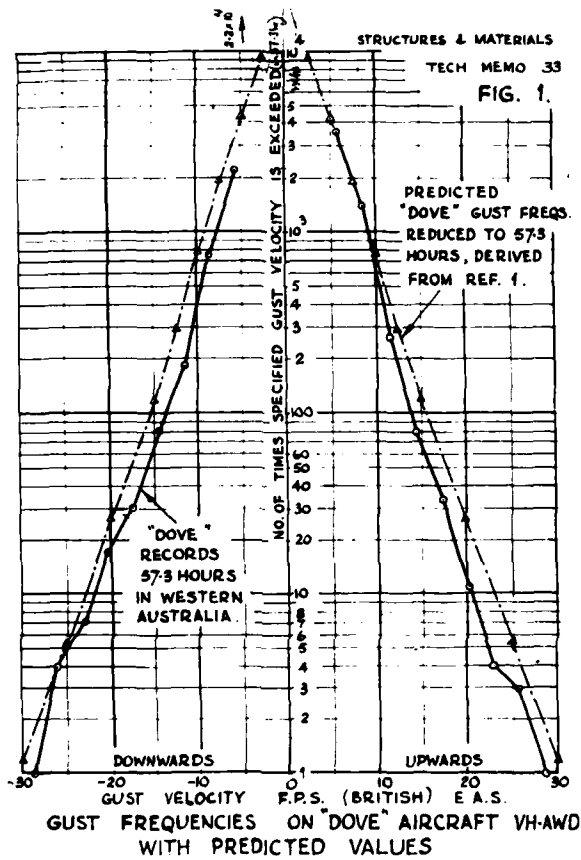


FIG. 7 FLIGHT LOAD RECORDS FROM A DOVE AIRLINER IN WESTERN AUSTRALIA

In seeking to explore why the accident occurred A.R.L. could find no fatigue data from any source for the particular material DTD 363, of which this component was made, a relatively new high strength aluminium alloy with zinc - chosen for its high ultimate tensile strength. Calculations using data from another aluminium-zinc alloy 75 ST, predicted, perhaps fortuitously, a mean life to failure of 9000 hours. They also showed that a recently permitted increase in the all-up-weight from 8000 lbs. to 8500 lbs. had no significant effect on the life, and also, that had the part been made in 24 ST to the same design factors, it would have lasted from 3 to 5 times as long.

At the time no fatigue design requirements for airworthiness existed. The manufacturer had, on his own initiative, made repeated load tests on the wing outboard of the fuselage primarily to test the performance of resin-bonded stringers. Tragically, he had represented the carry-through section across the fuselage by a steel framework, thus failing to test the critical part. The event confirmed the A.R.L. view that actual endurance testing was essential for airworthiness certification, that no important part should be left out, and that the actual test should be as representative as possible.

From this event sprang a number of investigations including tests on small specimens of newer materials, and full scale tests on Dove wings covering a period of eight years. Great interest arose in more properly representing in the laboratory the irregular load sequence occurring in flight.

For testing complete structures, load "programmes" were devised by grouping together load cycles of similar amplitudes in representative proportions or the load cycles were called up in "pseudo random" sequence to be repeated until failure. For testing small specimens a novel proposal was to employ electronic noise from a thermionic valve to produce a truly random stress history<sup>19</sup>, completely specified in the statistical sense by the r.m.s. and the damping coefficient. Fig. 8 shows the electromechanical part of the system and the specimen. In these tests the endurance was found to be significantly less than that calculated from constant amplitude tests - undoubtedly a result of stress interaction effects. This was a further argument for more realistic testing, and the technique was since further developed and used in the U.K., the U.S.A. and Europe.

The year 1956 saw the "International Conference on Fatigue of Metals" held in London and New York jointly by the Institution of Mechanical Engineers and the American Society of Mechanical Engineers. A.R.L. contributed three papers<sup>19, 20, 21</sup> thus marking another step forward for A.R.L. in achieving an international reputation for its work in fatigue.

