AD-A102 867 ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) F/G 13/8
NON-DESTRUCTIVE INSPECTION AND THE IMPLEMENTATION OF A DAMAGE T--ETC(U)
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ROYAL AIRCRAFT ESTABLISHMENT

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NON-DESTRUCTIVE INSPECTION AND THE IMPLEMENTATION OF A DAMAGE TOLERANT DESIGN PHILOSOPHY

by

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(11) February 1981

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(14) RAE-TM-STRUCTURES-982

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ROYAL AIRCRAFT ESTABLISHMENT

Technical Memorandum Structures 982

Received for printing 18 February 1981

NON-DESTRUCTIVE INSPECTION AND THE IMPLEMENTATION OF A DAMAGE TOLERANT DESIGN PHILOSOPHY

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D. E. W. Stone

SUMMARY

This Memorandum shows how increasing demands are being made for more quantitative NDI and in particular for data on the probability of detection at different confidence levels. Current inspection capabilities are discussed and found to be inadequate. The requirement for a UK programme on the reliability of NDI is examined.

1 INTRODUCTION

In order to ensure the airworthiness of an aircraft it is necessary to be able to state with confidence that there is no critical defect present in the structure; ie one which could result in catastrophic failure if 80% of ultimate load were applied. A great deal of effort has been expended in the past by the airworthiness authorities to ensure that such defects will not occur and until recently aircraft have been designed on a safe-life basis. Nonetheless, despite every care, it was inevitable that defects would from time to time be found to be present in service, or that structural tests would indicate that certain areas were suspect. The first requirement was then to investigate whether other aircraft in service contained similar defects and a range of NDI (Non Destructive Inspection) techniques have been developed to monitor these suspect areas. The objective of the inspection was primarily to detect the defect, although an ability to size it or to characterise it in some other way was clearly useful. However, unless it was practicable to scrap all the components concerned, it was also necessary to consider the implications with regard to airworthiness of the possible presence of a defect. Was it possible, for example, for a crack to grow to a critical size without being detected? This immediately raised the question of what size of crack could be detected, or more important what size of crack could be missed? Initially this question was answered by detectability limits that were assumed to be conservative. More recently, however, there have been pressures to produce more accurate data on defect detectability, but in reality the estimates made have been based more on limited experience and subjective judgement than on rigorous scientific investigation, and it will be shown later that these estimates may well be unduly optimistic.

These demands for more data on detectability limits have largely arisen as a result of moves towards the implementation of a damage tolerant design philosophy and it is especially important that urgent attention should be given to this question in the UK because a new set of UK Fatigue and Damage Tolerance Requirements are now being prepared. The objective of this paper is therefore to show how the inspection requirements are derived and specified, to examine the capability of currently available NDI techniques to meet these requirements and finally to consider the feasibility of mounting an exercise in the UK to provide additional data.

2 REQUIREMENTS

The inspection requirements may conveniently be divided into two categories (i) inspection in service and (ii) inspection at the manufacturing stage. It is, however, recognised that the same NDI methods - and the same queries as to their reliability - may well apply in both categories.

2.1 In-service NDI

Now and for the foreseeable future in-service NDI will be required on two types of structural component.

(i) Components that have been shown by service experience or by structural fatigue testing to be suspect and which must be treated on a damage tolerant (slow crack growth) basis.

(ii) Components that incorporate features such as redundant load paths or crack arresters. Such components can readily be incorporated in transport aircraft structures where in many cases the location and nature of the crack or other damage will often be such that visual examination (using fibroscopes etc if necessary) will be sufficient.

In either case the defect that is required to be detected and characterised will in the great majority of cases be a crack or an area of corrosion.

In the case of corrosion, however, it is usually only detection that is required. There is no formal procedure specifying an accept-reject criterion for corrosion damage. In general corroded areas are mechanically removed and re-protected. Nonetheless it is desirable to be able to estimate non-destructively the degree of damage so as to be able to judge whether it justifies a possibly expensive strip-down; additionally, early detection will minimise the costs of rectification. At present non-destructive methods of detection alone are not adequate and it is extremely difficult to quantify the degree of damage. However, since the role of corrosion is not considered in either the USAF requirement MIL-A-83444 or the new UK requirements, it will not be considered further in this paper.

