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Fixed-wing Aircraft Combat Survivability Analysis for Operation Enduring Freedom and Operation Iraqi Freedom

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FIXED-WING AIRCRAFT COMBAT SURVIVABILITY ANALYSIS FOR OPERATION ENDURING FREEDOM AND OPERATION IRAQI FREEDOM

THESIS

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Abstract

The primary tenet of the aircraft survivability discipline is threat definition. In order to deliver relevant capabilities and protection to the warfighter it is imperative; therefore, to provide timely, accurate, and actionable threat data to the survivability community. Application of this threat data is equally important to both new acquisition programs and long-term sustainment programs. In an attempt to identify the evolution of aircraft threats in today's combat environment, an analysis of fixed-wing aircraft battle damage was conducted. This analysis reports aircraft battle damage incidents from OPERATIONS ENDURING FREEDOM (OEF) and IRAQI FREEDOM (OIF). Additionally, reported battle damage incidents were then validated by cross-referencing aircraft maintenance records from this period to eliminate non-hostile fire data points. Thus, only combat hostile action incidents are considered. This revolutionary approach uncovered discontinuities, which were further explored to identify their root cause. As a result, significant Air Force policy changes in the realm of battle damage reporting procedures were suggested. The recommended changes, contained herein, are intended to increase the accuracy of the data presented to decision makers and the efficacy of survivability programs. In the end, lives will be saved because the acquisition community at large will have valuable threat data in which they can be confident.

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List of Abbreviations

AAA	Anti-aircraft Artillery
ABDR	Aircraft Battle Damage Repair
AIAA	American Institute of Aeronautics and Astronautics
ASDAT	Aircraft Shoot Down Assessment Team (USA)
CDIRS	Combat Damage Incident Reporting System
DoD	Department of Defense
DOT&E	Director, Operational Test & Evaluation
FAA	Federal Aviation Administration
FMC	Fully Mission Capable
GWOT	Global War on Terrorism
IADS	Integrated Air Defense Systems
IR	Infrared
ISA	Islamic State of Afghanistan
JASPO	Joint Aircraft Survivability Program Office
JCAT	Joint Combat Assessment Team
JTCG/AS	Joint Technical Coordinating Group for Aircraft Survivability
LFT&E	Life Fire Test & Evaluation
M&S	Modeling and Simulation
MANPADS	Man Portable Air Defense Systems
MDS	Mission Design Series
NMC	Non-Mission Capable

OEF	OPERATION ENDURING FREEDOM
OIF	OPERATION IRAQI FREEDOM
OSD	Office of the Secretary of Defense
PMSG	Principal Members Steering Group
RAF	Royal Air Force
RDT&E	Research ,Development, Test & Evaluations
RPG	Rocket Propelled Grenade
SAM	Surface-to-Air Missile
SA/AW	Small Arms/Automatic Weapons
SEA	Southeast Asia
SECDEF	Secretary of Defense
SURVIAC	Survivability/Vulnerability Information Analysis Center
TAR	Technical Assistance Request
TO	Technical Order
USA	United States Army
USAF	United States Air Force
USD/A&TL	Undersecretary of Defense for Acquisition, Technology & Logistics
USN	United States Navy
WMD	Weapons of Mass Destruction
WWI	World War I
WWII	World War II

FIXED-WING AIRCRAFT COMBAT SURVIVABILITY ANALYSIS FOR OPERATION ENDURING FREEDOM AND OPERATION IRAQI FREEDOM

I. Introduction

Engineers, scientists, and operators in the survivability community expend considerable resources trying to make sure the weapon systems fielded are safe and effective. They build threat models, perform simulations, and even conduct live fire tests. Nevertheless, when the flag goes up and the nation's warriors head off to war, all efforts up to that point are largely academic. For those in the profession of arms who build, maintain, and sustain weapon systems, combat is the ultimate test. Like all testing, the goal is to learn something. In the survivability community, the goal is to learn exactly how effective their efforts to reduce an aircraft's susceptibility and vulnerability have been. In addition, they want to learn whether or not they have accurately predicted the threats and whether the counters to those threats are effective. The time for the survivability community to gather, analyze, and disseminate combat data is now. The U.S. is currently engaged in two distinct operations. Thus, there is no better time to evaluate events. History has shown that if too much time is allowed to lapse between data collection and analysis, critical fidelity is lost.

Survivability is not a straight-line discipline. It is an iterative process. Therefore, it is imperative that, should a nation find itself (or its products) at war, the results of the test of combat not be lost. The acquisitions community uses those results to ensure modifications or new procurements are survivable against relevant threats. In doing so, lives will be saved. The sections to follow will briefly outline how the aircraft survivability discipline came into being.

1.1 Background and History

The first use of conventional fixed-wing aircraft as an instrument of war occurred during the 1911 Italo-Turkish War. In the early days of the war, the Italian Army Air Corps conducted a bombing raid on a Turkish camp at Ain Zara, Libya. Figure 1-1 shows a replica of a German monoplane fighter similar to the Italian aircraft of the period [1]. The raid marked the beginning for two diametrically opposed efforts. The first effort driven by the need to defend ground (and later sea) based forces from attack by air and the other compelled to make aircraft survivable in the evermore increasingly hostile air combat environment [2].

Figure 1-1: Early 1900's Era Monoplane (image courtesy of USAF) [1]

Aircraft survivability improvements in the early 20th century came largely as a byproduct of design innovations intended to increase performance parameters such as speed, altitude, payload, and reliability. While attributes, such as the ability to fly relatively fast and at relatively high altitudes, increase survivability in their own right, they also drive the need for more robust structures. Robust structural design, in-turn, leads to aircraft capable of sustaining more and more combat damage. During World War I (WWI), aircraft structural design and manufacture took their cues from bridge building and furniture making. Structural failures were all too commonplace. Near the end of WWI, the engineers—reacting to the demands to reduce structural failures—developed often times overdesigned aircraft structures [3]. In 1926, the U.S. federal government entered the realm of aviation regulation with the creation of an aviation branch within the Department of Commerce. Later the Civil Aeronautics Administration (CAA) would become a department independent of the commerce department. This precursor to the contemporary Federal Aviation Administration (FAA), laid the foundation for, among other things, minimum safety standards for aircraft design. During this era, the Daniel Guggenheim Fund sponsored a "Safe Airplane Competition" for the Promotion of Aeronautics. Primarily focused on low speed handling qualities and take-off and climb performance, the competition marked the emergence of serious efforts to solve many early aircraft design flaws. In hindsight, the competition also highlighted the interconnectedness of system safety and combat survivability. Unfortunately, due primarily to the widespread economic woes of the great depression, much of the progress made as a result of the competition was slow in finding its way into contemporary aircraft design [4]. Aircraft design followed a trend similar to the mid 1920's during World War II (WWII) and Korea where aircraft survivability efforts were largely reactive.

