Quantification of Fastener-Hole Quality

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This paper describes a method, the Equivalent Initial Quality Method, of quantifying the quality of fastener holes. This quantification is accomplished by representing the imperfections that are either inherent in a material or introduced during the manufacturing of a structural component with a fatigue crack of a particular size and shape. This initial quality representation can be used in a crack-propagation analysis to determine the life of the structural component. For example, the Equivalent Initial Quality Method can be used in design by providing the assumptions necessary to satisfy the USAF airplane damage tolerance design requirements (MIL-A-83444) and the USAF airplane durability design requirements (MIL-A-8866B). The method was used to assess the manufacturing quality of the F-4C/D/E(S) and A-7D aircraft. The more recent A-7D quality assessment is discussed in detail and the equivalent initial quality results for the F-4C/D and A-7D aircraft are presented. The potential applications (e.g., determination of required inspection intervals and maintenance and modification schedules, use in design, assessment of quality of manufacturing procedures, etc.), as well as the possible limitations (e.g., sensitivity of method to stress level, material, etc.), of the Equivalent Initial Quality Method are discussed.

I. Introduction

PAST experience with tests of structures under simulated flight loading has indicated that the time to initiation of cracks from most structural details (e.g., sharp corners, holes, etc.) is relatively short and that the majority of the life (i.e., 95%) is spent growing the cracks to failure.[1] It has also been discovered that a major source of cracks is the occurrence of initial manufacturing defects such as sharp corners, tool marks, etc. Thus, it is now common practice to consider the damage accumulation process as entirely crack growth with zero time to initiate the crack. This is illustrated in the following two military specifications.

The USAF airplane damage tolerance requirements, MIL-A-83444,[2] specifies that initial flaws shall be assumed to exist as a result of material and structural manufacturing and processing operations. Small imperfections equivalent to a 0.005-in. radius corner flaw resulting from these operations shall be assumed to exist in each hole of each element in the structure, providing the basis for the fastener policy requirements and the continuing damage and remaining structure damage assumptions. However, if the contractor has developed initial quality data on fastener holes (e.g., by fractographic studies), these data may be submitted to the procuring activity for review and serve as a basis for negotiating a size different than the specified 0.005-in. radius corner flaw.

The USAF airplane durability design requirements, MIL-A-8866B,[3] specifies that an analysis shall be conducted to demonstrate that the economic life of the airplane is in excess of the design service life when subjected to the design service loads spectra and the design chemical/thermal environment spectra. The approach shall account for those factors affecting the time for cracks or other damage to reach sizes large enough to necessitate the repair, modification, or replacement of components. One such factor that must be accounted for is the initial quality.

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One method of accounting for the initial quality is to represent the quality in terms of an equivalent fatigue crack of a particular size and shape. Such a method of quantifying the initial quality is the Equivalent Initial Quality Method[4] described in the following section.

II. Description of Equivalent Initial Quality Method

The Equivalent Initial Quality Method shall be described for fastener holes, the most prevalent source of cracking in aircraft structures.[5] For the purposes of this paper, quality shall be defined as a measure of the condition of the structure relative to imperfections, flaws, defects, or discrepancies that are either inherent in the material or introduced during manufacturing of the structure. It may be desirable to quantify these imperfections by representing them with fatigue cracks of a particular size and shape, such as the corner cracks illustrated in Fig. 1. Also illustrated in Fig. 1 are some of the parameters that can contribute to the initial quality of fastener holes. If an initial quality representation is performed for each of a number of fastener holes, an equivalent initial quality statistical distribution can be obtained. This equivalent initial quality statistical distribution can be used to indicate the quality of the fastener holes produced by certain manufacturing and processing procedures.

The initial quality representation, defined as the equivalent initial quality, can be obtained in the following manner. Consider a piece of structure with a fastener hole containing the defect of characteristic dimension l (Fig. 2). This defect results in fatigue crack initiation and propagation when subjected to some known load history. Upon failure of the structure, a fractographic examination of the fracture surface is performed to obtain as much of the crack growth curve as possible. Analytical crack propagation analyses are performed until there is good agreement between the analytical prediction and the fractographic test data. The initial crack length (crack length when the load history is first applied), a_i, of the analytical crack growth curve that correlates best with the fractographic test data is defined as the equivalent initial quality. Hence, a_i is said to be the analytical equivalent of the actual defect of characteristic dimension l if each results in a crack size a_e after N_e cycles of the same load history have been applied. Hence, fastener holes that contain actual crack lengths less than a_e after N_e cycles have been applied are of