In the case of a crack it has usually been left to the subjective judgement of an experienced inspector to estimate the crack size that is unlikely to be missed. The frequency at which inspections must be conducted is based on the size of this crack together with:

(i) the estimated load spectrum and predicted environment in the particular area,

(ii) the stresses calculated to be generated by these loads and, in particular, estimates of the local stress intensity factor,

(iii) the crack propagation characteristics of the material involved,

(iv) the residual strength of the structure based on (i)-(iii) and the fracture toughness of the material,

(v) factors of safety that take into account uncertainties and scatter in the above.

The required probability of detection and confidence level of the NDI technique (defined later in this section) will be specified in the new UK Fatigue and Damage Tolerance Requirements for Military Aircraft.

The basis of the current UK safe-life requirements is to ensure that the probability of damage reaching a critical size during the specified life does not exceed about 1 in 1000, and the new UK requirements for the in-service inspection of parts will be framed to achieve at least this standard of safety. This overall probability of 1 in 1000 will be arrived at by using the combined probability of (a) the specified initial crack being missed on inspection and (b) the probability of it then propagating to a critical size before the next inspection. In specifying when inspections should begin and what the inspection interval should be, account will also be taken of the probability of a crack being present.

If we take the usually assumed probability of detection of 90% this means that, out of any 100 components containing cracks of the specified size or greater, the cracks would fail to be detected in not more than 10 components. Thus the specified damage would be that which would be missed by scheduled inspection on not more than 1 in 10 occasions. In the simplest case if the overall probability of 1 in 1000 is to be maintained it would be necessary to show that the probability of this damage growing to a critical size before the next scheduled inspection interval would be not more than 1 in 100. The implications of varying the probability of detection (POD) and hence the probability of missing a defect (POM) on the required probability of propagation to a critical size (POP) for the same overall probability of 0.1% are shown in the following Table.

POD %	POM %	POP %
0	100	0.1
50	50	0.2
90	10	1.0
99	1	10.0

The implications of the two extreme cases are that if the POD is zero then the defect is certain to be missed by inspection so that there must be a very low probability (0.1%) of crack propagation to a critical size. Conversely if the POD were 99% then a much higher probability of crack propagation could be permitted. The new requirement will accept that the former case will often occur in practice, ie that areas of structure need not be inspectable if it can be shown that this inspection would be impractical or would lead to an overriding design penalty.

It is anticipated that established coefficients of variation for the initiation and propagation times can be used to derive life factors and stress factors for three alternative values of POD, 0% (equivalent to safe-life), 90% and 99%. The question of the confidence level of the POD will then need to be addressed. Currently it is envisaged that a 50% confidence level will be used.

2.2 NDI in manufacture as a basis for the 'initial flaw' concept

The USAF requirement MIL-A-8344, which does not cover accidental or corrosion damage, assumes that damage, represented by idealised fatigue cracks of specified sizes, is present in each component of an aircraft when it enters service. Thus no distinction is made in principle between defects created at the manufacturing stage and those occurring in service. For damage tolerant design purposes, however, these are considered to be equivalent to (or to be capable of generating at an early stage in the life) specified small fatigue cracks. From an NDI point of view the actual defects sought will often be of a very different nature, such as porosity, shrinkage or inclusions in castings.

The USAF Damage Tolerant Design Handbook[1] explains that it will normally be acceptable to represent the damage state by crack sizes that will be missed by scheduled inspection on only 1 in 10 occasions (POD of 90%) with 50% confidence for parts in category 2.1 (ii) above, and with 95% confidence for other parts. It may perhaps be helpful here to clarify what is meant by the level of confidence. If there is an x% POD with a 95% confidence level then there is a 5% probability that x% is an *overestimate* of the POD. Alternatively if a series of samples from the same population were tested then 95% of the samples would have a true POD of at least x%.

It will be shown later that with the present state-of-the-art the requirements placed on inspection in MIL-A-83444 are quite unrealistic. With the notable exception of the USAF Logistics Command programme on the reliability of NDI[2] (the so called "Have Cracks will Travel" programme) the evidence on POD in typical airframe situations is very fragmented, and quantified confidence levels for NDI of airframe components are almost non-existent. The full report on this programme[2] is a rather complicated document but McKenna has prepared a useful summary and discussion paper[3] for the MOD Co-ordinating Committee for NDT.

3 THE ACQUISITION OF RELIABILITY DATA

Essentially there are two ways of obtaining data on the reliability of inspection techniques; one can either prepare a series of defective specimens that reproduce as closely as possible the defects likely to occur in practice, or one can use field or production data. The former approach is expensive and has the disadvantage that the specimen defects may not be adequately representative, whilst the latter requires not only that a sufficient number of real structural defects should exist but also that destructive inspection is permissible to determine their size and character. The use of correlation functions[4] does, however, allow the amount of destructive inspection to be reduced somewhat.