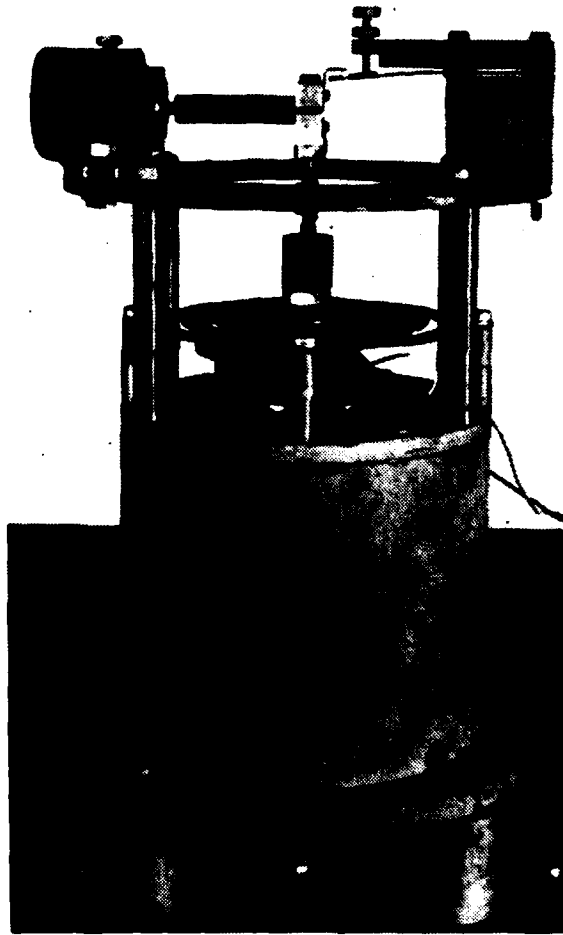


FIG. 8 RANDOM NOISE FATIGUE MACHINE SHOWING ELECTRO-MECHANICAL  
TRANSDUCER AND SPECIMEN

In 1957 there took place in Brussels the fifth Conference of the International Committee for Aeronautical Fatigue - a body comprising the fatigue expertise of seven European countries. By good fortune Australia was included in the British delegation, and thereby it was proposed that Australia be invited to join I.C.A.F. The invitation was offered and accepted in 1958. A.R.L. cemented its formal membership by the contribution of two papers<sup>21,22</sup> to the next Conference and first Symposium in Amsterdam in 1959 while in 1967 Australia was host to the Conference and Fifth Symposium, attended by 151 people. The membership of I.C.A.F. - still an unfunded informal but highly regarded association of various countries through their nominated national centres - has been of inestimable value to Australia as a forum of interchange of information, of debate and as a place of contact from which have sprung some highly valuable collaborative exercises.

In the late 50's and early 60's there emerged, first in the U.S.A., the concept of "safety by inspection" which depended on structural redundancy for safety. This concept was clarified and quantified by R.R. Shaw<sup>23</sup>, identifying the essentials for safety to be:-

- (a) a knowledge of where to inspect
- (b) knowledge of decay of strength with crack size
- (c) knowledge of the frequency of high loads
- (d) knowledge of crack propagation rate
- (e) inspection techniques capable of detecting cracks too small to jeopardise strength

In the tests on Mustang wings cracks occurred first in the skin, and grew detectably for tens of thousands of cycles. But what of the behaviour in solid members? In the early 60's A.R.L. was engaged on fatigue testing of Vampire aircraft, in which failure occurred through the main spar or through a steel root fitting. The load history was a programmed one, and the fractured surfaces showed typical concentric rings, taken to be successive positions of the crack front, but there was uncertainty whether each ring represented a complete programme or just a single application of one of the highest loads in the programme. Higher magnification with the electron microscope over large areas of rings revealed striations within each ring, in sets of 25 and 70 having a one-to-one correspondence with the second and third highest loads in the programme (Fig. 9), thus giving incontrovertable proof of the first interpretation, and engendering confidence in the method for "post mortem" crack propagation determination.

