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COMPILATION OF DAMAGE FINDINGS FROM MULTIPLE RECENT TEARDOWN ANALYSIS PROGRAMS

Dr. Gregory A. Shoales, P.E., [1] Dr. Scott A. Fawaz, P.E. [1]
and Molly R. Walters[1]

[1] Center for Aircraft Structural Life Extension
HQ USAFA/DFEM
2354 Fairchild Dr., Ste. 2J2A
USAF Academy, CO 80840-6240
USA

Abstract: Fleet managers depend upon various tools to assure the safe operation of their aircraft. Performing a structural teardown analysis program of one or more aircraft with known service history provides precise damage data resulting from a given usage. These data can then be used to validate NDI methods, update damage models and reduce uncertainty in the damage condition assessment of the remaining fleet.

In the past six years the USAF Academy Center for Aircraft Structural Life Extension (CAStLE) has been involved, at various levels, in multiple teardown analysis programs. CAStLE's level of involvement has ranged from consultant through failure analysis support to planning and executing all elements of an entire program. In each program large regions of selected aircraft were disassembled by precision means, cleaned of all coatings and inspected by a variety of NDI techniques. These NDI indications were then evaluated by failure analysis methods to determine the root cause of failure—the type of damage which resulted in the NDI indication. Failure analysis findings which were a result of aircraft operations were further analyzed to obtain detailed damage characteristics.

This work presents a summary of findings from teardown programs conducted on eight aircraft ranging from small military trainers to large transports. Comparisons are presented for damage types and categories of aircraft. Damage type and scale is also presented categorized by the type of damaged component (skin, stiffener, fitting, etc.). Data are also provided with regard to measurable features within regions of damage initiation.

AIRCRAFT STRUCTURAL TEARDOWN ANALYSIS PROGRAMS

To better understand the teardown program findings presented in this work it is important to understand the motivation and character of the programs which produced these data. Destructive analysis of aircraft structure by what is commonly referred to as a "teardown" has long been considered a requirement in satisfying many of the sustainment issues that arise in aging aircraft [1]. As both military and civilian fleets continue to age, the number of teardown programs continues to increase. In the United States Air Force (USAF) alone there have been more than a dozen such programs in the past 8 years. In fact, the unique methodologies employed in teardown programs prompted the USAF Aging Aircraft Program Office in 2007 to task The USAF Academy Center for Aircraft Structural Life Extension (CAStLE) to prepare a best practices guide for conducting such programs. This handbook was published in 2008 [2] and its development is the subject of an additional publication in this [3] and other conferences [4]. As detailed in the best practices handbook, all teardown programs share specialized tasks which are tailored to the unique program requirements. It is therefore useful here to present the most common teardown program goals/requirements and a summary of teardown program tasks used to satisfy those requirements.

Common Teardown Analysis Program Goals

USAF Military Standard [1] requires execution of a teardown program to assess the damage state of an aircraft after a known period of usage. The same standard also suggests using such a program to assess and potentially revise an aircraft's damage prediction models. The United States Federal Aviation Administration (FAA) and Delta Airlines conducted a teardown of a retired Boeing B727 in order to assess the damage state of high time aircraft fuselage structure [5]. The stated goal of a USAF program conducted 2004 and 2005 on a retired C-5A was to determine damage state and use this data to validate and adjust, if required, the aircraft's structural models [6]. In such programs the damage mechanisms and damage morphology is compared with applicable predictive models. In most cases predictive models only exist for fatigue crack growth and therefore model validation is limited to findings of this type. In any event it is important to characterize the damage mechanism, all relevant dimensions and the location of each damage finding.

A further and somewhat related teardown program goal is to assist in the validation of the non-destructive inspection (NDI) methods employed on operational fleets. NDI techniques are used the world over to ascertain indications of possible damage in operational aircraft while minimizing the impact to readiness of those aircraft. The desire is that NDI indications can be correlated to a damage type and scale in order to support fleet management decisions. Unfortunately, the only possible means to obtain an actual damage finding to perform such correlation is by the destructive means ordinarily referred to as failure analysis. Therefore, conducting typical operational NDI prior to a teardown analysis affords a unique opportunity to correlate indications of damage with the corresponding failure analysis results. As shall be shown in the next section, NDI techniques are further used to support the teardown tasks themselves.

Teardown Analysis Program Tasks

As outlined in the aforementioned teardown program best practices handbook [2], all teardown programs share a common set of tasks. While many seem outwardly similar to standard aircraft maintenance operations, the unique requirements of the teardown program drive similarly unique requirements to each task. These unique requirements are descried in great detail in the teardown handbook and are briefly summarized here.

Define Program Goals and Requirements. The first and foremost task in any teardown program is to define the goal and therefore the requirements of that program. A properly defined teardown program goal subsequently defines the requirements for aircraft type, number of aircraft subjects, subject structure within each aircraft, desired damage types and the characterization data required of each damage type from failure analysis. These requirements serve as the guide for all tasks which follow.

Prepare the Teardown Program Subjects for NDI. Given a defined goal which in some way requires the determination of damage findings in the teardown subject structure, fiscal and schedule constraints dictate tasks which facilitate the efficient focusing of program resources. Since it is not practical to apply destructive failure analysis methods to every element of structure in a given aircraft or aircraft component, the next tasks are directed at focusing failure analysis to the most likely damage sites. There can be an increasing degree of fidelity uncertainty when applying NDI methods to increasingly complex assembled structures. However, when inspections are performed on properly prepared disassembled parts, indications of damage are far more confidently obtained. The following teardown program tasks effectively “stack the deck” in favor of the employed NDI technique giving teardown program analysts the most reliable data.

