Design of Repair of Battle-Damaged Fixed-Wing Aircraft

Major Trent A. Greenwell
Department of Engineering Mechanics
2354 Fairchild Drive, Suite 6K-139
USAF Academy, Colorado, USA 80840

trent.greenwell@usafa.edu

ABSTRACT

Damaged aircraft, be it battle damage or by some other cause, in a deployed theater of operations fall into one of several distinct categories of repair. Within these categories, there are a number of options to include temporary or partial-capability repairs, the unique realm of aircraft battle damage repair. Specialty repair shops, such as metals fabrication or hydraulics, can assist in implementing a wide-range of permanent, full-capability repairs by creating replacement parts in accordance with manufacturing drawings. Generally, aircraft battle damage repairs neglect durability design criteria such as corrosion and fatigue resistance in favor of repair expediency. Special repair considerations are made with respect to fighter/attack aircraft due to their unique mission and smaller design tolerances.

1.0 INTRODUCTION

Design of Aircraft Battle Damage Repair (ABDR) is a complex matter. Options for repair design are tied to the architecture of the overall aircraft maintenance program. To understand the US Air Force (USAF) approach to ABDR requires a basic understanding of the USAF aircraft maintenance concept. Regardless of maintenance concept, there are generally a limited number of options for any aircraft repair. Options for temporary and/or partial-capability repairs are the realm of ABDR. USAF ABDR technical guidance follows an established set of damage classifications, structural categories, and system serviceability criteria. Damage tolerance plays a role in ABDR due to its role in USAF aircraft design. All of the aforementioned considerations lead to a general approach to the design of aircraft battle damage repair. Due to the high performance and highly-engineered nature of fighter/attack aircraft, some specific considerations must be made with regard to ABDR of these types of aircraft.

2.0 U.S. AIR FORCE AIRCRAFT MAINTENANCE CONCEPT

The USAF currently operates a two-level aircraft maintenance concept. The first and lowest level of maintenance is “organizational maintenance”, also termed “organic maintenance”, which consists of typical repairs and standard periodic maintenance, such as changing oil and rotating tires. Organizational maintenance personnel are part of the organization that operates the aircraft. This organization also employs the aircrew who operate the aircraft and is charged with meeting operational mission needs as dictated by higher operational authority. The personnel assigned to organizational maintenance are predominantly enlisted military personnel remain collocated with the aircraft, at home station and in deployed theatres of operation. Organizational maintenance sometimes employs highly-skilled civilian technicians to assist with more complex organizational-level repairs. These civilian personnel typically do not deploy with the aircraft. Organizational maintenance does not employ engineers.

The other, higher level of maintenance is “depot maintenance” which consists of the full-spectrum of disassembly, maintenance, repair, fabrication, and assembly required to restore the aircraft to a ‘like-new’ condition. The primary role of depot maintenance is to periodically inspect the entire aircraft for corrosion, fatigue, and other insidious damage and restore the original strength of the aircraft. Depots also

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14. ABSTRACT
Damaged aircraft, be it battle damage or by some other cause, in a deployed theater of operations fall into one of several distinct categories of repair. Within these categories, there are a number of options to include temporary or partial-capability repairs, the unique realm of aircraft battle damage repair. Specialty repair shops, such as metals fabrication or hydraulics, can assist in implementing a wide-range of permanent, full-capability repairs by creating replacement parts in accordance with manufacturing drawings. Generally, aircraft battle damage repairs neglect durability design criteria such as corrosion and fatigue resistance in favor of repair expediency. Special repair considerations are made with respect to fighter/attack aircraft due to their unique mission and smaller design tolerances

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conduct repair and restoration of extensively damaged aircraft on a case-by-case basis. Depot maintenance personnel are completely separate from organizational maintenance and may be managed by the military or a civilian contractor. Depots do not permanently possess any aircraft and only operate aircraft in their custody to the confirm proper functionality. Depot maintenance personnel are predominantly highly-skilled civilian technicians, engineers, and logisticians. USAF ABDR teams come from Combat Logistics Support Squadrons (CLSSs) which are military units attached to repair depots. USAF ABDR engineers are military engineers assigned to depots and usually come from within the sustainment program offices that manage the specific weapon systems the ABDR engineers are designated to support. Aside from these specially-designated ABDR personnel, depot personnel rarely deploy to combat zones and usually only do so on a case-by-case basis for specific repairs.

Prior to adopting the two-level maintenance concept, the USAF operated under a three-level maintenance concept similar to the current US Army aircraft maintenance concept. Three-level maintenance adds an "intermediate maintenance" level that includes some of the roles organizational and depot maintenance have assumed in the two-level maintenance concept. To offset the loss of this third level of maintenance, the USAF employs "backshops" on each base which can perform specialty maintenance tasks common to every aircraft model. These backshop specialties include machinists, sheet metal technicians, hydraulics technicians, and electricians, among other specialties.