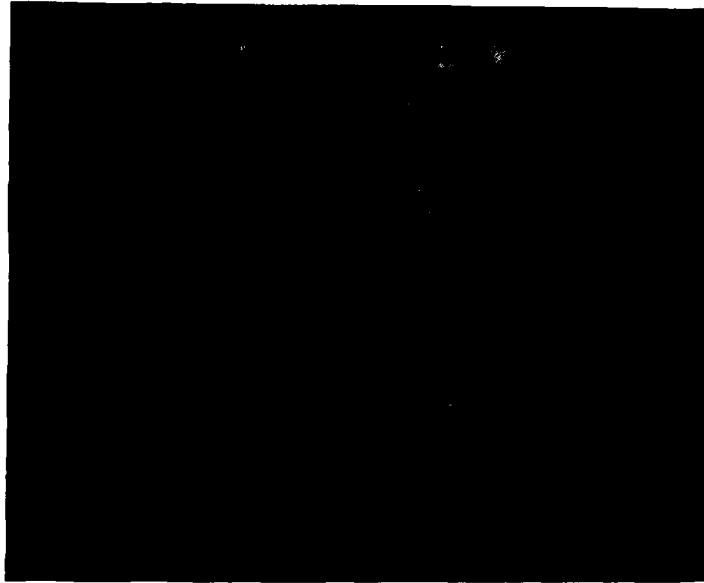


FIG. 9 FRACTURE SURFACE MOSAIC  
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5. NEW OPERATIONAL PROBLEMS: AGRICULTURAL OPERATIONS.  
HIGH ALTITUDE TURBULENCE, FLUTTER

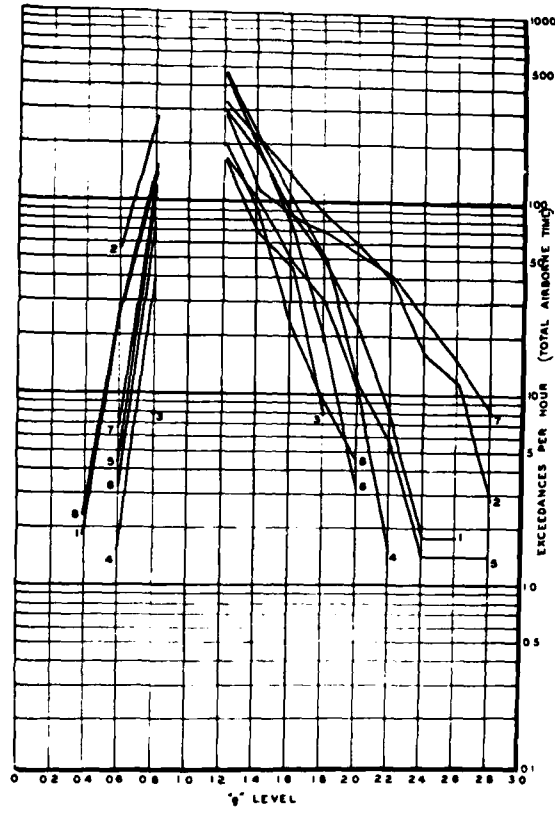
In the late 50's and early 60's some new operational problems emerged.

Agricultural use of aeroplanes became popular for crop-spraying and fertiliser-spreading, a type of service markedly more severe than the normal. The aircraft were flown from dawn till dusk, always fully laden, and always near the ground in the most severe topographical turbulence. Flights lasted about 5 minutes, manoeuvres between runs were severe, landings were frequent and often on unsmoothed paddocks. It is not surprising that some fatigue failures occurred.

At the request of the Dept. of Civil Aviation, and with excellent co-operation from the operators, A.R.L. installed instruments and began recording flight histories on aircraft at a number of locations in the country. The results of a typical test by Foden<sup>24</sup> with seven different pilots flying the same type of aircraft are shown in Fig. 10, as "g" exceedence spectra. Here two of the pilots (2 and 7) induced very much more severe and more frequent loads than the remainder, (and, for that matter, more severe loads than in normal operations of the same aircraft). This severity and variability creates a problem of airworthiness control, whether by safe life, fail safe or safety by inspection procedures.

In the early sixties just prior to the introduction of Concorde, structural specialists began to be concerned by reports of turbulence in the tropopause and stratosphere - in theory regions of stable atmosphere. Through contact between Structures Co-ordinators of the Commonwealth Advisory Aeronautical Research Council, a research programme (TOPCAT) was mounted jointly by the R.A.E. Farnborough and A.R.L. to search and measure high altitude clear air turbulence (C.A.T.) over Australia. Massive support was provided by Weapons Research Laboratories and by the Bureau of Meteorology, who provided weather forecasts every morning advising the likelihood of C.A.T.

The troposphere was searched on every day pronounced favourable, and C.A.T. was found, from mild to moderate, on half of the occasions. In general the patches of turbulence were found to be long in the wind direction and short in the vertical. Over South Australia it was commonly found around an altitude of 17000 ft., and on one occasion it was identified as resulting from wave flow over the Flinders Ranges some 10000 ft. below.