For example, the Royal Air Force (RAF) first used the Boeing B-17 “Flying Fortress” in combat under provisions of the Lend-Lease Act of 1941. Its design focused on the need to carry a relatively large internal bomb load (6,000 lbs) a distance of 1,100 miles. To accomplish this goal with the technology of the time required a large internal fuel capacity inside a relatively lightweight airframe. The solution involved a semimonocoque structure with a large area wing, which contained the necessary fuel reserves. Survivability equipment incorporated in the early designs included: medium caliber machine guns for self-defense and armor for crew positions. Initially, the RAF employed the first twenty aircraft in daylight bombing raids over France, Germany, and Norway. Without fighter escort, the relatively slow flying B-17s were highly susceptible to enemy fighter attack. Unfortunately, scenes like the one found in Figure 1-2 were

Figure 1-2: Boeing B-17 Flying Fortress Bomber Crash, Austria, 1944, (image courtesy of USAF) [5]

all too common. In the span of five months, eight of the original twenty B-17s were lost. This prompted the RAF to withdraw the B-17s from bomber service and relegate them to coastal reconnaissance missions. Boeing reacted to this by redesigning the B-17 to compensate for its survivability shortcomings such as inadequate crew armor and ineffective fuel tank sealing. The iterative design-redesign approach continued over the next several years. By war's end, the venerable B-17, as shown in Figure 1-3, was credited as one of the key factors that led to the

Figure 1-3: Boeing B-17 Flying Fortress Formation, 1945, (image courtesy of USAF) [5]

Allied victory over the Axis powers [6]. From a systems engineering perspective the initial aircraft design, with all of its vulnerability issues, was a failure due to the lack of consideration for survivability during the early stages of development. Subsequent redesigns corrected most of these problems, but costs both monetary and in human lives could have been minimized had a disciplined systems engineering approach —with consideration for effective survivability measures—been utilized from the outset.

This is not to say that efforts to decrease aircraft vulnerability were completely nonexistent during WWII and the post-WWII era. On the contrary, in 1948 representatives from all across the aircraft industry held the First Working Conference on Aircraft Vulnerability at the U.S. Army Ballistic Research Laboratory at the Aberdeen Proving Grounds, Maryland. Participants of the conference included subject matter experts such as representatives from: the Air Force Air Materiel Command, the Army Ballistic Research Laboratory, Johns Hopkins University Applied Physics Laboratory, University of Chicago Ordnance Explosive Group, and the Rand Corporation. The intent of the conference was to identify technologies necessary to reduce military aircraft vulnerabilities. Sadly, the efforts initiated by the conference failed to gain momentum due to the belief of the time that the world would fight all future wars with nuclear weapons.

This would prove to be a costly mistake during the Korean War when the U.S. military found itself, again, reacting to the effect of conventional weapon threats to its aircraft. However, the result of the subsequent reinvigoration produced new concepts in ballistic protection, damage tolerant designs, and fuel (system) protection [7].

During the war in Southeast Asia (SEA), aircraft performance increased exponentially along with a greater understanding of aerodynamics and structural analysis. Correspondingly, the threats military aircraft faced became more sophisticated. From the ground, radar-guided surface-to-air missiles (SAMs) and anti-aircraft artillery (AAA) replaced the act of simply filling the air blindly with a curtain of lead (although flak remains a significant threat). In air-to-air combat, infrared (IR) homing missiles and radar-assisted gun sights increased accuracy and the probability of hitting an adversary aircraft. Unfortunately, the design process (from a survivability perspective) remained reactive. The survivability improvements implemented on the F-4 Phantom II (Figure 1-4) illustrated this point. The perception existed of an unacceptably

Figure 1-4: McDonnell Douglas (Boeing) F-4 Phantom II (image courtesy of USAF) [5]

high tactical fighter loss rate in SEA. This perception prompted vulnerability analyses on most such aircraft operating in theater. These analyses were an attempt to identify the root cause of the tactical fighter losses. A United States Air Force (USAF) team determined that one of the major vulnerability factors in the F-4 was the lack of self-sealing fuel tanks and lines as well as the lack of adequate fire suppression. Recall, that Boeing made similar upgrades to the B-17 during WWII. Additionally, the F-4 hydraulic system, which was necessary to operate the flight controls, had potential single-point failure locations. One of these single point failure locations was in the empennage above the engine exhaust nozzles. Therefore, if damage occurred in this or any of the other single-point failure locations, the aircraft would become uncontrollable. To address the fuel system and control system issues, the USAF spent millions of dollars to retrofit the F-4 fleet. This corrective action saved many aircraft and numerous lives that would have otherwise been lost had the retrofits not been installed [6]. If not addressed, the type of damage illustrated in Figure 1-5 may have caused an aircraft loss. However, if the aircraft had designed for survivability against the probable threats, even fewer lives and dollars would have been lost.

In the 1970's, a major paradigm shift occurred when combat damage from the decades long conflict in Southeast Asia (SEA) was being analyzed and used to drive requirements for the next generation of aircraft that were being developed in the late 1970's and early 1980's. This act of analyzing actual combat data and formally applying the lessons learned to future systems marked the emergence of aircraft survivability as a discipline for military aircraft design. In 1971 in response to a high combat aircraft loss rate in SEA the Department of Defense chartered the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS). Initially, their charter focused on susceptibility and vulnerability reduction. In the mid-1980's the JTCG/AS

Figure 1-5: F-4 Empennage Battle Damage, courtesy of USAF [5]

established the Survivability/Vulnerability Information Analysis Center (SURVIAC). SURVIAC was chartered to collect and analyze historical combat data as well as threat and vulnerability data for all Department of Defense (DoD) agencies. During this timeframe, the DoD initiated the Joint Live Fire Program. The intent of both efforts was to provide realistic vulnerability test data to the Office of the Secretary of Defense (OSD). In 2003, JTCG/AS evolved into the Joint Aircraft Survivability Program Office (JASPO) and remains the DoD's primary advocate of aircraft survivability research and analysis [6].

JASPO provides guidance along with many other partners in the survivability community, which enables great strides in the enhancement of fixed-wing (and rotary-wing) aircraft survivability. To institutionalize these "lessons learned," the DoD maintains a series of military handbooks and standards for the acquisition community at large. Bear in mind, the guidance contained within these documents was initially produced largely during the Cold War. Therefore, it is incumbent upon industry, the acquisition community, and the end user to understand what kinds of threats to consider during procurement so not to repeat the mistakes of past programs. To that end, this document analyzes contemporary conflicts.

Following the attacks by the Islamic extremist, Al Qaeda, on September 11, 2001, the United States entered into the Global War on Terrorism (GWOT). President George W. Bush initiated OEF as a component of GWOT intended to disrupt terrorist training camps and eliminate a safe haven for terrorist organizations such as Al Qaeda in the country of Afghanistan. A decade of war with the Soviet Union and neglect by the international community created a tolerant environment in Afghanistan for Al Qaeda and the ruling Taliban. By Western standards, the Afghani military (i.e. the Taliban militia) did not possess equipment with high degrees of sophistication. However, the proliferation of small to medium caliber guns, rocket propelled grenades (RPGs), and relatively inexpensive MANPADS fuels the current insurgency and poses a significant threat to aircraft flying in the region. The various Afghani factions such as the Western backed, anti-communist Mujahedin and the Pakistani backed Taliban stockpiled these weapons. Moreover, although institutionalized government-supported training regimens were scarce, years of experience honed on the battlefield and hands-on training make these weapons effective.

After the withdrawal of the Soviet Union from Afghanistan in 1989, hard-line Taliban finally filled the subsequent power vacuum after a long civil war. Consequently, the Taliban was able to drive the Mujahedin, which had formed the Islamic State of Afghanistan (ISA), out of most parts of the country with the exception of the rugged northern territories. The Taliban confined the ISA— more commonly known as the "Northern Alliance"— to these territories until the U.S. led invasion in November 2001. At this time, the U.S. military and the Northern Alliance formed weak partnerships in order to overthrow the Taliban backed government. The war in Afghanistan continues today along with the various threats to coalition aircraft. Therefore, this document will analyze these threats to determine the most effective method for protecting U.S. materiel and personnel.