After the focuses of the teardown program or its “subjects” are identified, the first task to prepare those subjects for NDI is to extract a region of assembled structure which encompasses each subject. By separating these assemblies from the parent structure, the probability of inducing additional damage to the subjects is minimized. The assembled structure is then disassembled by precisions means which further prevents inducing damage, particularly to the fastener holes, as a result of the disassembly process. Disassembly in support of teardown differs somewhat from that of normal maintenance operations. While it might not be desirable to damage a fastener hole during maintenance operations it is also common practice to oversize and refinish the hole during reassembly. Therefore minor damage induced during maintenance disassembly might easily, and rightly so, be considered inconsequential. On the other hand, any damage induced during teardown disassembly is wholly unacceptable as such damage may at worst destroy desired damage data and at the least result in needless analysis of the NDI indication which might result from the induced damage.

After the assembled structure is fully separated into component parts, all coatings must be removed. Cleaning the metallic surfaces of all coatings not only enhances probability of damage indications detection for most NDI techniques, it is required for techniques such as florescent penetrant inspection (FPI). Here too, coating removal in support of teardown differs from that done in support of maintenance. Aircraft structure is commonly stripped of coatings to aid depot maintenance and inspections. At the completion of the depot maintenance program the structure is repainted. A minor etching of a metal part surface prior to painting is not necessarily detrimental and indeed is frequently highly desirable to enhance the quality of the repaint operation. In a teardown, however, any removal of the part surface risks the loss of critical program failure analysis data. A surface etch which removes only a few microns can destroy damage nucleating features, fatigue crack striations and further limit the complete characterization of damage. Like all teardown program tasks the level of sensitivity to surface damage depends upon the damage characterization goals of the teardown program.

Nondestructively Inspect Subject Parts. Depending upon the program requirements each teardown subject may be inspected by a variety of NDI techniques. Ordinarily the first techniques applied are visual in nature. The visual techniques range from a macroscopic un-aided eye inspection to various techniques designed to enhance visual detection such as magnified visual, FPI and magnetic penetrant inspection (MPI). Requirements to find small scale damage usually drives program NDI requirements to employ eddy current and even various ultrasonic techniques. NDI data are derived from either the exposed surface features or electronic signals which may indicate damage or other anomalies in the inspected regions.

Failure Analysis. All NDI indications are potential sites of damage which may be of interest to the aircraft maintainers and fleet managers and more importantly satisfy the program requirements. Accordingly, each site is considered a possible candidate for failure analysis evaluation. The first objective of failure analysis is to determine the root cause of the NDI indication. If the cause is from damage morphology which is of interest to the program goal then the remaining failure analysis objective is to fully characterize the damage. It follows that such characterization includes all parameters required by the program goal.

OVERVIEW OF SUBJECT AIRCRAFT CATAGORIES

In ICAF 2007 a summary of results from the C-130 teardown program was presented by this author. The present work addresses the culmination of all failure analysis findings from eight subject aircraft. In all, the teardown programs conducted on these eight aircraft resulted in 711 failure analysis investigations. These aircraft may be described by three categories and as such shall be referenced to these categories as their data is presented. After the description of each category the goal or focus of each teardown program within that category is also presented. This program focus is presented to help better understand the data presented herein.

Aircraft A: Small trainer/attack class aircraft.
Teardown programs conducted on this category of aircraft evaluated multiple wing sets in complete detail. The subjects of these programs included all structural elements of the wing and wing to fuselage attach structure. Additional programs were conducted which focused on all structural elements which, by fleet management practices, were considered fatigue critical. All aircraft evaluated had reached the end of their service life. CAStLE performed all failure analysis for these programs.

Aircraft B: Medium scale transport aircraft.
Teardown activities conducted on this category of aircraft focused on the center wing structure. This category included a single aircraft type. The center wing structure is considered the most critical structural element of this aircraft type and is the primary element used to determine aircraft life. While not established at program inception, according to operational limits (in equivalent flight hours) set by fleet management during the teardown program's execution, this center wing had exceeded its allowable life. CAStLE had oversight on all failure analysis for this program and performed 75% of all analyses.

Aircraft C: Large scale transport aircraft.
This category also included a single aircraft type. The primary focus of this teardown program was fatigue critical structure throughout the aircraft. While some corrosion damage was characterized, the damage morphology of greatest interest to the program was fatigue cracking. This aircraft was one of the first production aircraft of its type and had been retired by the using command. CAStLE performed 55 failure analyses for this program.

FAILURE ANALYSIS FINDINGS

These data shall be presented as a grouped summary of the failure analysis from all subject programs. Where appropriate, each data set shall also be presented by aircraft, damage, or other relevant category.

Damage Finding Type and Correlation to NDI Indications

As previously stated, the first goal of failure analysis is to determine the cause of a given NDI indication. Whereas failure analysis is a time consuming and relatively costly portion of any teardown program, assignment of an NDI indication to failure analysis is usually preceded by an analysis of the NDI indication data. Accordingly, the NDI indications which are referred to in depth analysis by failure analysis methods are generally those which have the highest confidence of coinciding with actual damage. Depending on the schedule and fiscal resources available, each program discussed in this work employed some system to evaluate and prioritize NDI indications for failure analysis. For example, NDI indications of surface anomalies should be further examined under high magnification before forwarding them to failure analysis. This step helps to differentiate between defects such as surface-breaking cracks which are of keen interest to aircraft managers and the more superficial defects such as light surface scratches which would be of less interest to the same group. Similarly, NDI indication from eddy current techniques are most useful if the strength of the signal is captured with the indication data. A common metric here is, after the eddy current device has been calibrated to a relevant standard, to record the strength of a given indication relative to this standard. This relative measurement is reported as a percentage of full screen height or %FSH. Prioritization systems may then give first priority to indication with higher %FSH. Conversely, eddy current indications less than 20-30% FSH are usually not evaluated further.