TOTAL 'g' SPECTRA — MEAN FOR EACH PILOT

FIG. 10 AGRICULTURAL AIRCRAFT FLIGHT LOAD SPECTRA

Results were reported by Burns and Rider<sup>25</sup> both in the U.K. and Australia. In a typical occurrence the turbulence had characteristics very close to those of homogeneous isotropic turbulence with a characteristic length of 1000 ft. and a standard deviation of 5.7 f.p.s., which was not severe enough to constitute a structural hazard but which might be of concern for control.

The U.S.A. also had a concern for atmospheric turbulence, and soon afterwards it proposed to include the Tasman in its survey. Australia and New Zealand participated in tests in which a specially instrumented U-2 aircraft was flown from Christchurch, N.Z. in June 1966 and from the R.A.A.F. Base, Laverton, Australia in July. C.A.T. was found more frequently over Australia than in other regions sampled: whether this resulted from better forecasting could not be determined. C.A.T. was frequently found in association with "jet streams" - long narrow belts of wind with a very high core velocity. As jet streams are detectable from meteorological data this was a useful result bearing on avoidance procedures.

In 1967, R.A.A.F. interest in the potential fatigue life of Mirage prompted a detailed review which revealed that gust loads on the wings and aerodynamic loads on the fin were highly significant. This prompted a series of flight trials for which an airborne magnetic tape data acquisition system was designed and built at A.R.L. by Patterson and Moody<sup>26</sup>, and a sophisticated gust probe was built capable of measuring gust velocity up to sonic flight speeds. The results of the trials were of particular value in deriving test load spectra when later it became necessary to conduct a fatigue test in Australia.

Aerolasticity, which describes the interaction of aerodynamic, elastic and inertia forces on a structure, continued quietly as a background problem during these years. Theory was available to calculate aerodynamic forces, but the interaction of inertia and elastic forces required determination by experiment of the natural modes of vibration. Traill-Nash<sup>27</sup> studied theoretically single-point-excitation and multi-point-excitation methods for determining the modes.

The Jindivik target aircraft, during its lifetime existed in many variants, without and with a variety of weighty items attached to its wings. For each variant the modes were determined experimentally by suspending the aircraft from a soft spring system, exciting the vibration and measuring the response over a range of frequencies with fixed and roving probes (Fig. 11). This was one of the many continuing demands placed on A.R.L. for military and civil aeroelastic analyses, (e.g. the G.A.F. "Nomad"), and vibration studies of naval and merchant ships.

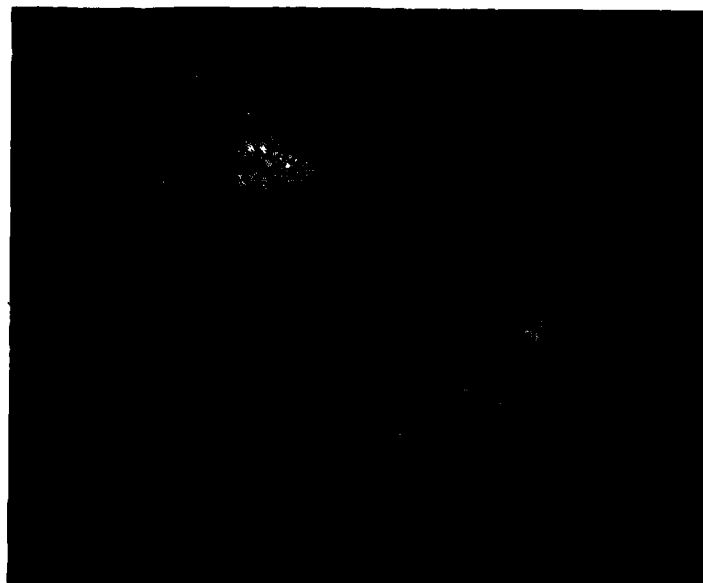


FIG. 11 JINDIVIK VIBRATION TEST

6. NEW TECHNOLOGY - ULTRA HIGH STRENGTH STEELS

In the late 1960's new technology and new materials of higher ultimate strength were explored in the search for lighter structures and better aircraft performance.

Steels with an ultimate strength of 200,000 p.s.i. had been in use for undercarriage components, and the new "leap forward" was to use these in main wing structure, viz. in the centre section or "carry-through-box" on which were pivoted the swing wings of the F-111 aircraft, ordered by Australia from the drawing board.

Delivery of the first aircraft was taken officially on Wednesday 4th September 1968 but confusion reigned when the news became public that eight days earlier an F-111 wing test article had failed catastrophically almost at the commencement of its fatigue test (Fig. 12).