In August of 1990, the United States led coalition forces in the Persian Gulf War against the country of Iraq. The United Nations (U.N.) authorized the war in response to the invasion of Kuwait by Iraqi forces. OPERATION DESERT STORM is the name given to the military response. During DESERT STORM, coalition forces decimated the Iraqi military machine. To minimize the threat of future aggression, the U.N. imposed crippling economic sanctions and mandated rigorous inspections of Iraq's military infrastructure. Following a decade of defying United Nations Security Council resolutions requiring the country of Iraq to dismantle its weapons of mass (WMD) programs; allow verification inspections; and cease and desist hostile actions against coalition aircraft patrolling the northern and southern no-fly zones—the U.S. invaded Iraq in March 2003. The military name for this action became known as OPERATION IRAQI FREEDOM (OIF). In contrast to Afghanistan, Iraq had a strong (autocratic) government, somewhat well established infrastructure, and a reasonably well trained and equipped military. Previously, during OPERATION DESERT STORM, Iraqi integrated air defense systems (IADS) had been severely damaged and subsequent sanctions left them in serious disrepair. The extent of its capabilities was unknown at the beginning of OIF. Military planners knew, although diminished, the Iraqi military threat to U.S. and coalition warplanes remained significant. Therefore, early in OIF significant coalition efforts were concentrated on gaining air superiority. Following the initial invasion and defeat of the standing Iraqi military, the campaign devolved into a large-scale insurgency and shares similarity with the hostile action in Afghanistan. Unlike Afghanistan; however, Iraqi military personnel were well organized and trained on the weapon systems in their possession prior to the U.S. led invasion. Therefore, after the toppling of the official Iraqi government and dissolution of the military, many of these personnel became members of the insurgency. Supplied by regional proxies and motivated by self-preservation the insurgents employ firepower and continually evolve their tactics with devastating effect. Although devoid of complicated IADS networks—small arms, RPGs, and MANPADS continue to threaten U.S. and coalition aircraft

1.2 Research Objectives

The primary objective of this research is to save lives by increasing the combat survivability of fixed-wing aircraft in current and future operations. The author accomplishes this objective by analyzing trends in combat damage from the most recent data sets available. The larger aircraft survivability [and acquisitions] community can use these trends to reduce susceptibility and decrease vulnerability.

Due to design improvements driven by lessons learned over nearly a century of combat aviation, an aircraft damaged does not necessarily equate to an aircraft kill. As a secondary objective, this research explores aircraft battle damage reporting procedures and repair guidance.

Finally, it is the goal of this thesis to provide constructive recommendations for these processes. The improved aircraft battle damage processes will provide timely, accurate, and actionable information to all necessary stakeholders.

Why is this research important? The USAF is currently developing high-profile acquisition programs such as the F-22 Raptor and F-35 Lightening II with survivability features intended to offset threats encountered during large state versus state conflicts. Such conflicts would require state of the art stealth technology, net-centric command and control, precision attack capability, and unparalleled aircraft performance to overcome highly sophisticated integrated air defense systems (IADS). Both OEF and OIF have shown that once allied forces have established air superiority, the fight continues. Additionally, this document will show that even the most advanced aircraft of the day remains vulnerable. Therefore, the answer to the question of why this research is important is to highlight omnipresent vulnerabilities. Armed with this knowledge, leaders in the operational and acquisition communities can make informed choices to defend man and materiel from harm—even in conflicts where a substantial technological advantage over the enemy may exist.

A commonly used expression in the military is, "Low risk does not mean—no risk." To quantify this risk, acquisitions professionals utilize a risk assessment matrix like the one found in Figure 1-6. Despite the best efforts of the survivability community, the likelihood of an aircraft experiencing some form of damage (susceptibility) during combat is high. While avoiding damage altogether pays the highest dividends from a risk mitigation perspective, it is also important to identify methods to minimize the consequences of damage (vulnerability). From an aircraft survivability perspective, if damage occurs, warfighters hope the aircraft design is such that it is capable of completing the mission and returning to base safely. However, the

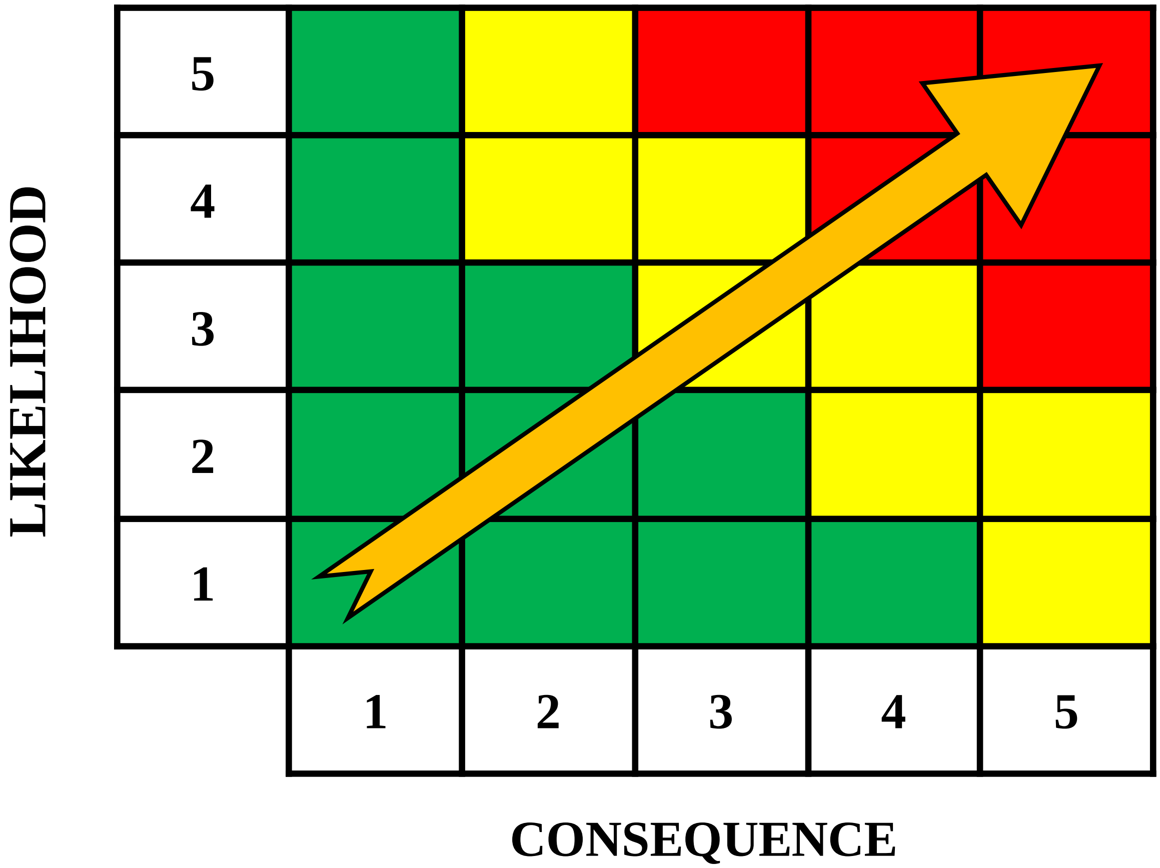


Figure 1-6: Risk Assessment Matrix

threat essentially killed the aircraft if it is unable to fly another mission. During OPERATION DESERT STORM, a single AC-130 gunship was lost to hostile fire. The loss of this aircraft represented twenty-five percent of the gunships deployed for the operation. Furthermore, if propagated for the entire campaign, this event would cause the loss rate for AC-130s to spike to nearly 10 per 1,000 sorties [10]. Clearly, such a loss rate is unsustainable. In addition to the need to decrease aircraft vulnerability, this example emphasizes how losing a relatively low number of aircraft can affect a deployed force's strength. Therefore, given the high probability that aircraft will sustain combat damage and the impact a single aircraft loss has on campaign survivability; it is foolhardy not to plan for such scenarios.