It follows from the preceding discussion that a first priority examination of failure analysis data might be to evaluate the findings relative to the NDI indications that led to the failure analysis requirement being levied. Performing such an analysis allows the investigator to assess the criteria used to evaluate and prioritize NDI indications. All failure analysis findings presented here were the result of a NDI indication prioritization scheme whose goal was the evaluation of the most likely sites of relevant damage.

The first comparison between findings and NDI indications is qualitative and shows the overall damage finding types resulting from all 711 failure analysis evaluations. Figure 1 shows the number of findings in each type while Figure 2 shows the same information but broken out by teardown program aircraft category. As is evident in both figures, despite careful consideration of NDI indication data during the prioritization phase, no damage was found at just over 100 indication sites. In all cases of a “no damage” finding, the CAStLE failure analysis practices [7] ensured that there was no damage larger than 0.5 mm at the indication site.

These practices have been further documented in a failure analysis protocol for the C/KC-135 teardown program [8]. The development and validation of all C/KC-135 teardown program protocols have been previously presented elsewhere [9]. Referencing the damage types listed in these figures it is useful to distinguish between findings from operational usage damage and findings which are not related to operational usage. In the later case, strong NDI indications often result from mechanical damage such as deep gouges in the bore of a fastener hole. Even if a mechanical gouge is confirmed through the initial visual examination of failure analysis the investigation must be completed in depth. The reasoning here is that this sort of damage can serve form a highly localized stress concentration and in fact is often analyzed as part of the initial discontinuity state or IDS [10]. A further example of a non-operational usage related finding is a material defect. The four material defects findings shown in Figure 1 are from either material processing pores or interstitial particles which were aligned in the radial hole bore direction—thus mimicking a pattern followed by a crack. The last non-operational damage type applies to a damage finding which, after analysis, was determined to have been caused by loads not related to normal aircraft usage. Most of this damage type was from the two category A aircraft which had sustained damage while in storage and prior to being selected for the teardown analysis program.

While a detailed analysis of each finding is presented in the applicable teardown program report, a brief explanation of those damage types classified as resulting from usage is warranted. The "bore corrosion" type refers to corrosion pitting which was found on the bore of a fastener hole. This type of damage was of keen interest to several programs and as such has been separated from other surface corrosion. The "IGC" type is intergranular corrosion. This is distinguished from the "exfoliation" finding category where the IGC progressed in a laminar fashion such that layers of material exfoliated. In-plane cracks again represented a unique type found throughout the category A aircraft programs and were observed in the parts originating from the bore walls and propagating parallel to the part surface. However, due to their extremely small size, opening was not practical. Therefore, specific damage mechanisms could be positively identified for these cracks. To be conservative, findings which could not be positively associated with any damage mechanism and therefore listed as "unknown" were considered to be from operational usage. Corrosion-fatigue, stress corrosion cracking (SCC), fatigue and overstress follow accepted definitions of those damage types [11].

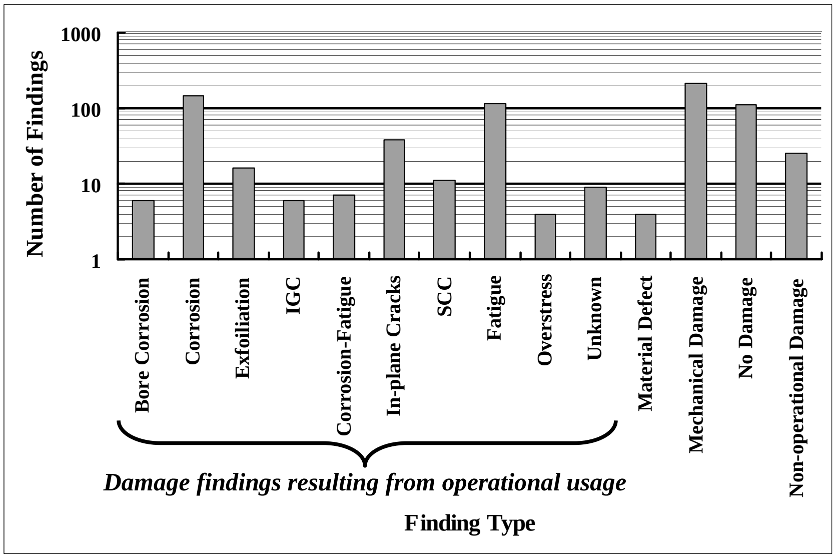

Figure 1: Damage finding types for all teardown analysis programs.

For clarity of presentation the finding types shown in Figure 1 have been group according to their source for Figure 2. All corrosion mechanisms are therefore grouped under the "environmental" damage source. As given in Figure 1, these include bore corrosion, corrosion, exfoliation and IGC. Damage which stems from environmental factors but also has a stress component includes in-plane cracks and SCC. Damage types from stress alone include fatigue and overstress. The non-operational sources include the previously described non-operational damage along with mechanical damage. Failing any definitive source, the unknown damage type is retained separately in Figure 2.