This event assumed a significance comparable with the crash of the Stinson in 1945. The R.A.A.F. sought the assistance of A.R.L. to which the Chief Superintendent, Dr. J.L. Farrands responded by sending individual scientists with appropriate expertise to visit the designers and the factory at Fort Worth to obtain relevant information at first hand, and by setting up, with himself as chairman, a Scientific Advisory Panel to co-ordinate the A.R.L. study and assessment of the problem. The U.S.A. reaction was to set up a Scientific Advisory Board, comprising specialists from universities, research laboratories and other aircraft manufacturers, and A.R.L. scientists visiting the U.S.A. were made temporary members of this board. Inspection of the failure revealed that it had started at an unsatisfactory metallurgical structure ("untempered martensite") in a hole in the lower rear edge of the box - highly stressed by a loss of continuity round a rectangular hole in the rear face; moreover all holes in the box had poor surface finish. A second and a third test box also failed prematurely, pointing to the fault being one of design.

Late in 1969 a R.A.A.F. - A.R.L. Scientific Advisory Team was set up and sent to Fort Worth and Washington to explore, review and report on progress. After some two months study it was to recommend to the Government not to accept the aircraft until substantial redesign and strengthening and other improvements had been carried out. This, however did not conclude the problem. Late in December 1969 a U.S.A. F-111 collapsed in flight because of a pre-existing flaw in its wing pivot fitting, not found by inspection during manufacture. This raised the question of a reliable method of ensuring initial freedom from cracks and of continuously monitoring integrity. The solution was to institute a detailed pre-service inspection of every aircraft, followed by "cold proof testing" in a cold chamber at -40°C with wings extended and swept back, later to be repeated at regular intervals of some thousands of hours throughout the life. The adoption of the test was vindicated by the failure of two of the first 330 airframes on test, and later of two out of four replacement aeroplanes bought by the R.A.A.F.

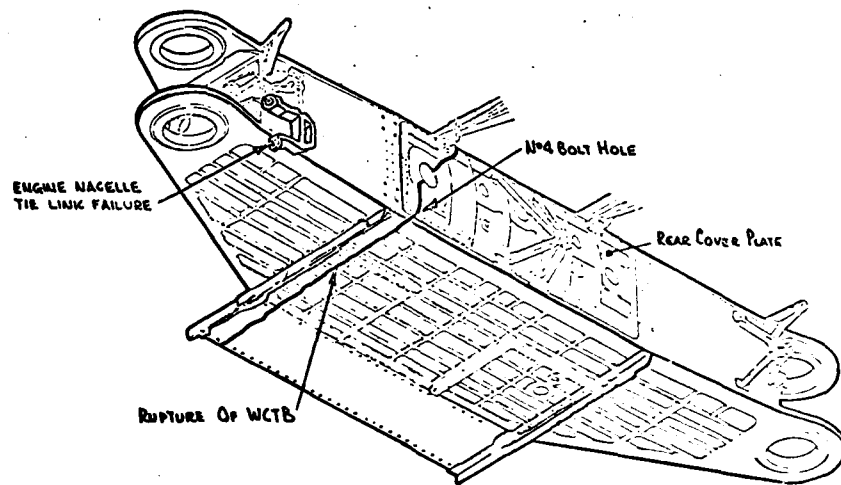


FIG. 12 F-111 WING CARRY THROUGH BOX FAILURE

As part of A.R.L. research, 12 large specimens representing the lower rear flange of the carry-through-box were acquired, initially to investigate scatter. One specimen failed very early with very rapid crack propagation. The reason was discovered by a scientist of Materials Division, A.R.L. with a keen sense of smell, who observed a distinct aroma from the initiation point. The aroma was confirmed to be from proprietary cleaning fluid entrapped during bolting operations, and its corrosive property had a catastrophic effect on cracking. The manufacturers concurred, and thereafter changed the cleaning and assembly procedures for ultra-high-strength steel parts.

In the final outcome Australia took delivery of the first of its F-111's in March 1973, each incorporating the redesigned stronger carry-through-box together with over 240 lesser structural improvements.

## 7. STRUCTURAL ANALYSIS

Research on structural analysis was an early priority of the laboratory. During the Second World War, interest in the strength of wooden aircraft structures led to research by Silberstein, Wills and Radok<sup>28</sup> into the strength of wooden box beams, and by R.C.T. Smith into the buckling of plywood plates<sup>2</sup>. Basic research in the elastic and plastic ranges of bars and rings was initiated by Shaw<sup>29</sup> and by Smith and Wills<sup>30</sup>.