Contingency planning should thus be focused on the ability to generate equal numbers of sorties with fewer aircraft; thereby, minimizing the required logistical footprint without sacrificing combat capability. In the current environment, dependence on tenuous relationships with host nations influences strategic planning. Therefore, the ability to provide needed airpower using the minimum number of aircraft is all the more vital. This fact was evident in the highly publicized negotiation for the use of Manas AB, Kyrgyzstan. In early 2009, the Kyrgyz government agreed to allow the United States to continue operations if, in-turn, the U.S. would agree to a three-fold increase in rent for the facilities. Therefore, yet another benefit of this research is to identify ABDR focus areas on which leaders should concentrate resources in order to produce maximum aircraft availability using the minimum number of aircraft. One such focus area is aircraft design that eliminates the need for immediate repair. Current ABDR technical data exists for most combat aircraft in the active USAF inventory. This technical data identifies categories of damage, with which the aircraft can continue to operate unrepaired. By recognizing trends in aircraft battle damage from OEF and OIF from an ABDR perspective, it is possible to incorporate—early in the weapon system design process—damage tolerant structures, which enable rapid repair or preclude the need for repair altogether. This enables combatant commanders to efficiently generate and sustain airpower with limited assets.

II. Literature Review

As illustrated in Figure 2-1, aircraft survivability is a balance between the threats posed by an adversary and a weapon system's survivability features. Most importantly, aircraft survivability hinges on mission requirements. This chapter intends to provide the reader with a brief overview of the aircraft survivability discipline. Additionally, this chapter introduces several key components of the battle damage reporting process. The components include assessors who gather information, analysts responsible for processing information, and consumers who apply the lessons learned in order to make weapon systems more survivable. The goal of this chapter is to provide a framework of understanding for the research methodology presented in Chapter 3.

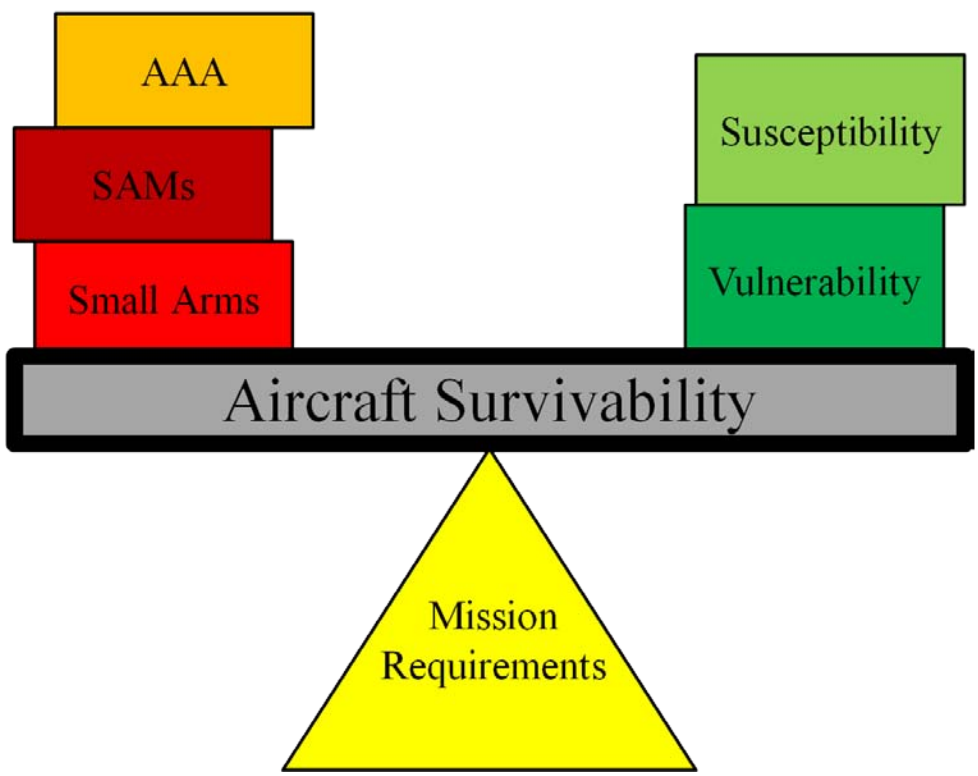


Figure 2-1: Aircraft Survivability Balance

2.1 The Aircraft Combat Survivability Discipline

Dr. Robert Ball defines aircraft combat survivability as the capability of an aircraft to avoid or withstand a man-made hostile environment. He further subdivides survivability into susceptibility: the inability of an aircraft to avoid a man-made hostile environment and vulnerability: the inability of an aircraft to withstand the man-made hostile environment. The antithesis of survivability is killability. If an aircraft is susceptible *and* vulnerable to a man-made hostile environment (a specific threat type), then it is killable. Aircraft combat survivability is a quantifiable. To quantifying survivability, one must calculate probabilistic values for events that would lead to an aircraft kill. Therefore, the probability that an aircraft is survivable (P_S) is the complement of the probability that an aircraft is killable (P_K), Equation 1.

Thus,

$$P_S = 1 - P_K \qquad (1)$$

$$\text{Survivability} = 1 - \text{Killability}$$

As alluded to earlier, killability is composed of two components—susceptibility and vulnerability. From an aircraft combat survivability perspective, susceptibility is the probability that an aircraft is hit (P_H) by a given threat—i.e. it cannot avoid the man-made hostile environment. Similarly, the probability that an aircraft is killed assuming it is hit ($P_{K|H}$) defines vulnerability. Probabilistically, the product of these values is equivalent to killability (Equation 2.) Hence,

$$P_K = P_H \cdot P_{K|H} \qquad (2)$$

$$\text{Killability} = \text{Susceptibility} \cdot \text{Vulnerability}$$

Thus, the combination of Equations 1 and 2 yield Equation 3.

$$P_S = 1 - P_K = 1 - P_H \cdot P_{K|H} \qquad (3)$$

Survivability = 1 – Killability = 1 – Susceptibility · Vulnerability

An aircraft's ability to avoid the man-made hostile environment is the complement of susceptibility (P^c_H). Similarly, the degree an aircraft can withstand a particular man-made hostile environment is the complement of vulnerability ($P^c_{K|H}$). Therefore, survivability is as follows:

$$P_S = P^c_H + P_H \cdot P^c_{K|H} \qquad (4)$$

Survivability = Complement of Susceptibility + Susceptibility · Complement of Vulnerability

Figure 2-2 illustrates the kill chain for a single aircraft versus a single shot from a single threat. Note that the threat does not necessarily have to be ground based. The above discussion raises the important question of how to assign values to the subject probabilities. Such probability values are highly dependent on the details of given scenario [6]. For example, consider the ludicrous example of a fly versus sledgehammer. Obviously, the fly is extremely vulnerable to the impact of a sledgehammer; therefore, the $P_{K|H}$ must be equal to one. Consequently, the survivability of the fly is dependent on its ability to avoid the sledgehammer—its susceptibility. For the sledgehammer to be a threat, it must be active; able to detect the fly; track the fly; initiate a swing toward the fly; and finally squash the fly. When combined with $P_{K|H}$ these factors describe the links of the so-called “kill chain” (the red arrow in Figure 2-2.) If any single link in the kill chain is disrupted the fly will survive the scenario. This is equivalent to following a green arrow on the in Figure 2-2. The kill chain is also broken into phases. The phases, shown in blue, mark the transition from one stage of the scenario to another.