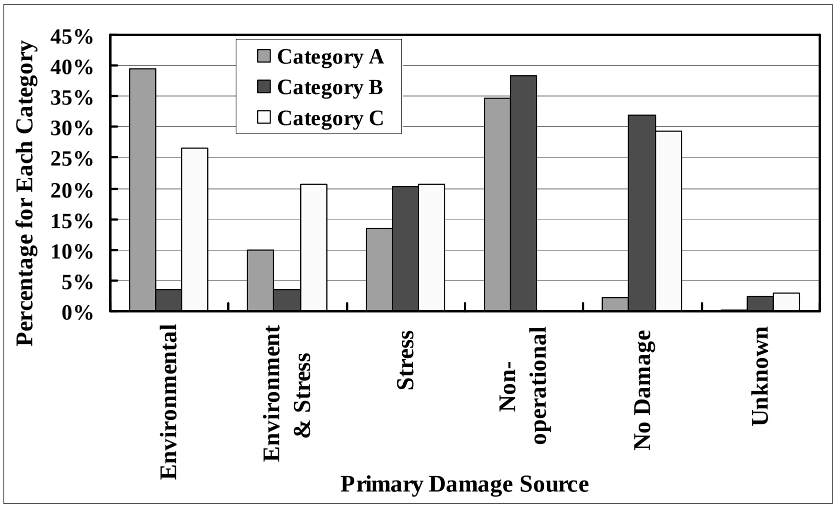

Figure 2: Damage finding types for all teardown programs broken out by aircraft category.

The next comparison between findings and NDI indications is quantitative. In this comparison the data set is limited to fatigue cracks which were found at the site of eddy current indications. Figure 3 shows maximum damage dimension compared to eddy current %FSH. For this comparison the maximum dimension of the confirmed fatigue crack, either in the thickness direction or the radial direction, is taken as the maximum damage dimension. As is evident from this figure, the strongest indication (highest %FSH) does not necessarily directly correlate to largest damage dimension. As may be expected however, the largest number of confirmed cracks occur with stronger (higher %FSH) eddy current signal. Although it is a somewhat weak correlation in the mid %FSH range, this graph shows a trend of confirmed crack size decreasing with decreasing %FSH. The category B aircraft teardown programs used 20% FSH as the prioritization cut-off. Even so, only one crack of less than 0.4 mm was confirmed below 30% FSH.

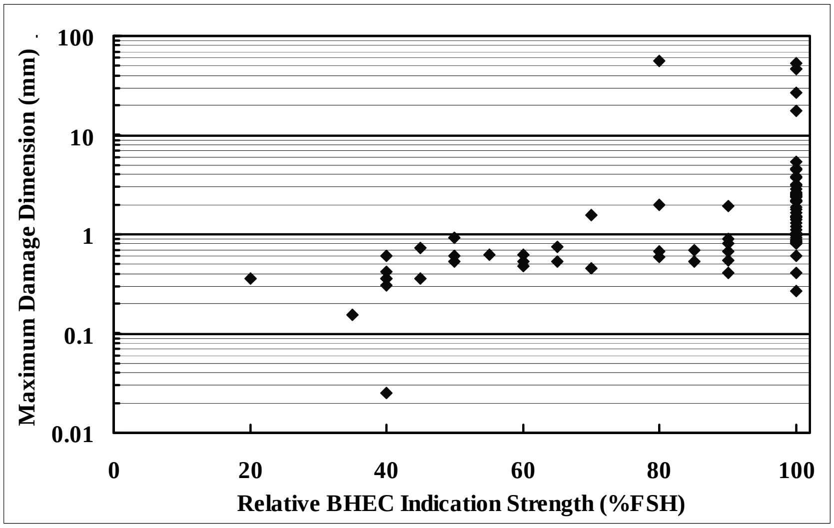

Figure 3: Maximum fatigue crack damage dimensions as a function of eddy current indication in %FSH.

Damage Scale

In the previous comparison the maximum fatigue crack dimension found during failure analyses evaluation was compared with the strength of the eddy current indication which led to that evaluation. It follows that this comparison was only made for those findings which could be correlated to eddy current NDI indication locations for which corresponding %FSH data was available. The data presented in this section is also the maximum damage scale but includes all findings of operational usage crack damage regardless of the available NDI indication data. As in the previous comparisons the maximum dimension determined during the damage evaluation is used in the presentations which follow. Figure 4 presents a histogram of the maximum damage dimension for all damage which was judged to be the result of operational usage, either environmental or stress, from all teardown programs. Figure 5 presents the same data broken out by the same damage source categories used in Figure 2. Lastly, Figure 6 presents these data separated out by aircraft category (A, B or C).

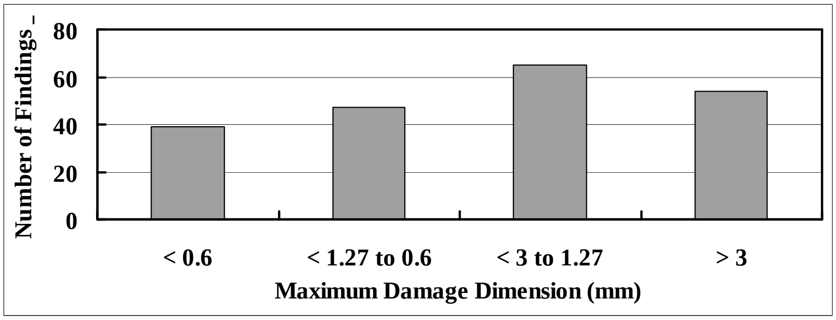

Figure 4: Histogram of the maximum damage dimension for all operational usage crack damage characterized in the subject teardown programs.