In the late 1940's Wittrick<sup>31</sup> studied the problem of swept-back wings, then coming into use in high speed aeroplanes, and Shaw and Guest<sup>32</sup> and Mitchell<sup>33</sup> investigated the triangular areas where the two wings meet. The buckling of rectangular and oblique plates was important to the ultimate design strength of spar webs and wing skins: these were studied by Wittrick<sup>34</sup>, Guest<sup>35</sup>, and Radok<sup>36</sup>, while Solvey<sup>37</sup> addressed the problems of structural efficiency.

About the year 1960, the concept of "fail safe", implying as it did that an aircraft structure may be safe though flawed or cracked, led to studies of the strength of cracked structures, the forte of fracture mechanics. The idealised crack has an infinitely small tip radius and, under elastic analysis, a stress singularity there: the intensity of the singularity is the "stress intensity factor". The residual strength problem relates critical stress intensity to material fracture toughness, while the work of Paris in 1962 relates ("subcritical") fatigue crack growth to crack tip stress intensity.

Hoskin et al.<sup>38,39</sup> directed elasticity theory to fracture in cracked sheet and in tension panels, while Keays<sup>40</sup> reviewed stress intensity factors for various geometries, and Jones and Callinan<sup>41</sup> developed finite element analyses for calculating stress intensities.

Until the mid 1970's no aeroplane with known unrepaired cracked structure would be allowed to take the air, but by that time A.R.L. research was able to give the R.A.A.F. confidence in flying Macchi aircraft with known cracks in the main spar, with regular monitoring and repair as cracks approached a limiting safe size.

Repairs to damaged or cracked structure are often performed by patching, and the advances in structural mechanics have replaced earlier "rule-of-thumb" methods with vastly more precise and efficient design methods<sup>42</sup>. A perhaps expected result is that well designed adhesively bonded repairs may be much more efficient than riveted repairs<sup>43</sup>.

#### 8. ADVANCED RISK AND RELIABILITY ANALYSIS

In the early 1950's, when the assessment of fatigue endurance had developed somewhat, the significance of variability in endurance of (nominally) identical structures was appreciated. This led to the concept of a limiting "safe life" statistically calculated to be potentially achieved or surpassed by all but a very small number of aircraft of the type. The safe life was derived from the estimated mean life by dividing by a "scatter factor" derived from the variability of the distribution.

In Australia the R.A.A.F. chose, in discussion with A.R.L., a probability of survival of 0.999, or a probability of failure during the lifetime of 0.001, to define the safe life; a risk not regarded as excessive compared with other risks associated with military aircraft operation. In 1959 Lundberg<sup>44</sup> developed a quantitative statistical approach to aircraft fatigue and proposed for civil aircraft, an acceptable risk per hour of  $10^{-9}$ , i.e. one in one thousand million. The figures were regarded as very desirable but unlikely of achievement.

By 1961 as interest developed in the risks of operating aircraft on a "fail safe" basis, Eggwertz<sup>45</sup> of Sweden contributed a paper to the I.C.A.F. Symposium on determining the appropriate intervals to inspect for cracks so as to keep the risk of failure below chosen limits, taking into account the properties of crack propagation and the associated loss of strength. Almost simultaneously in the U.S.A. Freudenthal<sup>46</sup>, introduced the "reliability" approach in an unpublished report on fatigue sensitivity of mechanical systems, including aircraft structures, while in 1964, Freudenthal and Payne<sup>47</sup> developed the theme of "structural reliability" of airframes in another unpublished report.

Interest in these techniques remained dormant in Australia, it would appear, until the proposal to cold-proof-test F-111 structures raised questions of the appropriate intervals between such tests. The methods were then applied in making Australia's estimates of the appropriate intervals. Because of the complexity and subtlety of the subject there followed an intensive study of it over more than ten years with contributions from Payne and Diamond<sup>48,49</sup>, Hooke<sup>50,51</sup>, Ford<sup>52</sup> and Mallinson<sup>53</sup>.

"Reliability" is the "survivorship" or probability of survival to time  $t$ , and is the exponential function of the negative integral of risk rate per unit time. This analysis depends upon mathematically representing the essential features of the critical region or regions of a family of structures, having distributed initial strengths, distributed rates of crack propagation and perhaps times to initiation, and distributed residual strengths at any crack size, when they are subjected to a random load history which, with military aeroplanes, may very occasionally exceed the ultimate strength. The risk rate of failure per unit time is the probability that a structure meets an applied load greater than its current strength, while the risk of withdrawal is the probability that its crack length exceeds that size at which the calculated risk reaches the acceptable limit.