3.1 Laboratory specimens containing induced cracks

Consider first the former approach. If it is required to determine the POD of a defect lying in given size range then it is possible to specify statistically how many defects of this given size must be successfully detected from a finite number of samples if a particular confidence level is to be satisfied. The following Table taken from Ref 5 illustrates how just one failure to detect a defect that is present can result in quite large numbers of specimens having to be tested.

For a reliability of 90% the required number of successes, and hence the permitted number of misses, to achieve two different confidence levels are tabulated against the total number of trials.

Confidence %	Number of successes	Number of misses	Number of trials
95	29	0	29
	45	1	46
	59	2	61
	72	3	75
	85	4	89
	98	5	103
50	7	0	7
	16	1	17
	25	2	27
	34	3	37
	43	4	47
	52	5	57
	61	6	67
	70	7	77
	79	8	87
	88	9	97

There must be at least as many defect-free specimens as there are specimens containing defects. Therefore, if we take the frequently quoted 95% confidence level, it can be seen that 58 specimens would have to be inspected and no defects missed if this confidence level is to be attained. If only one defect is missed then the number of specimens has to be increased to 92 with no further defects missed for the required confidence level to be regained. Bearing in mind the fact that this number of specimens is required for each defect size it can be seen that even for a modest range of defect sizes it is very easy to generate a requirement for a large number of specimens.

There have been some recent attempts in the UK to produce simple multi-hole tensile specimens containing a range of fatigue cracks. By careful selection of the stress range it has been possible to ensure that if a specimen is fatigued unattended until fracture occurs at one hole, then a reasonable distribution of fatigue crack sizes will be present at the remaining holes. This is a comparatively cheap procedure but many of the cracks produced are too large to be useful so the advantages may be illusory. A more sophisticated procedure was employed by Lockheed[2] on the same type of specimen for comparison with cracks in real structures. Crack starters in the form of fine saw cuts were introduced at different stages of the life and crack growth monitored optically; when the required crack sizes had been attained the crack starters were machined away. This procedure guaranteed cracks of approximately the right size but was much more demanding in terms of manpower.

It should be noted that there may be a number of factors such as ease of access, an unrepresentative surface finish to the bore holes, or an absence of corrosion products that may make such tests on laboratory specimens unrealistic. Nevertheless the value of such an approach should not be underestimated; it demonstrates the 'base-line' level of detectability that is unlikely to be exceeded in-service and allows a quantitative estimate to be made of the probable effect of some practical variables, such as the tightness of the crack or the presence of corrosion.

3.2 Actual fatigue-cracked structural components

The "Have Cracks" programme did use real structural components, but these had been carefully selected to provide cracks of a suitable size and complete destructive inspection was possible. It was an ambitious and well planned programme but was inevitably very expensive, the estimated cost being $750K-$1M. The data produced, which was rather alarming, will be discussed briefly in the next section. Initial attempts in the UK merely to collect suitable structural specimens have not been very successful so it must be concluded at this stage that the chances of mounting anything more than a very modest exercise are not very great. Such an exercise might not even yield sufficient data to extract PODs with an adequate level of confidence, but it would at least indicate the likely degree of degradation in performance to be expected when transferring from simple specimens to real structures. It should be noted that even the specimens used in the "Have Cracks" programme were not entirely representative because they were unstressed. For some components this is not important, but when considering cracks in wing skins for example it must be borne in mind that the lower skin, which is largely loaded in tension, will in fact be in compression for all in-service inspections unless arrangements are made to jack up the wings. The importance of this has not been quantified, but it is unlikely to be insignificant.

Finally consideration should be given to the possibility of extracting reliability data from the large amount of routine inspection that is in progress all the time. When defects are found they are almost inevitably repaired but the rectification may not be done in such a way that the defect size is measured and recorded. Even bearing in mind the limitations imposed by operational requirements it should still be possible for more to be done in this area. This would not of course directly give any information on defects that have been missed but it may be possible to estimate the probable crack growth since the last inspection and hence the probable size of crack that was missed at the last inspection. It would also be extremely valuable to ensure that data of this nature was accompanied by as much detail as possible on the circumstances in which a given crack was detected or missed. Factors such as accessibility and contamination should be recorded together with any peculiarities revealed by destructive inspections. More use might also be made of those components that have to be scrapped; destructive inspection would reveal whether other defects had been missed.