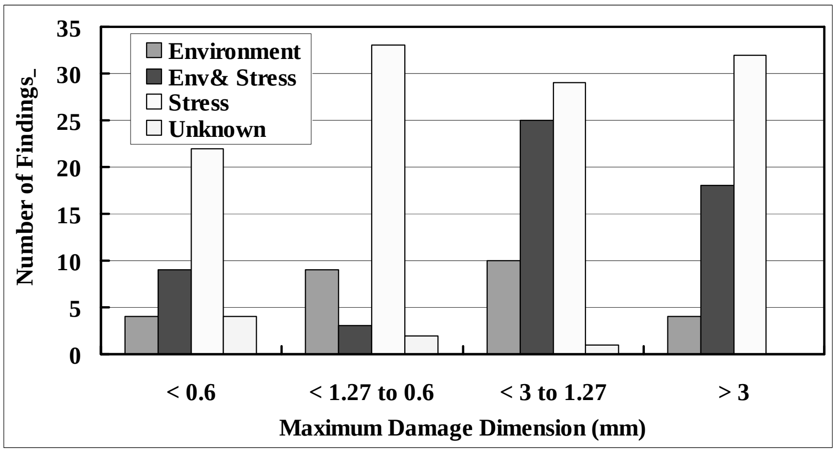

Figure 5: Histogram of maximum damage dimension for all operational usage damage cracks characterized in the subject teardown programs broken out by primary damage source.

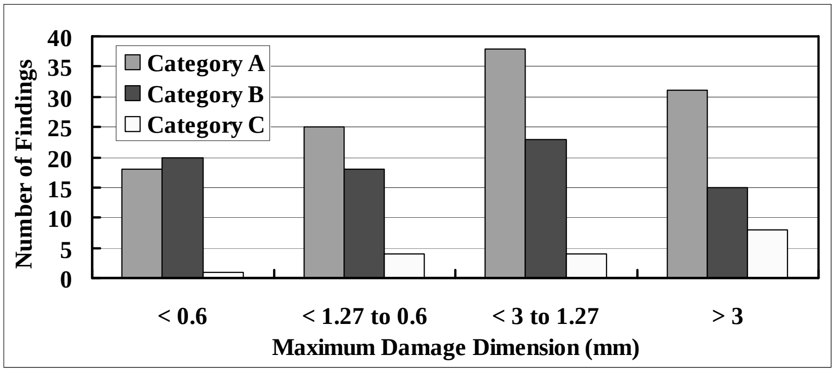

Figure 6: Histogram of maximum damage dimension for all operational usage damage cracks characterized in the subject teardown programs broken out by aircraft category.

The preceding 3 figures highlights how little damage was found in any of eight retired aircraft which exceeds the 1.27 mm flaw size used in most damage tolerance analysis. Of 711 findings, 119 (less than 17%) are operational damage with a dimension of 1.27 mm or greater. Referencing Figure 5, damage due to stress dominates the findings of all aircraft while damage which combines the affect of stress and environment were found at the higher end of the dimension range.

A further presentation of findings focuses on regions of surface corrosion damage. The characteristic from such damage which are normally of greatest interest to fleet managers is the amount of material lost. The surface corrosion damage data from all teardowns are summarized in the scatter diagram of Figure 7. Each data point plotted in this diagram represents a single evaluated site of surface corrosion. The maximum thickness lost expressed in percentage of thickness of the affected part is plotted against the total surface area of the site evaluated.

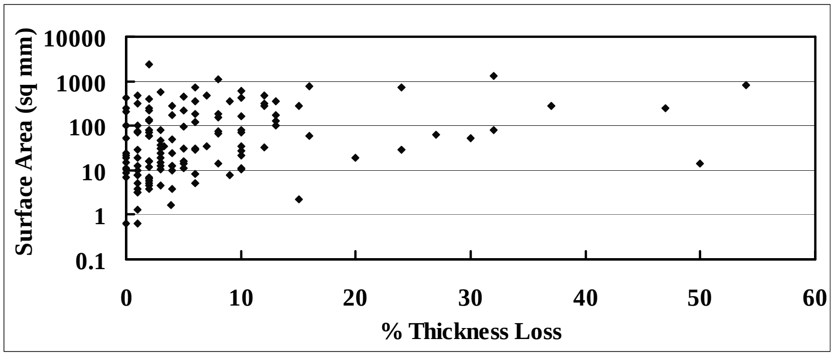

Figure 7: Percentage of maximum part thickness lost due to surface corrosion damage plotted against the total surface area affected at the evaluated site.