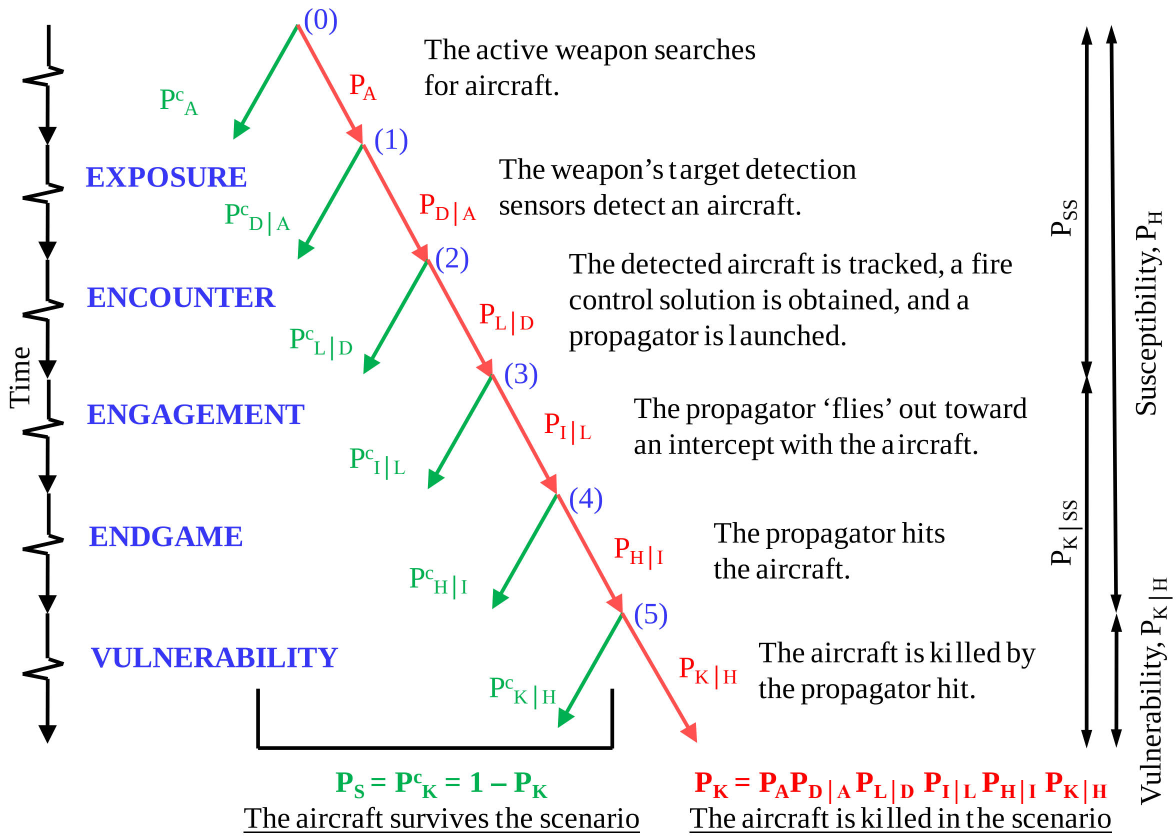


Figure 2-2: **One vs. One Kill Chain (Single Shot), taken from [6]**

In a scenario analogous to the fly vs. sledgehammer, to kill an aircraft the exact same chain of events must occur. Figure 2-3, notionally depicts the kill chain for a hypothetical scenario. Figure 2-3 is identical to Figure 2-2 except realistic descriptions for the event phases are used. In this scenario, a single insurgent armed with a small caliber rifle lies in wait along an aircraft's flight path. The flight path is on the approach to a forward operating base with an unimproved runway. From an aircraft defense perspective, designers should focus on disrupting the kill chain at any point possible. To prevent, for example, the insurgent from actively searching for aircraft to fire upon, increased security patrols may be necessary. In turn, this reduces the overall P_K for the scenario.

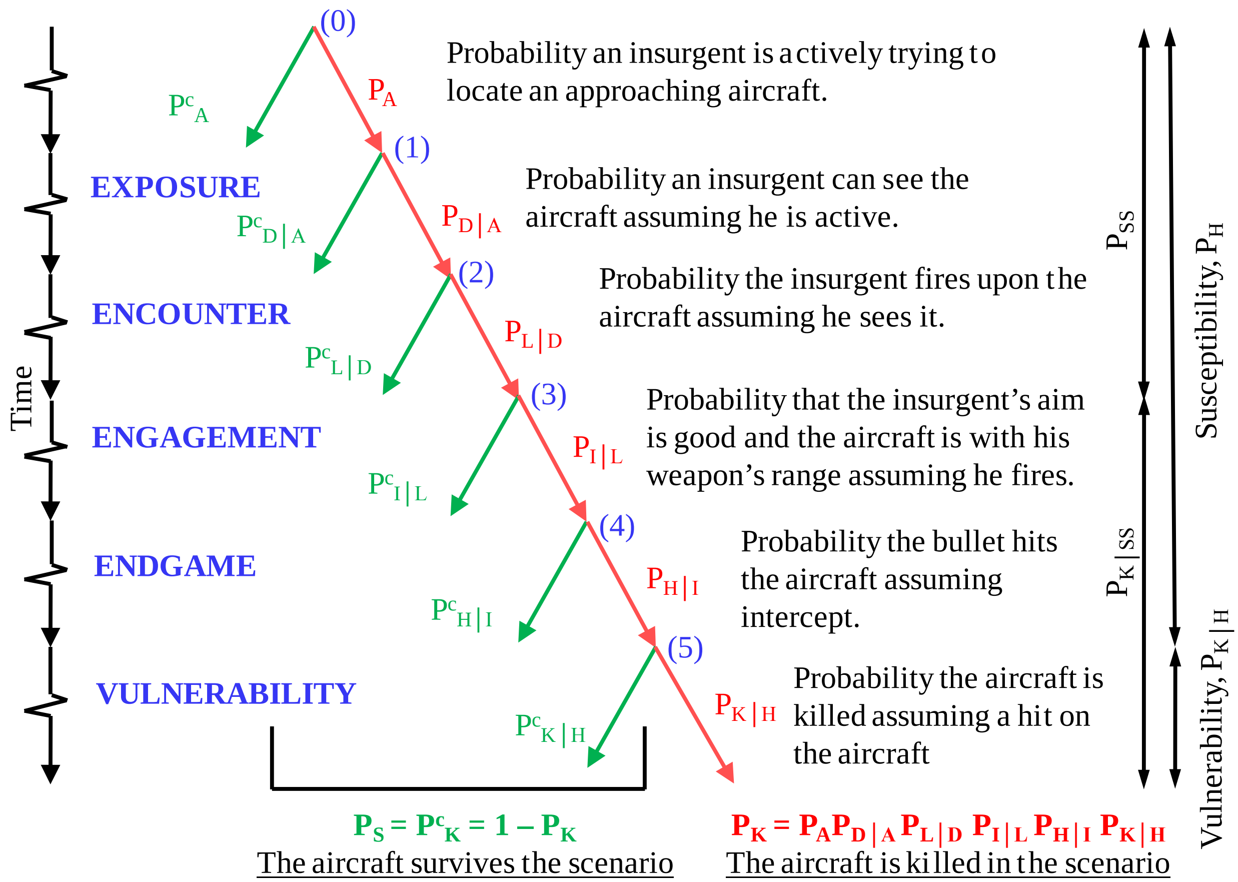


Figure 2-3: Hypothetical Kill Chain Illustrating an Insurgent vs. Aircraft, Single Shot Scenario

The purpose of this extremely brief introduction to the aircraft combat survivability discipline is to identify events leading up to the vulnerability phase of a given scenario. It is important to understand that, while the research contained herein focuses mainly on aircraft vulnerability, the ability to break the kill chain prior to the vulnerability phase is equally important. Additionally, assignment of probability values is not, by any means, arbitrary. Engineers conduct extensive research to define threat capability and aircraft susceptibility and vulnerability. Additionally, researchers perform exhaustive modeling and simulation to predict real world performance of these systems. Without this important work, survivability as a formal discipline would be less concise.