With regard to repair authority, it is important to understand the distinctions of aircraft 'ownership' in the USAF. Organizational maintenance 'possesses' the aircraft, but they do not 'own' the aircraft; the parent Major Command owns the aircraft. Organizational maintenance is similar to a tenant in a rental apartment; they can vacuum the floors and clean the windows, but they cannot install an air conditioner without permission of the property owner. The USAF has a central "Materiel Command" which manages the aircraft configuration and supply chain. The Materiel Command also determines airworthiness of any changes to the aircraft configuration. In essence, the Materiel Command 'owns' the aircraft configuration. Back to the rental property analogy, the Materiel Command is similar to the property manager who is charged with performing major repairs, stocking common supplies, and ensuring commonality of features among the many units in the rental property. Organizational maintenance is not allowed to deviate from the approved configuration of the aircraft; only Materiel Command engineers are authorized to deviate from the approved configuration and certify airworthiness.

3.0 REPAIR OPTIONS

Repair options for damaged aircraft fall into a few specific categories, depending on the extent of the damage. It is important to note that ABDR teams and Depot Field Teams are similar with regard to the complexity of repairs they can affect. Depot Field Teams cannot implement temporary, partial-capability repairs without the oversight and approval of an engineer; ABDR teams can implement such repairs using published technical guidance without an overseeing engineer. Depot Field Teams are usually comprised of highly-skilled civilian technicians capable of more complex repairs than ABDR teams, but they do not typically deploy to combat zones as ABDR teams do. Typical aircraft repair options are as follows:

3.1 Fully-Reparable On-Site with Organic Maintenance

This most-common repair option exists when organizational maintenance can affect a repair using published repair manuals, readily available parts, and on-hand tools, equipment, and facilities. Access to engineering support from remote sources is included in this repair option. The defining feature of this option is that a full and permanent repair can be made by organic maintenance personnel without special training, support, or facilities.

3.2 Fully-Reparable On-Site with ABDR or Depot Field Team

This repair option involves bringing outside personnel, tools, equipment, and materials to the damaged aircraft where on-hand facilities are adequate to affect the repair. This repair option is exercised when the repair complexity exceeds the capability of organizational maintenance. The defining feature of this option is that a full and permanent or semi-permanent repair can be affected on-site.

3.3 Partially-Reparable On-Site with ABDR or Depot Field Team

This option of repair is the primary reason to have an established ABDR program. Using ABDR principles and techniques, ABDR teams can affect expedient, temporary aircraft repairs to rapidly restore adequate strength for partial mission capability. In situations outside of combat zones, this can also be done by civilian Depot Field Teams under the direction of an overseeing engineer. An ABDR team can affect this repair option using published ABDR manuals with or without an engineer present. Depot Field Teams can implement partial-repairs for the sole purpose of ferry flights back to a depot repair facility. ABDR teams can implement partial repairs for ferry flights or to restore limited mission capability to meet mission needs. The defining feature of this type of repair is that it can be conducted on-site in order to fly the next sortie for a very specific purpose, such as only dropping bombs in straight and level flight or only refuelling other aircraft at low altitudes or only flying straight and level to another repair facility.

3.4 Beyond Local Repair, but Salvageable by ABDR or Depot Field Teams

An aircraft is beyond local repair if the equipment and facilities necessary to conduct a repair are not on-hand nor feasibly transportable to the aircraft's location. This is typical of aircraft that 'ditch' away from a base. Aircraft which have extensive damage requiring complex repair located at a base may also fall into this category. The important feature of this option is that the aircraft is potentially salvageable, in which case the economical option may involve transporting the aircraft to a capable repair facility, with or without some level of disassembly. For example, outer wings may be removed from a small aircraft in a field allowing the remainder of the fuselage to be hoisted onto a flatbed truck with a mobile crane and transported back to base for shipment to a depot. Alternatively, the intact aircraft may be airlifted by a heavy-lift helicopter back to base for repair or disassembly and shipment. This repair option assumes the aircraft is within economical repair limits when including the cost of recovery. ABDR or Depot Field teams are both capable of disassembling and packaging an aircraft for shipment.

3.5 Beyond Economical Repair

The final option is for cases when aircraft repair is too complex to be affected within the value of the aircraft. This situation can be caused either by extensive damage requiring multiple economical repairs adding up to a cost beyond economical repair or by a single damage to a critical component which is too costly to repair or replace. Main longerons or center wings are examples of the latter; the time and expense required to disassemble an aircraft to the level where a repair can be made to these parts often exceeds the value of the aircraft itself. In cases where an aircraft is beyond economical repair, it should be stripped of all valuable parts to the maximum extent possible given the circumstances and scrapped or, if located in a hostile area, destroyed.