In a typical application of this method, in the absence of inspections for cracking, the survivorship falls at the "safe life" to that value upon which, in the conventional approach, the "safe life" is determined.

If the structure is inspectable in its critical region this "reliability", or rather "risk" analysis enables partitioning of the total risk at variable time between members which are uncracked or cracked but unweakened ("static ultimate failure risk"), and those with larger, weakening cracks ("fatigue failure risk"). If the time instant is an inspection time, the second fraction can be partitioned between those with cracks greater than a nominated rejection size, which are therefore to be removed from service ("rejection risk"), and those with cracks smaller than the rejection crack size ("reduced failure risk"). The fatigue failure risk may thus be kept within limits by choice of a rejection size, and consequent inspection intervals, or vice versa. Withdrawal of rejects at an inspection immediately drops the fatigue failure risk to the value corresponding to "continuous inspection" with rejection at the same size; then the fatigue failure risk gradually outstrips the "continuous inspection" risk until the next inspection, with its rejects.

At the same time, account must be taken of the survivorship, for, in certain circumstances of severe load spectra, the choice of a very small rejection crack size may result in insignificant reduction of the total risk while rapidly rejecting the whole fleet well before the conventional safe life.

Reliability and risk theory provides mathematically exact solutions with precise input data. In all practical problems, however, input data are based upon small sample estimates of, for example, virgin strength, mean endurance and their distribution parameters, and the calculated risks are associated with the convolution of the poorly determined lower tails of the distributions. Thus a sensitivity analysis is desirable in any practical case.

Nevertheless reliability analysis provides an intellectually satisfying philosophy and rationale within which to review conventional and perhaps arbitrary judgements used in establishing safe fatigue lives or safe inspection times and withdrawal crack sizes for fail-safe aircraft structures, and other engineering situations involving randomness of load and strength.

#### 9. TODAY'S TECHNOLOGY - FIBRE COMPOSITE MATERIALS

For many years it has been known that the strength of glass is greatly enhanced by drawing into fibres: nowadays fibres such as graphite, boron, kevlar, etc. having high specific elastic modulus are finding application in aircraft.

Some 15 years ago research on structural elements of fibre in resin was begun by Solvey on compression panels, and by Ellis and Hoskin<sup>54</sup> on torsion tubes, contributing to insight and revealing subtleties of the behaviour. To give A.R.L. experience in design, manufacture, handling and service experience, applications were sought in reinforcement of a naval patrol boat propeller shaft bracket and an army mortar tripod leg.

From 1975 onward the first applications were made to repair of cracked structures, supported by research on strength and stiffness of available fibres, properties of resins, shear strength of adhesives, surface preparation of the underlying metal, undertaken by Baker and Hutchinson. A classic example of this repair technique was in life extension of Mirage. In 1972, when it began to appear that the life-of-type might be limited by fatigue a full scale test of a wing was made in Australia, and the first failure occurred as a large crack across the inboard corner of the lower wing panel near the spar, at about half the total life to collapse. Similar cracks were found in the wings of an aeroplane tested in Switzerland. In anticipation of this occurring in service a "precautionary patch" was designed by Hoskin and Jones. In the event, cracking in service was first observed at a fuel drain hole, through a leakage of fuel. Attention then passed to the drain hole, and, using the experience of the precautionary patch, a repair for this region was designed, and developed by Structures and Materials Divisions<sup>55</sup> (Fig. 13), standardised procedures and affixing equipment were developed, and under A.R.L. supervision every R.A.A.F. aircraft was repaired, whether cracked or not. The patches have performed excellently in service.



FIG. 13 BORON FIBRE PATCH TO MIRAGE LOWER WING SKIN

Later there arose a need for further enhancement of the fatigue life by attention to spar bolt holes; a topic which there is not room here to detail.

New aircraft being introduced into Australia (e.g. FA-18, Fig. 14) utilise more and more fibre composites, and the need was realised to spread the expertise to potentially interested parties. To this end a symposium on composite materials was organised in 1982 by Hoskin and Baker<sup>56</sup>, attended by over 150 people. It has been assessed as being as informative and advanced as any such symposium in the world.