2.2 Aircraft Battle Damage Repair Evolution

In the example presented in Figure 2-2, there is an important caveat. An aircraft can potentially be hit but not killed. Such a condition defines the complement of the probability of kill given a hit on the aircraft ($P^{c}_{K|H}$). Assume the aircraft in the hypothetical scenario returns to base with battle damage. If maintainers cannot return the aircraft to mission capable status, the result is an aircraft kill. This factor is the source for development of aircraft battle damage repair (ABDR). The need to perform ABDR existed from the earliest days of aerial combat. Over time, a number of repair philosophies evolved. However, the goal of ABDR, regardless of philosophy, is to generate and sustain combat airpower.

The aircraft involved in WWI were very simple by current aerospace standards. Consequently, if a warplane of that era sustained battle damage, it was likely a total loss. However, there are records of simple repairs performed during this period. Advances in aircraft design during WWII vastly increased performance and cost. Aircraft of the WWII period, therefore, required more involved repair schemes in order to operate effectively and, because of the higher costs involved, were much less expendable than WWI era aircraft. It was during WWII that two distinct ABDR philosophies emerged. The first philosophy utilized rapid, temporary repairs in order to provide the highest number of combat capable aircraft in the shortest amount of time. The second philosophy, which emerged relied heavily upon a well-established logistics infrastructure. The infrastructure enabled field-level repairs to be accomplished using original equipment parts. If technicians deemed repairs to be above a field-level repair threshold, they shipped the aircraft to depots. In both cases, the result was aircraft in like-new condition. Either philosophy has its uses in modern aerial warfare. If time allows, it is certainly more advantageous to have aircraft in pristine condition. However, when fighting a war of attrition, the ability to rapidly return aircraft to the fight becomes a force multiplier. If a damaged aircraft returns to base, yet technicians cannot repair it in time to contribute to the campaign it is, in essence, a dead aircraft.

During hostilities in SEA, ABDR came of age out of necessity. For the first time the DoD formally captured damage, loss, and repair data. The data showed combat losses were becoming untenable and deployed maintenance operations were overwhelmed. In response, the depots built teams of civil service technicians and engineers that would deploy into combat zones to perform depot-level repairs and ABDR. Later, in response to the drawbacks of deploying civilians into a combat zone, the USAF formed all-military teams dubbed Combat Logistics Support Squadrons (CLSSs). Depot repair teams, including CLSS and specially trained ABDR engineers, reconstituted an estimated 1,000 of SEA's 11,800 battle-damaged aircraft [11].

In the post-SEA era, CLSS and depot engineers built upon the lessons learned and further institutionalized ABDR training. This training paid dividends during Operation Desert Storm with significant increases in aircraft availability. Following Desert Storm, CLSS and the formal ABDR program remained largely unchanged for most of the 1990's. Air Force Instruction (AFI) 21-101, AIRCRAFT AND EQUIPMENT MAINTENANCE MANAGEMENT drives Air Force Materiel Command (AFMC) to the requirement to have a robust ABDR program.

In 1997, the United States Air Force Scientific Advisory Board (SAB) Committee on United States Air Force Expeditionary Forces produced a report outlining a new vision for employing global airpower. The resulting combination of operation concepts; systems; technology and training; and organizational changes lays the foundation for the Aerospace Expeditionary Force (AEF) concept. The report defines AEFs as follows:

> *Aerospace Expeditionary Forces are tailorable and rapidly employable air and space assets that provide the National Command Authority and the theater commanders-in-chief with desired outcomes for a spectrum of missions ranging from humanitarian relief to joint or combined combat operations.* [12]

The SAB report also identified what it terms as the necessary "keys" for the AEF vision to be successful. Figure 2-4 illustrates the interconnectedness of the keys to the AEF vision. The core competencies of the Air Force: air and space superiority, global attack, rapid global mobility, precision engagement, information superiority, and agile combat support remain unchanged. However, the keys defined a pathway by which the USAF could maintain its core competencies with a leaner more efficient force. Of particular interest is the concept of the AEF being "light." Being light means that an AEF will deploy only what is necessary to accomplish the intended mission. For example, the USAF would only deploy the essential operational, command, support, and force protection assets with an AEF in an effort to minimize the necessary logistical footprint. For an AEF to be light, especially from an aircraft maintenance perspective, it must also adopt a Lean Logistics (LL) philosophy. LL is a concept developed by the RAND Corporation to deal with the problem of uncertainty of demand for products and services used by maintenance organizations.

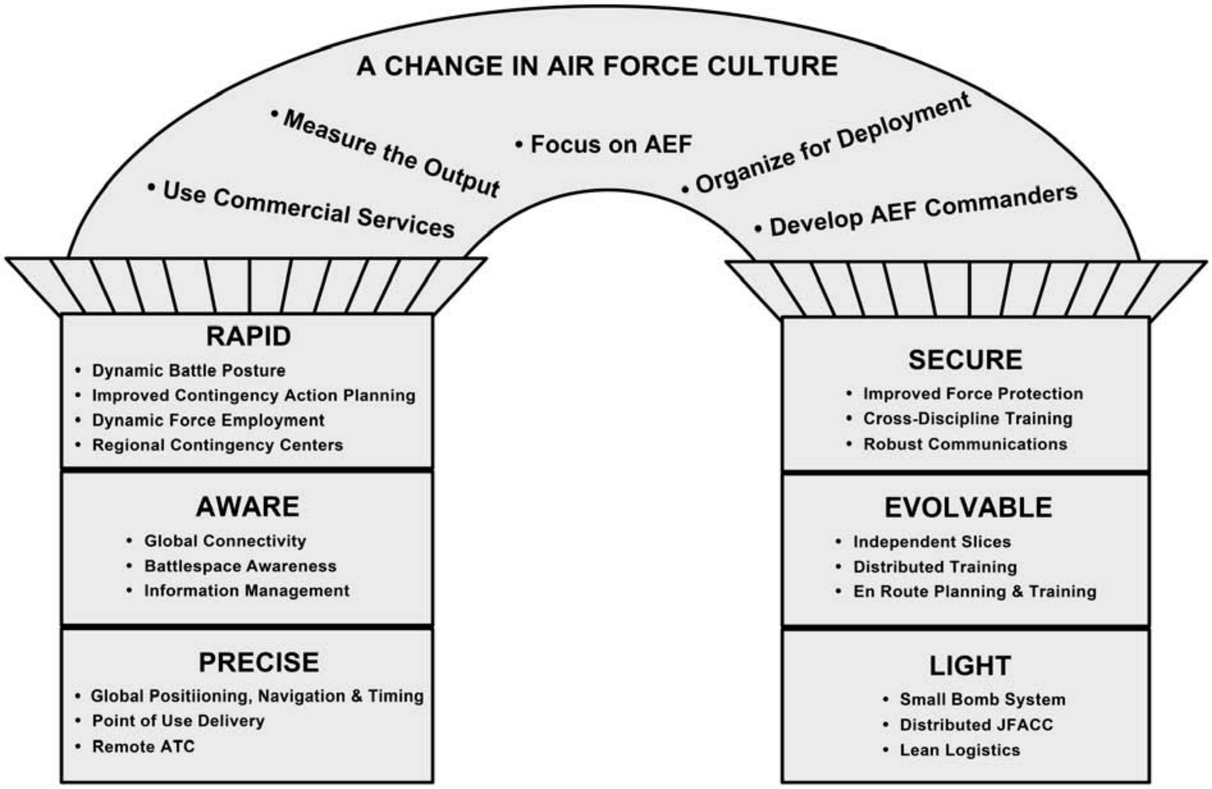


Figure 2-4: Keys to the AEF Vision, taken from [12]