4.0 DAMAGE CLASSIFICATIONS

USAF ABDR guidance divides each incident of aircraft damage into one of four classes, detailed as follows:

4.1 Class A: Degraded Capability

Class A damage describes the maximum damage that can be left unrepaired and still allow a partial-capability, also termed “restricted”, sortie. Depending on mission needs, Class A damages can be repaired if time permits or left unrepaired if the threat condition requires an immediate restricted sortie. Sortie restrictions are weapon system specific and are outlined in weapon system specific ABDR assessment manuals.

4.2 Class B: Reparable Damage

Class B damage describes the maximum damage that can be repaired using ABDR techniques and allow for an unrestricted sortie. This classification describes the limits of an NCO assessor’s repair capability.

4.3 Class C: Acceptable Damage

Class C damage describes the maximum damage that can be left unrepaired and allow for an unrestricted sortie. This is the best case scenario for ABDR as it allows the aircraft to return to combat without delay for repair actions.

4.4 Class E: Engineering Disposition Required

Class E damage requires an engineer’s assessment of reparability. Class E damages are typically damages to critical primary structure. Once the engineer is involved, they can design a repair for Class E damage from scratch or modify a common repair from the appropriate manual, if the damage is reparable.

5.0 STRUCTURAL CATEGORIES

USAF ABDR guidance divides aircraft structures into five different categories to help assessors and engineers determine repair requirements and damage class. These structural categories are defined as follows:

5.1 Category I: Primary Structure

Category I, or “Cat I” for short, structure encompasses structure which carries significant flight or weight loads and without which the aircraft could not maintain structural integrity. It basically describes the critical foundation of the aircraft’s load carrying capability. The loss of any Cat I structure could lead to failure of other Cat I structure due to the transfer of critical loading. Cat I structure is essential and should be given primary consideration in repair design. Main longerons, bulkheads, and all wingbox components are primary structures.

5.2 Category II: Secondary Structure

Cat II structure encompasses structure which carries significant flight or weight loads but without which the aircraft could maintain structural integrity. Cat II structure usually transfers loads between primary structures, so some level of strength and stiffness should be restored to damaged Cat II structures. Cat II structure is less-essential and can sustain greater damage without requiring repair than Cat I structure. Non-stress skins, intermediate ribs, stringers/stiffeners, and frames/formers are secondary structures.

5.3 Category III: Tertiary Structure

Cat III structures are superfluous structures that neither carry load nor serve any aerodynamic purpose. Cat III structures are non-essential. Tail cones, landing gear pods, and pylons are tertiary structures.

5.4 Category IV: Aerodynamic Components

Cat IV structures serve the sole purpose of maintaining aerodynamic qualities. Cat IV structures are essential to aircraft performance and controllability, therefore they must be repaired if damaged. These repairs must focus on restoring aerodynamic qualities or supporting pressurization rather than restoring strength or stiffness. Radomes and nacelles are aerodynamic components.

5.5 Category V: Not-Reparable Using ABDR

Cat V structure encompasses structure which cannot be repaired using procedures found in ABDR repair manuals. Cat V structures are usually complex forgings, machined parts, or special extrusions which cannot be repaired or fabricated in the field. Cat V structures are generally only reparable by replacement, though minor damage which can be blended out may be acceptable.

6.0 SYSTEM SERVICEABILITY CRITERIA

System serviceability criteria are applied to aircraft systems other than structures and basic flight controls and landing gear. These include avionics, weapons, navigation, and other such systems. The system serviceability criteria are usually governed by the weapon system's mission essential systems list which is a list developed by the operational users to describe those capabilities which are critical to mission needs. This list is often developed with full combat capability in mind, however, so confirmation of critical systems should be made with operations in case of a partial-repair for limited capability, such as a ferry flight. Specific serviceability criteria are "Full Capability for essential systems, such as altimeters and basic radios; "Degraded Performance" for desirable systems, such as radars or countermeasures, and; "Not Required" for non-essential systems, such as anti-collision systems or coffee makers.