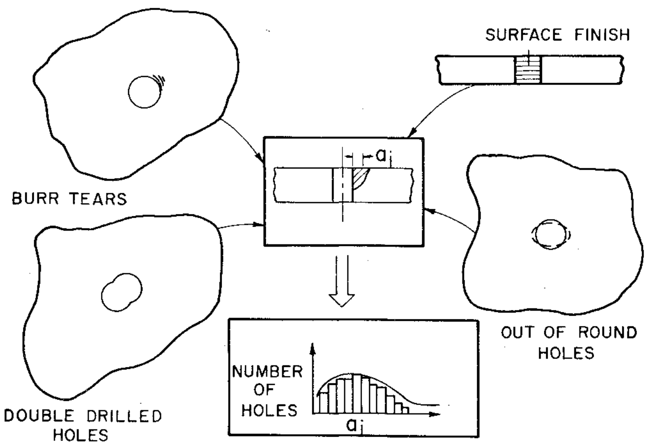


Fig. 1 Parameters that affect fastener-hole initial quality.

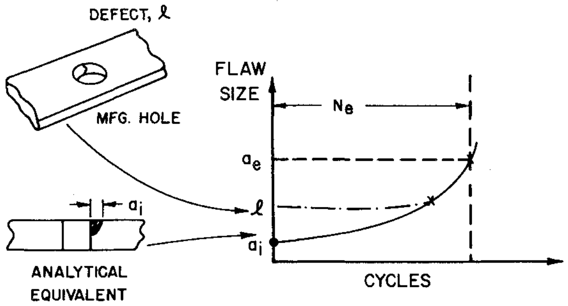


Fig. 2 Definition of equivalent initial quality.

better quality than those that contain actual crack lengths equal to or greater than a_e after N_e cycles.

III. Applications of Equivalent Initial Quality Method

Applications of the Equivalent Initial Quality Method include its use on the F-4C/D,[6] F-4E(S),[6] and A-7D[7] Aircraft Structural Integrity Programs (ASIP). This paper presents a detailed description of the more recent A-7D quality assessment program, followed by the A-7D and F-4C/D equivalent initial quality results.

A-7D Quality Assessment

The purpose of the A-7D quality assessment was to establish the manufacturing quality (a_i) of the A-7D aircraft. This was accomplished using the Equivalent Initial Quality Method. The method was applied to a sample problem involving an A-7A wing fatigue test failure. Next, specimens were cut from an A-7D production aircraft and tested to failure under a selected block loading. The fracture surfaces were then fractographically examined and the equivalent initial quality was established.

A photograph of the failure area of a full-scale fatigue test of an A-7A wing was available to be used as a sample problem to check out the Equivalent Initial Quality Method. The wing had been subjected to a 10-level, blocked, low/high stress spectrum. Fractographic measurements were taken from the photograph (Fig. 3), making it possible to generate a large portion of the crack growth curve.[8] Crack propagation analyses were performed using the computer routine EF-FGRO and the Wheeler Retardation Model until the analytical crack growth curve correlated well with the fractographic test data.[9] This correlation is presented in Fig. 4, which indicates that the manufacturing quality of the test hardware at the failure location was equivalent to an initial crack of length $a_i = 0.00109$ in. This excellent correlation of the analytical crack growth prediction with the fractographic test data indicates that the Equivalent Initial Quality Method was quite successful for this particular problem.

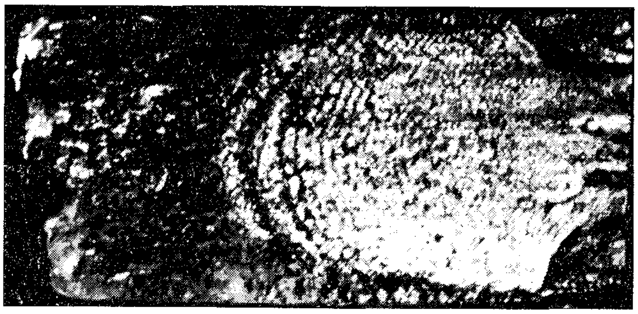


Fig. 3 A-7A wing fatigue test fracture surface.