The SAB report outlines what it calls the "Key elements of the LL concept." The elements are as follows:

> • *Significant acceleration of both organic repairs, addressed by the Depot Repair Enhancement Program (D-REP), and contractor repairs, addressed by a matching Contractor REP (C-REP)*
> • *Reliable and rapid (time-definite) transportation between engaged forces and sources of supply*
> • *Information systems that provide the necessary connectivity to the logistics support system including transmission of field failure data to accompany returned items*
> • *Ways to rapidly fabricate items not in stock, especially older items whose original source is no longer available*
> • *Continuous improvement based on results of exercises and field experience* [12]

As the Air Force entered the new millennium, it implemented the recommendations of the Scientific Advisory Board report. OEF and later OIF put the effectiveness of these recommendations to the test. However, what effect does the AEF construct have on ABDR? Relatively speaking, OEF and OIF have required very little support from ABDR specialists because air superiority was rapidly established. Therefore, following the AEF philosophy, there was no need to deploy CLSS as part of the overall force package. The unintended consequence of this fact is the perception that ABDR is not as relevant today as it was in the past and their skills are not in high demand. Compounded with budgetary constraints, this mindset has forced drastic reductions in the ABDR program. These reductions; however, are contradictory to significant elements of the AEF vision. For example, the SAB report suggests that the ability to significantly accelerate depot repairs and fabricate items not in stock were elements key to LL success. This is a crucial capability possessed by the CLSS. Additionally, the SAB report points to a reduced demand on maintenance personnel to perform routine maintenance. This, in-turn, enables leaders to task AEF personnel with determining the most efficient means of returning battle damaged aircraft to some level of functionality. This too is a capability possessed by CLSS. Therefore, the reduction of CLSS to expeditionary maintenance (EDMX) flights with only a fraction of their previous manpower and capabilities is contrary to core recommendations of the 1997, United States Air Force Scientific Advisory Board (SAB) Committee on United States Air Force Expeditionary Forces report. Moreover, the manner in which the USAF implemented the AEF system has other unintended consequences. Later chapters explore these issues in more detail. However, at this point, understand that maintenance personnel are a key component in the effort to gather battle damage information.

2.3 Director, Operational Test and Evaluation (DOT&E)

One of the primary stakeholders in the aircraft survivability community is DOT&E. In accordance with Title 10 U.S. Code, Section 139, the President of the United States shall, by and with the advice and consent of the Senate, appoint a Director of Operational Test and Evaluation. By the authority of the Secretary of Defense (SECDEF) the DOT&E defines policies and procedures used to conduct operational test and evaluation for all branches of the DoD; provides guidance to the SECDEF, Under Secretary of Defense for Acquisition, Technology & Logistics (USD/A&TL), and the Secretaries of military departments with respect to OT&E; coordinate Joint OT&E; monitor and review all DoD OT&E activities; make recommendations to the SECDEF regarding OT&E financial matters; and monitor and review all DoD LFT&E [13].

Currently, the DOT&E has defined four key initiatives. These initiatives are as follows:

1. Field new capability rapidly.
2. Engage early and improve requirements
3. Integrate developmental, live fire, and operational testing
4. Substantially improve suitability before initial OT&E [13]

Initiative 1, harkens back to the reactive nature of design for survivability. To some extent, survivability will always be one-step behind the current threat. Threats are constantly evolving. Therefore, researchers should conduct survivability studies and present the results to the survivability community as soon as feasible. As such, timely, accurate, and actionable—and thereby relevant—information is the key to fielding new technology more rapidly. Researchers must also disseminate results as widely as prudent. Such research ensures all stakeholders have applicable data on current threats and fulfill DOT&E initiatives two and three. Moreover, live fire test and evaluation (LFT&E), required by law (U.S. code Title 10, Section 2366), falls under the purview of DOT&E. The objective of LFT&E as defined by the Defense Acquisition Guidebook (DAG) is as follows:

> *The objective of Live Fire Test and Evaluation (LFT&E) is to provide a timely assessment of the vulnerability/lethality of a system as it progresses through its design and development prior to full-rate production. In particular, LFT&E should accomplish the following:*
>
> - *Provide information to decision-makers on potential user casualties, vulnerabilities, and lethality, taking into equal consideration susceptibility to attack and combat performance of the system;*
> - *Ensure that knowledge of user casualties and system vulnerabilities or lethality is based on testing of the system under realistic combat conditions;*
> - *Allow any design deficiency identified by the testing and evaluation to be corrected in design or employment before proceeding beyond low-rate initial production; and*
> - *Assess recoverability from battle damage and battle damage repair capabilities and issues.*
>
> *The LFT&E Strategy for a given system should be structured and scheduled so that any design changes resulting from the testing and analysis, described in the LFT&E Strategy, may be incorporated before proceeding beyond low-rate initial production.* [14]

DOT&E has the authority to designate any new or existing program for LFT&E oversight. If so designated, the program becomes a "covered system." The ability of DOT&E to accomplish the outlined objectives hinges on the ability to precisely define the threats to aircraft or aircraft systems and defining what constitutes survival. These definitions must be in place early in the acquisition process. Doing so ensures that all parties understand the requirements and prevents duplication of labor. Finally, as with all aspects of system development, accurately defining suitability requirements as early in the process as possible increases the degree to which the end user can satisfactorily field a system. To accomplish this goal, DOT&E produces an annual report, which outlines deficiencies and successes of covered systems. With regard to survivability, DOT&E must define success against a relevant threat. Therefore, DOT&E is a major consumer of battle damage analysis.

2.4 Joint Aircraft Survivability Program (JASP)

As mentioned earlier in this document, JASP evolved from the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS) and is the Department of Defense's (DoD) focal point for joint service enhancement of military aircraft non-nuclear survivability.

The commanders of the USN Naval Air Systems Command, USA Aviation and Missile Command, and USAF Aeronautical Systems Center charter the JASP. It coordinates and conducts RDT&E to improve military aircraft survivability; develops and standardizes aircraft survivability modeling and simulation (M&S); facilitates information exchange on aircraft survivability; and supports aircraft survivability education for the DoD and U.S. aircraft community. Each chartering command provides a senior aircraft survivability expert for the JASP Principal Members Steering Group (PMSG), which guides the program and approves projects for funding. The JASP assesses and reports on combat damage incidents through the Joint Combat Assessment Team (JCAT); is the Executive Agent for the Joint Live Fire Aircraft Systems Program managed by the Live Fire Test office of DOT&E; and is also an Executive Agent for the Survivability Vulnerability Information Analysis Center (SURVIAC), the repository for aircraft survivability information [16]. To better understand the organizational relationship between the listed organizations refer to Figure 2-5. JASPO is a critical node for battle damage information. Their members are involved in all phases (collection, compiling, and consuming) of the battle damage information flow.