Damage Initiation Features

Also of keen interest to the aircraft sustainment engineers and researchers is the feature or features which initiate the damage mechanism. While fractographic analysis of laboratory specimens to identify such characteristics may be somewhat routine, obtaining such data from operationally damaged surfaces is frequently problematic. For example, fatigue cracks which occur in service may be subject to compressive stresses which can smear and otherwise damage the fracture surface. Sufficient damage to the fracture surface can cause a loss of damage morphology data such as the identification and measurement of the initiation feature. The fracture surface of an open crack may also be damaged by corrosion—resulting in deposition of corrosion product and loss of the substrate material. While proven methods exist to remove corrosion product from the facture surface without damaging that surface [8], substrate material lost due to in-service corrosion causes a corresponding loss of all data contained on that portion of the fracture surface. Even so, every effort was made to measure the region of damage initiation and identify the feature(s) within that zone. The damage initiation zone is defined as the region between the smallest resolvable fatigue striation and the specimen edges. Observed corrosion pits or other features within this zone were recorded as such. The authors recognize that within this damage initiation zone, as defined, there could be very slow fatigue crack growth but no visible fatigue striations. Table I presents a summary of all identified damage initiation features from all three teardown aircraft categories. Measured dimension distribution parameters for each damage initiation zone and the percentage of initiation zones located on part joining or faying surface are also given in this table.

Table I: Summary of all identifiable damage initiation features, initiation zone dimension distribution parameters and faying surface location percentage of these zones.

Initiation Feature	%	Dimensions (mm)		
		Minimum	Maximum	Average
Corrosion Pit	80%	0.022	0.624	0.135
Mechanical Damage	20%	0.040	0.326	0.156
Percentage of Initiation Sites on Faying Surface				31%

The study of damage initiating feature is also relevant to structural teardowns in that it in part drives the requirement to evaluate sites where nothing can be identified but mechanical damage. As discussed previously, mechanical damage such as drill marks, gouges and deep scratches potentially represent stress concentration features. A long held view is that such stress risers will nucleate fatigue cracking and other continuing damage mechanisms. Mechanical damage indications are therefore frequently prioritized for failure analysis to ascertain whether further damage exists. While Table 1 indicates that 20% (a total of 15) of all identifiable initiations sites were from mechanical damage it is worth recollecting that 216 of findings of 711 total (or 30%) evaluations were mechanical damage which did not nucleate any continuing damage. Figure 8 illustrates the distribution of initiation feature size along with the number of occurrences of each. As shown here, mechanical damage features were found only within the lower size range of the corrosion pits feature.

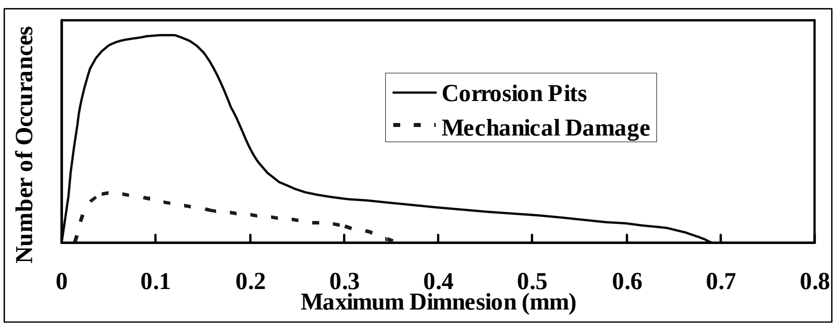

Figure 8: Distributions of measured initiation features by feature type.

<u>Damage Location and Proximity to Other Damage</u>

The last presentation of teardown findings to be made concerns the location of damage. The first area of interest is the component type where relevant damage was found. The next area of concern is the accumulation of damage in close proximity to other damage.

Damaged component. For the purposes of this work the structural components are divided into five categories. Those are skin, skin stiffeners, rib cap, spar cap and fitting. Skins webs are simply the planar parts which generally cover the outer surfaces of an aircraft but also included webs. Stiffeners are linear elements which are mechanically fastened to skins and serve to increase their stiffness. Caps and fittings on the other hand are typically components of three dimensions which serve the function of transferring load, often times between multiple elements. A summary of damage types broken out by component category is given in Table II. Fatigue cracking seems to be slightly more prevalent in skin and spar caps but is otherwise evenly distributed. There is a predominance of corrosion findings in spar caps. This result was predominately from extensive spar corrosion found in the category A aircraft. The in-plane cracks were exclusive to the category A aircraft and were thought to be in part due to a somewhat unique material specification in that structure.

Table II: Number of finding of a particular damage type broken out by structural component category.

Component Type	Corrosion	Corrosion-Fatigue	SCC	In-Plane Cracks	Fatigue	Overstress	Unknown
Skin & Webs	3	1	1	0	1	0	1
Skin Stiffenner	0	1	0	0	1	0	3
Rib Cap	2	0	0	0	1	1	0
Spar Cap	2	0	1	1	1	2	1
Fitting	1	1	1	1	1	1	1

Proximity between damage findings. When assessing structural risk, the proximity of damage to other damage, regardless of the size, frequently has equal emphasis as the damage morphology of individual findings. This emphasis was a result of concerns raised by fleet managers about widespread fatigue damage (WFD). WFD is characterized by the simultaneous presence of cracks at multiple structural details that are of sufficient size and density whereby the structure will no longer meet its damage tolerance requirements; for example, not maintaining required residual strength after partial structural failure [12]. Indications which, after evaluation reveal multiple fatigue cracks along a common wing station in a single wing panel are an example of multi-site damage (MSD). Similarly, multiple fatigue crack findings in common holes of joined structural elements are an example of multi-element damage (MED). WFD, MSD and MED are currently prime structural concerns in many aircraft fleets.