Having successfully checked out the Equivalent Initial Quality Method on the above sample problem, the method was next used to establish the A-7D quality assessment. This assessment was accomplished using test specimens cut from the lower wing skin of an A-7D production aircraft that had been used as a gunfire target.[10] Because this particular aircraft had low flight time (691.9 h), the probability of cracking in the wings was very low. The location of each specimen in the lower wing skin is illustrated in Fig. 5. Each specimen was made of 7075-T6 aluminum and contained multiple holes. The geometric details for each specimen are presented in Table 1, indicating that the thickness ranged from approximately 3/16 in. to 1/4 in. and the nominal values of the width and hole diameter were 3 in. and 1/4 in., respectively. The specimens contained two types of holes – countersunk holes (wet-wing region) and straight-shank holes (dry-wing region).

The test specimens were subjected to a fatigue stress spectrum consisting of 5000 cycles with a maximum stress of 20 ksi and a stress ratio of 0.1 followed by 100 cycles with a maximum stress of 30 ksi and a stress ratio of 0.1. The block spectrum was chosen because it produced test lives of reasonable length (less than 20 blocks) and fracture surfaces that were readily readable.

Table 2 contains a summary of the number of fastener holes involved, the number of flaws detected, the number of flaws fractographically examined, the crack length range at the time of specimen failure (a_f), and the range of the equivalent initial quality (a_i). All but 2 of the 44 holes contained double flaws. One of these two holes contained one crack, while no crack was detected in the other hole. This resulted in a total of 85 flaws, of which 44 were examined fractographically. The flaws were arbitrarily chosen for fractographic examination at magnifications ranging from 30× to 400× using a universal measuring microscope. The equivalent initial quality range for all the holes was found to be 0.00015-0.0022 in. A statistical distribution of the A-7D equivalent initial quality was obtained and is discussed subsequently.

The fractographic examinations revealed the origins of the flaws for both the straight-shank holes and the countersunk

Table 1 Geometric details of A-7D quality assessment specimens

Specimen	Thickness[a]	Width[a]	Hole diameter
101	0.226	2.93	0.253[b]
201	0.226	2.93	0.253[b]
301	0.217	3.00	0.253[b]
401	0.231	3.00	0.253[b]
501	0.183	2.9	0.253[c]
502	0.176	3.00	0.253[c]
601	0.263	3.00	0.253[c]
602	0.264	3.00	0.253[c]

[a] Dimensions in inches.
[b] Countersunk hole.
[c] Straight-shank hole.

Table 2 A-7D quality assessment test results

Specimen	No. holes	No. flaws	af[a] range	Flaws tracked	ai[a] range
101	7	14	0.05-0.75	14	0.0004-0.0022
201	6	12	<0.01-1.10	12	0.0004-0.0012
301	4	8	0.01-0.65	1	0.0003
401	3	6	0.02-0.50	6	0.0002-0.0014
501	8	14	0.00-0.60	1	0.0007
502	8	16	<0.01-0.62	1	0.0006
601	4	8	0.02-0.50	8	0.00015-0.0009
602	4	7	0.00-1.05	1	0.0006
Total	44	85		44	

[a] Dimensions in in.

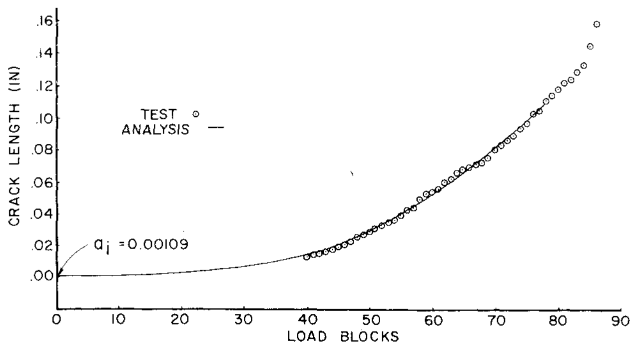


Fig. 4 Equivalent initial quality results for A-7A wing fatigue test failure.

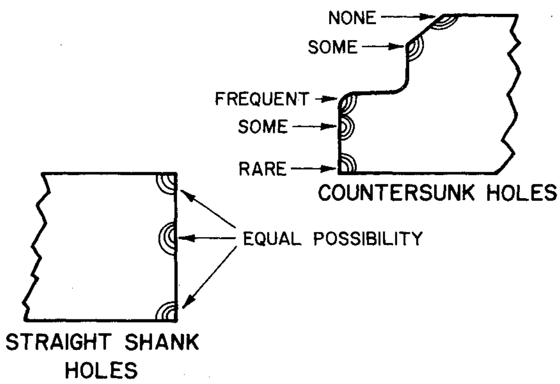


Fig. 6 A-7D flaw origins.