7.0 ROLE OF DAMAGE TOLERANT DESIGN IN ABDR

Damage tolerant design (DTD) is a method of designing aircraft that considers allowable damage sizes in addition to strength and buckling criteria. Additional strength is added to the part in the form of extra material or changes to geometry to assure that any flaw, usually a fatigue crack, reaches a detectable size long before it reaches a critical size where it can cause rapid and spontaneous catastrophic failure of the part. DTD is based on the science of fracture mechanics and replaced the "Safe Life" method of design previously used on USAF aircraft up until the late 1960s. Because DTD calculates maximum flaw sizes as well as flaw growth rates for the basic design of Cat I and Cat II structures, these values can be used to develop ABDR damage limits for ABDR manuals. Because the engineering analyses to determine damage limits has already been conducted in the development of these manuals, they can be used by non-engineering personnel to assess damage and affect repairs.

8.0 GENERAL ABDR DESIGN APPROACH

With a basic understanding of the factors surrounding design of repair now discussed, a general ABDR design approach can be addressed. The general approach to USAF ABDR is strength analysis versus stress analysis. In stress analysis, the maximum loads on an aircraft are evaluated and a part is designed to support that load with a certain safety factor. This process allows for the most weight-efficient repairs, but requires thorough and time-consuming analyses. Strength analysis evaluates the structures present on the aircraft in terms of the strengths provided by their material and geometry and uses a simple reverse-engineering approach to replace the strength of the original structure. This approach allows technicians to perform simple reverse-engineered repairs by implementing identical component materials and sizes, or slightly larger, to bridge damages.

Some additional features of an ABDR approach which are unique to ABDR are founded on the temporary nature of the repairs and consideration of aerodynamic impacts and moving parts. Because ABDR is generally temporary, time-consuming steps to mitigate corrosion and fatigue are ignored for sake of expediency. Because ABDR generally implements external repair, aerodynamic impacts must be balanced with mission needs to assure adequate time is spent on the repair to assure the aircraft remains airworthy. Aircraft controllability requires a delicate balance of external repair bulk and weight. Bulky, non-flush repairs on forward fuselages and wing surfaces can cause dangerous changes in airflow which can affect trim characteristics, control response, and engine performance. Heavy repairs on wings and horizontal or vertical stabilators can dramatically affect the aeroelastic response of the airfoil leading to dangerous conditions of flutter, divergence, or control reversal. Heavy repairs on control surfaces or other moving parts must be avoided to prevent overloading control actuators causing degraded and/or ineffective controllability. Bulky repairs on moving parts can cause obstruction of designed movement.

To summarize, the general approach to ABDR is to restore lost strength based on the dimensions and material of the original structure. When implementing repairs, corrosion and fatigue precautions can be neglected. When implementing repairs on aerodynamic surfaces, special care should be taken to minimize the repair bulk to avoid disruption of airflow. When implementing repairs on airfoils, special care should be taken to minimize weight to avoid introduction of flutter, divergence, and/or control reversal. When implementing repairs on moving parts such as landing gear doors or control surfaces, special care should be taken to minimize weight and bulk to avoid overloading control actuators and prevent interference of moving parts.

9.0 FIGHTER/ATTACK SPECIFIC CONCERNS

Fighter/attack aircraft have many unique considerations over other aircraft. Due to their unique design to maximize performance, fighter/attack aircraft have less tolerance for damage than other aircraft. The high performance nature of the fighter/attack mission means they have a lower tolerance for damage before mission degradation occurs. The complex structures of fighter/attack aircraft are more difficult to repair due to highly-engineered and often non-prismatic components designed to minimize weight as well as the extensive use of composite materials. In general, fighter/attack aircraft require replacement of parts instead of repair. This is contrary to larger, heavy aircraft which are generally comprised of more traditional and simpler structural components. Heavy aircraft components are also often too large to simply replace. These factors make repair of heavy aircraft components more economical than replacement. The smaller size of fighter/attack components also means there is relatively less room to fit a repair. External repairs to fighter aircraft add complexity due to consideration of impacts to stealth characteristics. Finally, compound-contoured bubble canopies are difficult to repair. Repairs to bubble canopies also detriment aircrew visibility.

10.0 CONCLUSIONS

A cohesive ABDR program requires a clear foundational philosophy of repair. Within the USAF maintenance concept, the foundation for ABDR allows for both rapid, temporary repairs and permanent repairs, depending on mission needs. The USAF ABDR program also employs both engineers and experienced maintenance troops in the role of designing repairs. Repair design is governed by a few different repair options. USAF ABDR guidance outlines a group of damage, structure, and system serviceability categories which can be used in a general approach to ABDR design. Fighter/attack aircraft have a number of unique considerations when approaching the design of battle damage repair.

11.0 REFERENCES

This paper draws extensively throughout from USAF ABDR technical manuals, particularly TO 1-1H-39, as well as my own personal experience. As such, there are no specific references annotated in the body of text for the reference below.

[1] United States Air Force. Technical Order 1-1H-39. *Aircraft Battle Damage Repair.*15 Sep 2002