It is for this reason that post teardown analysis must consider the proximity of damage finding locations. Given the wide variation of aircraft category scale and structural configurations this comparison is only useful between teardown findings from the same aircraft type. The lower center wing of teardown aircraft category B at the usage level of the subject aircraft was thought to be prone to widespread fatigue damage. Figure 9 illustrates the location of all damage findings after a complete inspection of that structure. Left and right side damage are distinguished by symbols. While the numeric scale has been omitted for release purposes, the vertical and horizontal scales are shown at the same relative size to one another. The damage grouping at the aft inboard location corresponds to the wing life tracking point used by most operators of this aircraft. The grouping along the entire outboard wing station represents the outboard attachment which is currently undergoing a redesign due to damage propensity in this location.

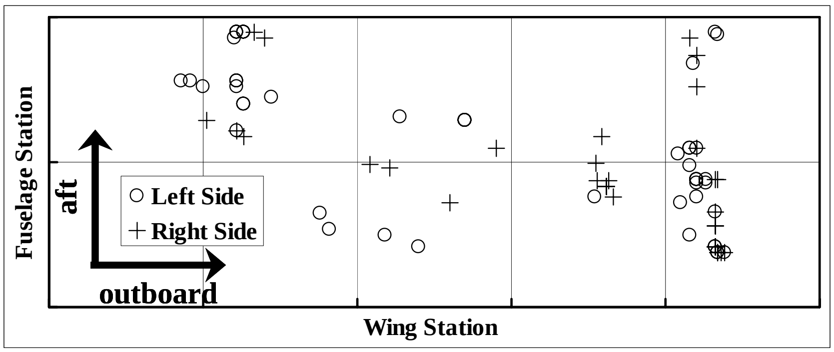

Figure 9: Wing station (WS) and fuselage station (FS) location of all operational usage damage findings in the center wing of the category B aircraft teardown program.

The data in Figure 9 represents the findings from a single teardown aircraft. As with any attempt to represent a population (such as an aircraft fleet) with a sample (such as teardown aircraft) it is far more meaningful to combine the findings from multiple aircraft subjects. The wing damage findings from the six category A teardown aircraft are combined in Figure 10. Like Figure 9 this figure shows the locations of all operational usage damage findings but, due to the larger sample size, with arguably far more statistical significance. Here again, left and right side damage is distinguished by symbols and the vertical and horizontal scales are shown at the same relative size to one another. Clearly evident in this figure is the predominance of damage on both spars and the aft spar in particular. A concentration of damage at an approximately mid-span rib is also evident.

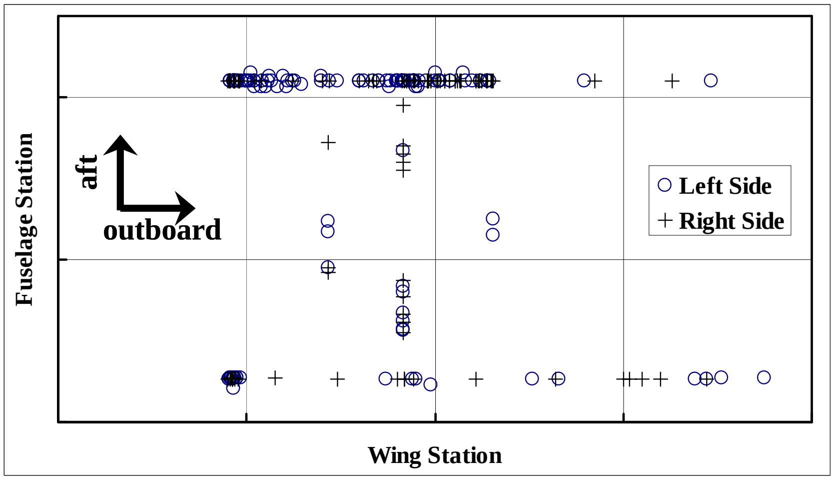

Figure 10: Wing station (WS) and fuselage station (FS) location of all operational usage damage findings in the wing of all category A aircraft teardown programs.

Both of the preceding examples demonstrate how the morphology of individual damage findings must be considered in concert with the proximity to other damage.

DISCUSSION AND CONCLUSIONS

The findings presented here represent the wide variety of damage morphologies that may be expected when conducting a teardown analysis program of aged aircraft structure. Given the specialized inspection of structure required by the goals of most teardown programs, the scale of damage findings should also be expected to be far smaller than can be detected by in service inspections. Even so, without careful application of NDI procedures teardown program resources may be unnecessarily taxed. Recalling Figure 2, the number of NDI indication failure analysis evaluations which resulted a “no damage” finding varied greatly by teardown aircraft category. The most obvious difference is the comparatively small percentage of these findings for the category A aircraft programs. This result is not entirely by coincidence. In fact, the large number of these findings in the earlier occurring category B and C aircraft teardown programs served as a lesson learned for future programs. NDI process improvements were published in 2008 by Air Force Research Laboratory [13]. A draft version of these new best practices were applied to the category A teardown programs. The benefit of reducing the number of needless evaluations and thus controlling program cost and schedule is made clear by this comparison. A further NDI observation comes from Figure 3. The maximum damage dimensions at each value of %FSH are directly proportional to %FSH. This result supports the practice defining some lower bound to these indications when prioritizing fro failure analysis. Caution is advised however, to carefully consider the program's damage fidelity requirements before defining an overly aggressive cut-off value just to save cost—lest valuable data may never be evaluated.

As already stated, the comparisons of damage scale presented in Figures 4-6 show how few findings from any of the eight programs even exceed the assumed damage tolerant flaw size (1.27 mm quarter circular corner crack at a hole). Also observable here is that stress is the primary source of damage. It may be thought that this conclusion is skewed by the fatigue damage emphasis on the category B and C aircraft programs. Failure analysis of the six category A aircraft however, accounted for 56% of all evaluations performed. If the aforementioned "no damage" findings are removed this number increases to 66%. Furthermore, despite the fatigue emphasis on the category C aircraft teardown, corrosion related damage findings accounted for 2/3 of all CAStLE evaluations.