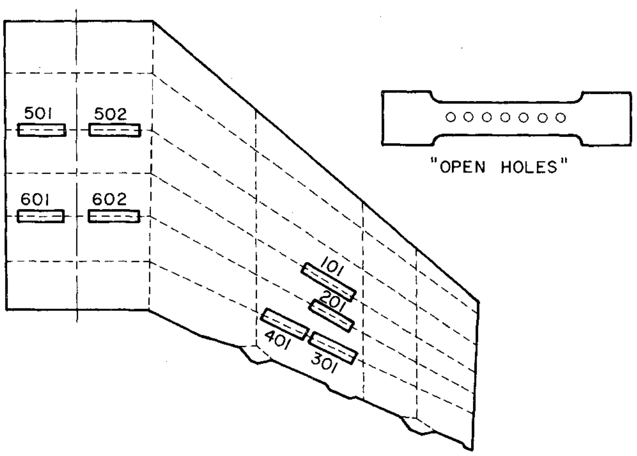


Fig. 5 A-7D quality-assessment specimen locations.

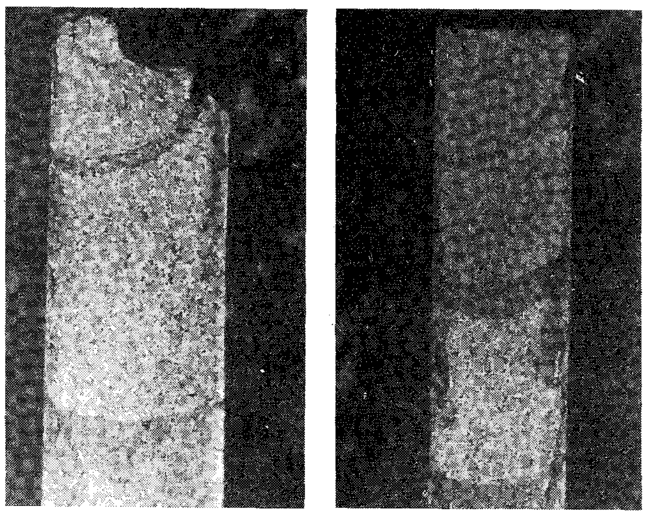


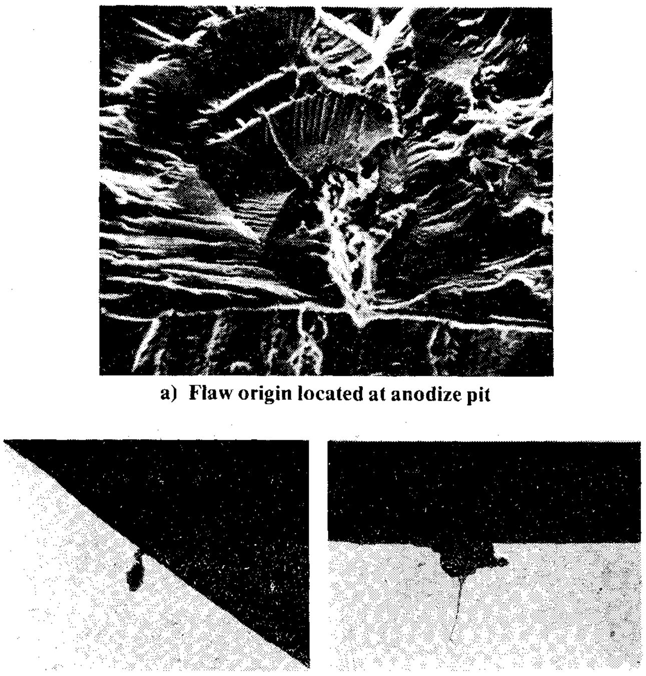
Fig. 7 Fracture surfaces for countersunk (left) and straight-shank (right) holes.

holes as illustrated in Fig. 6. There is equal possibility of flaw occurrence along the bore of the hole for the straight-shank hole, while the most frequently occurring flaw location for the countersunk hole is at the inside radius of the small-diameter portion of the hole. Typical flaw origins for each type of hole are shown on the fracture surfaces of Fig. 7. Also illustrated in Fig. 7 is the readability of the fracture surfaces for the selected stress spectrum, with the dark marking bands resulting from the application of the high-load (maximum stress of 30 ksi) portion of the spectrum.