4 CURRENT INSPECTION CAPABILITIES

As one might expect from the comments in the above section, among all the data that have been published on the probability of detecting real cracks there is only a very limited amount available on statistically significant numbers of specimens. Rummel, et al[6] investigated the detectability of tight fatigue cracks in flat specimens of 2219-T87 aluminium alloy; they provided three independent inspectors with 118 specimens containing a total of 328 fatigue cracks, together with 13 flaw-free specimens. POD was presented at the 95% confidence level for X-ray, ultrasonic, penetrant and eddy current methods with the specimens in three conditions

(1) as fatigued and machined
(2) after flash-etching
(3) after (2) and proof loading to 85% of yield stress.

The electro-discharge machined crack-starter notches were machined away after fatigue testing and this would have tended to smear over the cracks so condition (2) is probably more representative of a service crack. Condition (1) is, however, still of direct interest because it represents the commonly encountered situation where inspection is employed to ensure that all fatigue damage has been removed by reaming out holes, etc.

The way in which the data are derived and presented is rather confusing but the following Table gives the smallest crack size (depth) that could be detected with 95% confidence at different probabilities of detection (condition (2)).

Probability of detection %	Smallest detectable crack depth (inches)			
	X-ray	Penetrant	Ultrasonics	Eddy current
95	-	-	-	
90	0.18	0.11	-	0.06
80	0.09	0.05	0.06	0.04
50	0.05	0.01	0.02	0.01

An interesting reliability exercise was also performed by the Netherlands National Aerospace Laboratory (NLR)[7] using 102 specimens tested in bending fatigue. The specimens contained a milled step down region designed to represent a step down in a fighter wing access panel that had exhibited fatigue cracks in service. Each specimen contained two radii so that a total of 204 radii potentially contained cracks. The principal concern was to evaluate the reliability of inspection from the outer (flat) surface, but penetrants were also employed on the radius itself. Only POD was presented and no confidence levels are quoted, but this programme demonstrates clearly the difficulties encountered in comparing destructive and non-destructive data. It also demonstrates the degree to which the presence of corrosion will degrade the inspection capability.

The definitive programme to date, however, has been the "Have Cracks" programme. It used a range of real structural components containing fatigue cracks at features such as fastener holes, cut-outs and other radii and great care was taken in establishing confidence levels. Most of the major NDI techniques were employed but it is to be regretted that, since no steel specimens were included, no data on the capability of magnetic techniques were produced. There is a great deal of complicated detail in the report[2] and for the purposes of this paper McKenna's summary[3] is probably sufficient. The following extract from the General Conclusions does, however, make painfully clear the situation that was revealed:

"Of foremost importance is the realization that the previously established 90-95 per cent reliability criteria (90 per cent probability of detection with a 95 per cent confidence bound) cannot be attained with normal inspection methods. With the exception of fluorescent penetrant inspection, the NDI techniques employed in the program demonstrated considerable difficulty achieving a 50 per cent probability of detection for a 1/2-inch crack size with a 95 per cent confidence level. It should be pointed out, however, that all conclusions contained in this report are based on the data obtained during the NDI reliability program which used the NDI techniques and equipment currently available at the Air Force Installations visited.

"The state-of-the-art is constantly changing in NDI technology. Inspection reliability improvements resulting from recent refinements in NDI methods, presently undergoing service evaluation were not included in this study. There was a limited opportunity to evaluate the effectiveness of semi-automatic eddy current and ultrasonic equipment, beginning at the 13th base visit (out of a total of 21). Unfortunately, due to the late incorporation of semi-automated equipment into the program, the data quality restricted determination of a reasonable confidence level for this equipment, but the mean crack detection levels obtained from using this type of equipment indicate that 90-95 per cent reliability criteria may be possible at crack sizes considerably smaller than 1/2-inch".

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It should also be noted that a distinctly higher level of success in flaw detection was achieved at one particular depot and this was attributed solely to individual proficiency. It is therefore to be hoped that the RAF technicians, who are much more carefully selected and are also probably more highly motivated, would also exhibit a higher standard.