The corrosion damage depiction of Figure 7 shows what appears to be a predominantly mild attack to the evaluated structure. This is based upon the fact that most repair manuals permit surface corrosion grind-out in excess of the depth shown. The permissible loss of material is indicative of design margins in the part sizing. If these sites were left unchecked the pitting corrosion could possibly be followed by more aggressive corrosion mechanisms such as exfoliation. Exfoliation could easily result in unacceptable levels of material loss. Such likelihood may not seem relevant in aircraft that had reached their service limit. The danger to safety comes from uninspectable corrosion sites in the presence of a more aggressive environment or an earlier onset to corrosion damage. All corrosion sites, regardless of size must be fully addressed by the fleet's corrosion prevention and control program. The most critical sites should be considered for additional inspections in the remaining fleet.

The next characteristics presented in this work were the sites of damage initiation and the identifiable features within them. The majority of initiation features observed as the source of damage are corrosion pits. Brooks Peeler, Honeycutt, and Prost-Domasky made this observation when forming their holistic life prediction models [14]. In their analysis they state that damage begins with corrosive pitting attacks at material discontinuities. This was the experience of some of the analysis performed in the subject teardowns. Many more of the pits formed when protective coatings broke down and permitted the contact of dissimilar metals. In one example the analysis revealed that a steel fastener had lost a portion of its cadmium coating, either in service or during an aggressive installation process, allowing contact with the aluminum part. In some installations these fasteners are further protected by installing them with sealant, commonly referred to as a "wet" installation. Analysis of these installations where pitting corrosion formed anyway revealed that the sealant had become brittle with age and subsequent cracking permitted the pitting corrosion to take place. A further example is where the failure analysis showed evidence that a part edge was machined, most likely to accommodate installation, thus eliminating the protective aluminum clad layer (Alclad). Whatever the source, a discontinuity system was established and corrosion pits formed on the part surface. After pits form the next phase in their proposed holistic life modeling is that cyclic loading at the corrosion pits results in fatigue crack nucleation and growth. This observation is also consistent with the findings presented in this work. Of all corrosion pits identified as the source of damage, 78% led to continuing damage by fatigue mechanisms. Furthermore, of the mechanical damage features identified in initiation sites, 93% led to fatigue damage mechanisms. In the previously cited work of Brooks and company [10], the relative scale of various initial discontinuity states are compared to one another. Figure 11 is reprinted from the presentation of that work at the 1999 ASIP Conference. Manufacturing defects in this figure equate to what is called the mechanical damage in Figure 8. The distributions of mechanical and corrosion IDS compare favorably between both figures.

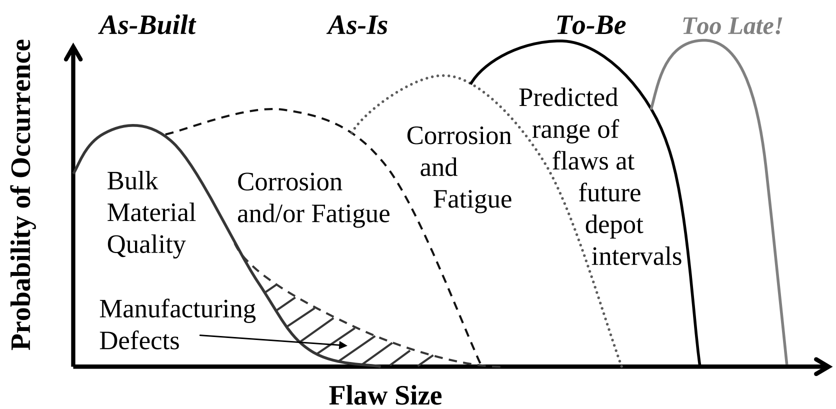

Figure 11: Comparison of various IDS dimensions from C. Brooks 1999 ASIP Conference presentation titled "Correlation of Life Prediction Methods with Corrosion-Related Tests"

The last set of findings presented were that of damage finding location. These data are most useful to fleet managers when considered in whole. For example, a majority of corrosion findings in one component type versus another may illuminate a problem in the protective strategies. Any grouping of findings would of course be compared with predictive models to ensure damage is being modeled at those locations. Recalling the previous discussion of WFD, MSD and MED, a complete analysis of teardown program findings requires equal consideration of damage type, damage size, affected component(s), aircraft coordinates and of course the damage density. Significant findings in unexpected locations require that predictive models be enhanced to include these new areas.

One goal suggested in the introduction of this work is the assessment of fielded inspection programs. To answer this requirement the precise tracking of each finding's location back to its original location is essential. It is only by doing so that indications from the fielded inspection may be analyzed with respect to the damage findings.

The data and comparisons presented here, rather than addressing the goal of any specific program, were aimed at presenting a wide variety of possible analysis that may be performed on teardown findings. It is offered to show how findings from diverse aircraft types with differing program goals can both be different and similar. For any one teardown analysis program it is of course essential that the analysis performed on the findings satisfy the stated program goals. It therefore follows that clear program goal(s) identification must always be the first step to program planning. This step is then to be followed by the definition of comprehensive data requirements to answer that goal. Having done so, the best way to ensure program validity is to use the defined program data requirements to guide each and every teardown program task.

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