Metullurgical investigations of the A-7D flaw origins revealed that the flaws were the result of two different sources – anodize pitting and mechanical sources. The majority of the flaws (86.4%) initiated from anodize pits in the following manner. Insoluble microconstituents were exposed along the bore of the hole during the hole-drilling operation. The anodizing ate away the microconstituents and caused pitting. The exposed pits were then filled with aluminum oxide, resulting in flaw initiation. The remaining flaws (13.6%) were due to the mechanical aspects of machining the holes. An example of flaw initiation from anodize pitting is presented in Fig. 8.

Figure 9 presents the fractographic test results for a typical straight-shank hole. The crack length for this particular hole was determined to be 0.0139 in. at the time of failure of the specimen, which occurred during the 12th block of loading. The selection of the stress spectrum to mark the fracture surfaces was indeed a good choice since it was possible to determine the crack length at the beginning of the high-load segment of each loading block. The crack length at the beginning of the high-load segment of the first block of loading was taken as the equivalent initial quality. The equivalent initial quality for each of the other flaws fractographically examined was determined in a similar manner.

Some general observations can be made from the results of the A-7D quality assessment program. Fatigue cracks were found to initiate from both anodize pits and mechanical



a) Flaw origin located at anodize pit

b) Typical anodize pit c) Fatigue crack initiation from anodize pit

Fig. 8 Flaw origin from anodize pit.

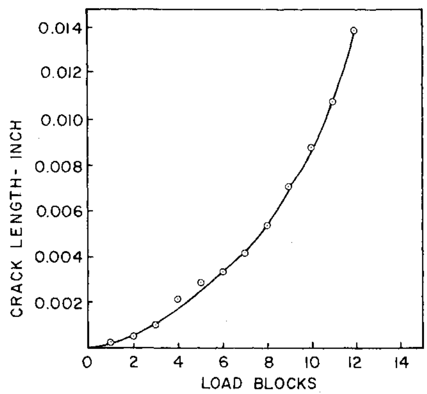


Fig. 9 Typical A-7D quality-assessment test results.

sources. Although anodizing provided corrosion protection, it also resulted in the majority of the fatigue cracks. All but two of the holes contained double flaws, of which none were through-the-thickness flaws. The selected stress spectrum marked the fracture surfaces extremely well, making it possible to determine the crack length within each loading block. Hence, it was possible to fractographically determine the equivalent initial quality for each flaw examined.

A-7D and F-4C/D Equivalent Initial Quality Results

One of the objectives of the A-7D and F-4C/D quality assessment programs was to determine the economic life of each aircraft, i.e., that time when the population of cracks in each aircraft just reaches sufficient size that rework or repair is no longer cost-effective. Typically, the economic limit on rework for fastener holes is approximately 0.060 in. on the diameter, or the next nominal hole size.[1] Thus, for this particular case, the economic life would be based upon the time required for a flaw to grow from its initial size to 0.30 in. The Equivalent Initial Quality Method was used to select the initial flaw size used to determine the economic lives of the A-7D and F-4C/D aircraft.

Figure 10 presents the probability density of occurrence versus the equivalent initial quality for the A-7D and F-4C/D

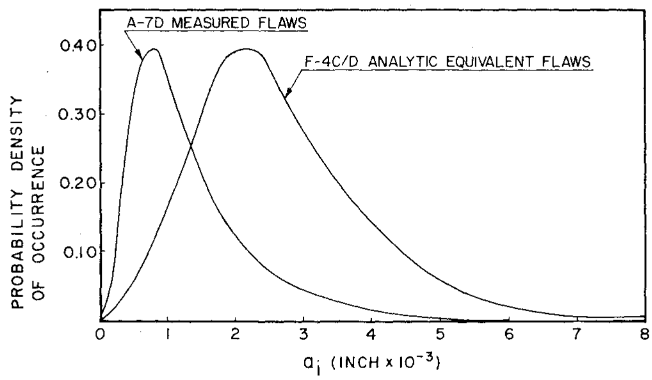


Fig. 10 Probability density of occurrence of A-7D and F-4C/D equivalent initial quality.