#### 10. TOMORROW'S TECHNOLOGY - ACTIVE CONTROLS

The Bleriot monoplane, the first aeroplane to cross the Channel, was reputed to be longitudinally unstable, and its wayward inclination to pitch required the continuous correction of an alert and active pilot at the controls. When automatic pilots were introduced they were the first (or second) example of active controls.

Given the present advances in technology of servo-systems, electronic sensors of motion, of strain, etc. a limitless horizon appears to be opening up by which control systems of aircraft can be designed to alleviate passenger discomfort in turbulence, to alleviate structural stress, to create artificial stability etc. A most promising method is digital "fly-by-wire" control, in which computer generated control messages are conveyed by wire to a translator at the control surface itself, where the message is translated into a control movement.

Readers of the aeronautical technical press are aware that the new F-18 has such a digital "fly-by-wire" control system, which, for instance, can be programmed to deflect differentially the wing flaps to provide rolling moments near the aileron reversal speed, and to deflect the ailerons in the opposite direction for rolling at above this speed.

A unique advantage of a digital computer control system is that its program can be written not only to command deflections of a particular control surface desired by the pilot: it can also command deflections of other surfaces to correct undesired secondary effects, e.g. yawing moments due to rolling.

Structures Division has already had some experience in a kindred field. The fatigue test of the Mirage wing used 14 servo-hydraulic jacks to load, and it fell to Mr. E.S. Moody to devise and build a computer controlled system to command and control the forces and deformations with great accuracy and at high operating rates. This gave A.R.L. some preliminary experience in a field which is expected to produce many pressing demands for research in future years.

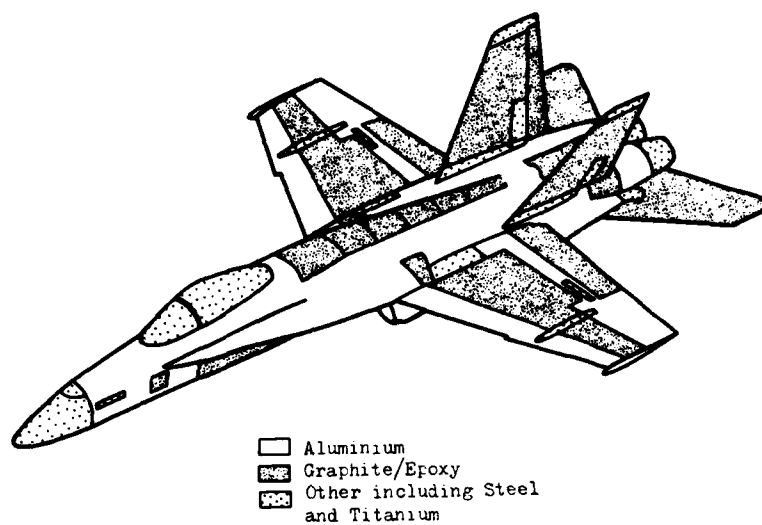


FIG. 14 USES OF FIBRE COMPOSITE IN FA-18

11. THE FUTURE

Looking towards the future it is quite clear that certain fields will demand continuing research.

Fatigue, like the poor, will be always with us, primarily because of the relentless race towards more efficient use of material, the cheese-paring of structural strength and the requirement of extended life-of-type. Active controls is an emerging feature of current-future aircraft, and promises to bring with it problems and potential advantages which A.R.L. will be expected to solve or exploit. Aeroelasticity and vibration problems have not "gone away", but appear to be areas of growing potential problems as aircraft become slimmer, less stiff, and operated by more complex control systems.

To be equipped for the future I see the structural research laboratory to need:-

- (a) staffing with initiative and imagination, to perceive areas for research as or preferably before critical problems emerge;
- (b) basic research approaches to provide a groundwork for treating problems in a "polytechnic" way;
- (c) a strong structural analysis research capability to enhance the understanding of the real behaviour of structures;
- (d) adequate experimental test staffing and equipment to undertake and document the complex tests now needed for through-life support of complex aircraft;
- (e) external publication of all but security-classified research and testing, to encourage a two way flow of ideas and criticism;
- (f) greatest possible exposure of staff to other specialist opinion in conferences and symposia in Australia and overseas;

- (g) firm control of ad hoc research and problem solving to prevent absorption of creative thought (of those capable of it) in uncreative routine; and
- (h) enhancement of an atmosphere conducive to research.

Many of those who were there in the early days see those days as a heyday. One would hope that those who are young scientists now will look back from 40 years hence and say the same.

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