Nonetheless, on the available evidence it must be concluded that the current capabilities of NDI have not been demonstrated to be sufficient to support the damage tolerant design philosophy advanced in MIL-A-83444. In the longer term, however, it may well be that automated or semi-automated equipment operated intelligently by experienced personnel will have this capability, at least for a certain number of structural situations. A number of new devices has already been developed since the above programme and there is considerable activity in the use of small computers to capture, process and present NDI data. There is no doubt that these devices will be capable of significantly higher PODs but it will be necessary to establish exactly how good the performance is in a given situation.

5 THE REQUIREMENT FOR A UK NDI RELIABILITY PROGRAMME

The new UK requirement covering fatigue and damage tolerance will specify the probability of detection and confidence level required for in-service inspections. It would appear therefore, that there is no alternative to mounting some form of NDI reliability programme. Even on a modest scale this will be an expensive exercise and there will almost certainly be great difficulty in finding a suitable organisation to do the work. Even if these difficulties can be overcome, however, there are still a number of reasons to question the value of such an exercise.

(1) There must still be serious doubts as to the extent to which human factors, which are hard to quantify, would affect the validity of the data.

(2) Only a very limited number of structural situations could be covered and the degree to which data obtained could be read across to other situations is uncertain.

(3) NDI techniques are developing rapidly and the data would soon be out of date (as demonstrated by the "Have Cracks" programme).

However, most of the current military aircraft, although designed on a safe-life basis, contain fatigue-prone features that are treated as damage tolerant. In many cases such aircraft would be scrapped or faced with expensive modifications if such an approach were not allowed. The safety of these aircraft depends upon being able to estimate with confidence the size of defect that could not be missed by inspection. At present this is an almost impossible question for the NDI specialist to answer and any information, however idealised, on the reliability of modern inspection devices would be extremely valuable. Thus, whilst it may be concluded that there will be considerable difficulty in attaining inspection standards consistent with the initial flaw size requirements of a damage tolerant philosophy, investigations to determine the reliability of NDI systems are justified in order to maintain acceptable safety standards with existing practices.

There is another important area in which the application of a damage tolerant philosophy may already not only be feasible but also necessary; this is in the "Retirement for Cause" approach to the inspection and replacement (if necessary) of gas turbine components. In the case of discs for example it would appear that there could soon be a situation where there will be a large number of similar components that are nominally life-expired; the potential savings to be gained by being able to return many of these discs to service could well justify the expense of an NDI reliability exercise.

6 CONCLUSIONS

(1) There are components in the generation of aircraft now in service, which were designed on a safe-life philosophy, that are acknowledged to be susceptible to the presence of cracks and if airworthiness clearance is to be granted on the basis of quantified slow crack growth then situations will occur where it is necessary for techniques to be available to detect such cracks with a known probability of detection and known confidence level.

(2) Data on the attainable probability of detection at a given confidence level is extremely sparse but there is good reason to doubt whether NDI techniques are currently capable of meeting the demands placed upon them.

(3) The growing implementation of a damage tolerant design philosophy, and in particular the drafting of the new UK Fatigue and Damage Tolerance Requirements for Military Aircraft, will inevitably make these damands more severe.

(4) If the new requirements are to be implemented then it will be necessary to mount some sort of reliability programme in the UK, but it must be recognised that not only will this be both difficult and expensive to perform, but also the rapid growth in NDI technology may well mean that the data obtained will rapidly become out of date.

(5) In the short term it will only be practicable to produce idealised 'baseline' data using laboratory specimens; the limited number of real components available should however be used to estimate the extent to which this data can be applied to practical situations.

(6) In the longer term far greater use should be made of cracks found in service and of components that have to be replaced. Strenuous efforts should be made to ensure that these are as fully investigated and documented as possible.

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REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

1. DRIC Reference (to be added by DRIC)	2. Originator's Reference RAE TM Structures 982	3. Agency Reference N/A	4. Report Security Classification/Marking UNLIMITED

5. DRIC Code for Originator 7673000W	6. Originator (Corporate Author) Name and Location Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code N/A	6a. Sponsoring Agency (Contract Authority) Name and Location N/A

7. Title Non-destructive inspection and the implementation of a damage tolerant design philosophy

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials Stone, D.E.W.	9a. Author 2	9b. Authors 3, 4	10. Date February 1981	Pages 12	Refs. 7
11. Contract Number N/A	12. Period N/A	13. Project	14. Other Reference Nos.		

15. Distribution statement

(a) Controlled by – Head of Structures Department

(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Non-destructive Inspection. Reliability. Airworthiness.

17. Abstract

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