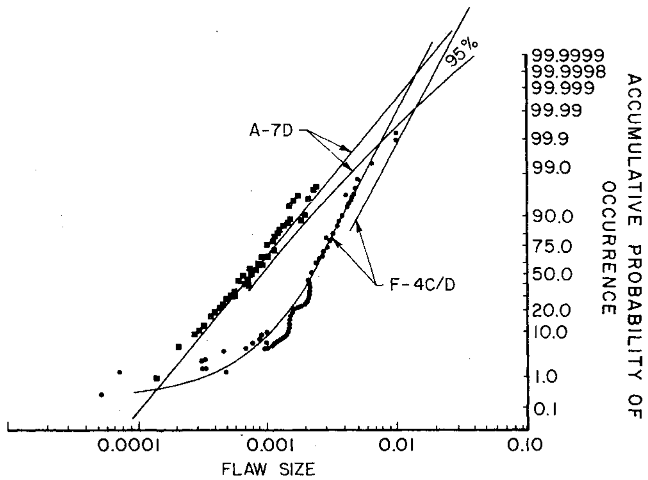


Fig. 11 Cumulative probability of occurrence of A-7D and F-4C/D equivalent initial quality.

aircraft. It should be noted that the A-7D equivalent initial quality was determined by fractography alone, since it was possible to measure the crack length during the application of the first block of loading. However, because it was not possible using optical fractography to determine the crack length at time zero for the F-4C/D aircraft, the F-4C/D equivalent initial quality was determined from combined fractographic and crack propagation analyses.[6]

The probability density of occurrence (Fig. 10) was used to determine the cumulative probability of occurrence for the A-7D and F-4C/D aircraft. Figure 11 presents the cumulative probability of occurrence versus the equivalent initial quality for these aircraft. Also presented in Fig. 11 is the cumulative probability of occurrence with 95% confidence for each aircraft. For example, Fig. 11 indicates that with 95% confidence, 99.9% of the F-4C/D flaws have an equivalent length less than 0.01 in. This means that one out of a thousand flaws have an equivalent length greater than 0.01 in. Hence, the cumulative probability of occurrence curve can be used in conjunction with a knowledge of the number of fastener holes per structural component that can be reworked economically to select the initial crack length used to determine the economic life of the structural component. Figure 12 presents the average initial flaw size and the durability initial flaw size (initial flaw size used to determine the economic life) for the A-7D and F-4C/D aircraft.

IV. Conclusions

The Equivalent Initial Quality Method has been used to assess the manufacturing quality of such existing aircraft as the A-7D and F-4C/D/E(S). The analytical representation of the actual manufacturing quality is needed for the deter-

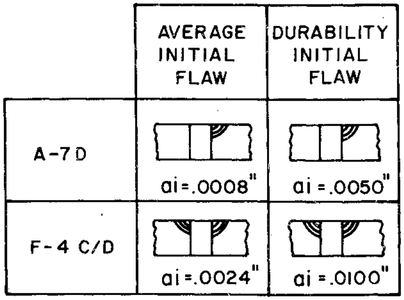


Fig. 12 A-7D and F-4C/D equivalent initial quality.

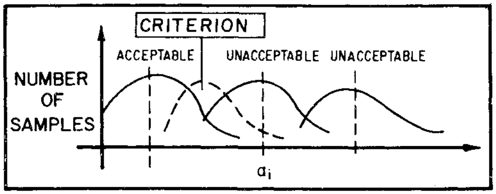


Fig. 13 Acceptability of manufacturing procedures.

mination of the economic lives, required inspection intervals, and maintenance and modification schedules for these aircraft. The Equivalent Initial Quality Method could be used to evaluate the manufacturing quality of other existing aircraft as well as be used in the design of new aircraft. For example, the method could be used to satisfy the safety and durability design requirements of the military specifications MIL-A-83444 and MIL-A-8866B, respectively.

The Equivalent Initial Quality Method could potentially be used to determine the acceptability of a particular manufacturing procedure. For example, equivalent initial quality statistical distributions could be obtained for a number of different manufacturing procedures. Once an acceptable initial quality was established (e.g., acceptable initial quality to meet the economic life requirements, MIL-A-8866B), the acceptability of each manufacturing procedure could then be determined (Fig. 13). Hence, the Equivalent Initial Quality Method could be used to evaluate any new manufacturing method. If a manufacturing method that produces fastener holes of an acceptable quality were used in production, the nondestructive inspection (NDI) requirements could be minimized, resulting in manufacturing cost savings.

While the Equivalent Initial Quality Method appears to have great potential for quantifying the manufacturing quality of fastener holes, it is felt that further research is required to reveal the limitations of the method. For example, studies are necessary to investigate the sensitivity of the method to type of damage, damage size and shape, stress level, material, load transfer, type of fastener system, etc. Such studies are required to determine both the strengths and the limitations of the Equivalent Initial Quality Method.

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