Organizationally JCAT supports the JASPO mission. JCAT is comprised of assessors from the Army, Navy, Air Force, and Marine Corps. The DoD specifically trains JCAT members to

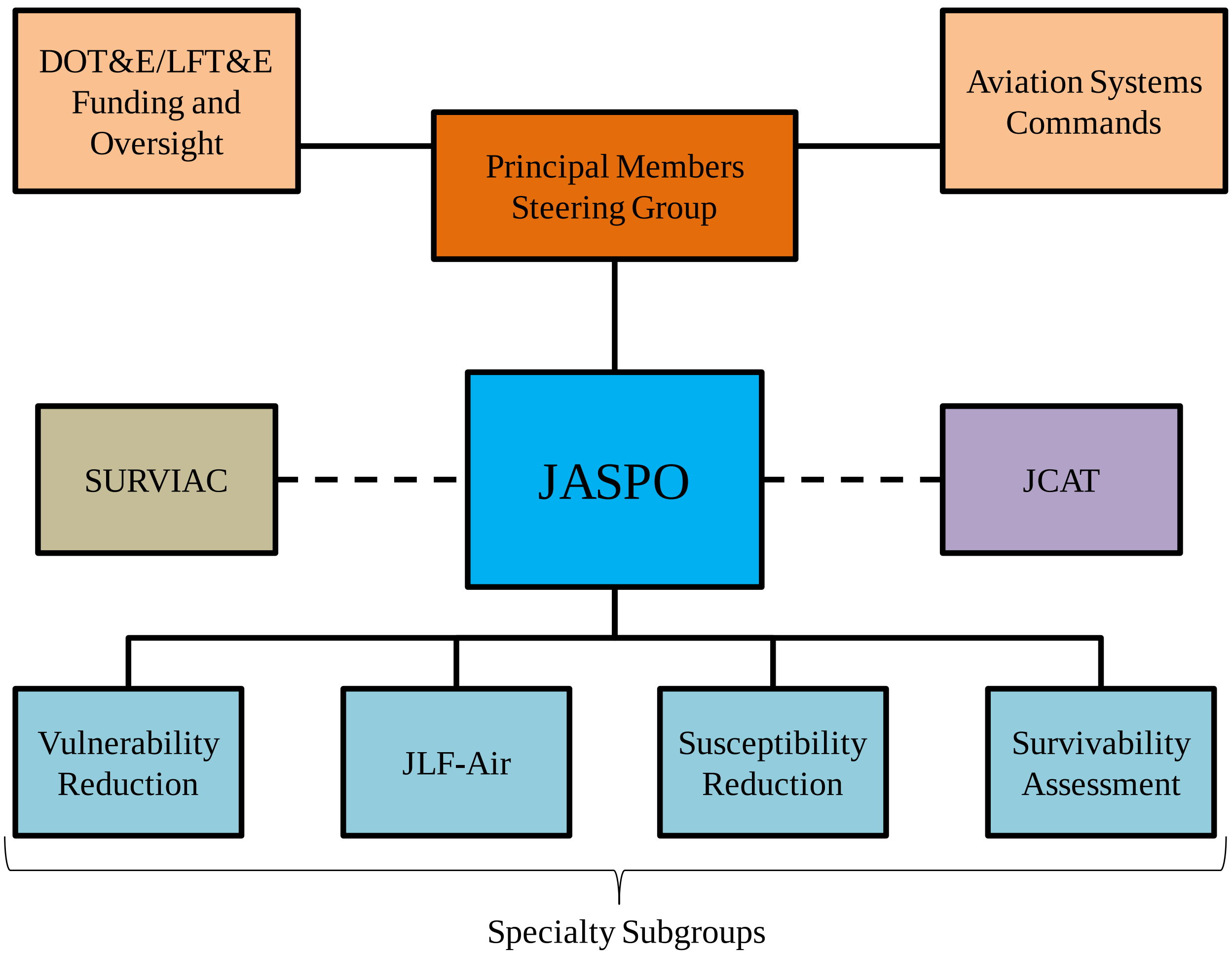


Figure 2-5: JASPO Organization, taken from [6]

conduct combat damage forensics and assessments on battle-damaged aircraft. To perform these evaluations, team members are often required to forward deploy. Training consists of three phases. ASDAT hosts phase one at Fort Rucker, AL. Phase one consists of basic combat damage forensics. During this phase, future assessors learn how to identify damage associated with specific threat weapon types. Phase two, conducted at China Lake Naval Air Warfare Center in California, continues the assessors training on actual fixed wing and rotary wing aircraft used in weapons live fire tests and evaluations. This provides hands-on experience to the assessors in analyzing real world damage caused by representative threat types. Phase three—the Threat Weapons and Effects seminar. During this phase of training, assessors receive classified briefings on current threat weapons and their effects. The capstone of the seminar, and the final component of JCAT training, is live-fire exhibition with a follow-on assessment [17]. JCAT's mission is to assess the threat environment for operational commanders and collect data to support aircraft survivability research and development.

Like JCAT, SURVIAC supports the JASPO mission. Furthermore, SURVIAC is the DoD focal point for survivability data. Their capabilities include the development of vulnerability data; modeling and simulation; threat weapon analysis; and U.S. weapon effectiveness. SURVIAC is the primary recipient of combat damage and loss data. Through JASPO, SURVIAC is also involved in analyzing live-fire test results. Three distinct entities— JCAT, Combat Logistics Support Squadrons (CLSSs), and operational units collect aircraft battle damage data, which is routed to SURVIAC. Each group has their own specific mission. CLSS and the operational unit's mission differs from that of JCAT in that instead of ultimately trying to identify the threat for intelligence purposes, their mandate is to return the aircraft to flying status as soon as possible. CLSS possesses special skills, unavailable to typical maintenance units, to help facilitate this mandate. Regardless, Technical Order (TO) 1-1H-39 requires that all aircraft battle damage be reported. The data captured by JCAT members is catalogued in CDIRS and data captured by CLSS and maintenance units is recorded on AFTO FORM 97/A. When notified of an incident, JCAT (or CLSS) team members rapidly mobilize to capture as much detail about the incident as possible. A crucial component of the investigation and ensuing report is the aircrew interview. As such, it is important to interview the aircrew as soon as possible because their memories lose fidelity with time. During the interview, debrief section members record specifics surrounding the incident such as altitude, airspeed, fuel load, heading, countermeasures employed, etc. When assessors inspect the aircraft, they look for clues to determine what type of threat the aircraft encountered. Threat types include (but are not limited to) the following: small arms/automatic weapons (SA/AWs), rocket propelled grenades (RPGs), and other man-portable air defense systems (MANPADS). Finally, assessors compile and upload the information in the SURVIAC database for further analysis. For reasons discussed later, operational units are often times unaware of the requirement to capture and submit aircraft battle damage information to SURVIAC. However, some aircraft repair documentation may capture battle damage indirectly. Figure 2-6 illustrates the ideal flow of battle damage information through SURVIAC from those charged with collection to the end users.

In summary, field units such as ABDR teams, JCAT, or operational maintenance units collect battle damage information. The units then forward the information to SURVIAC for analysis. JASPO communicates the battle damage data and analysis from SURVIAC to a variety of aircraft survivability stakeholders. Such stakeholders include DOT&E, weapon system developers, etc. Exercising the principles of the aircraft survivability discipline, the stakeholders ensure new and existing acquisition programs are survivable against real-world threats.

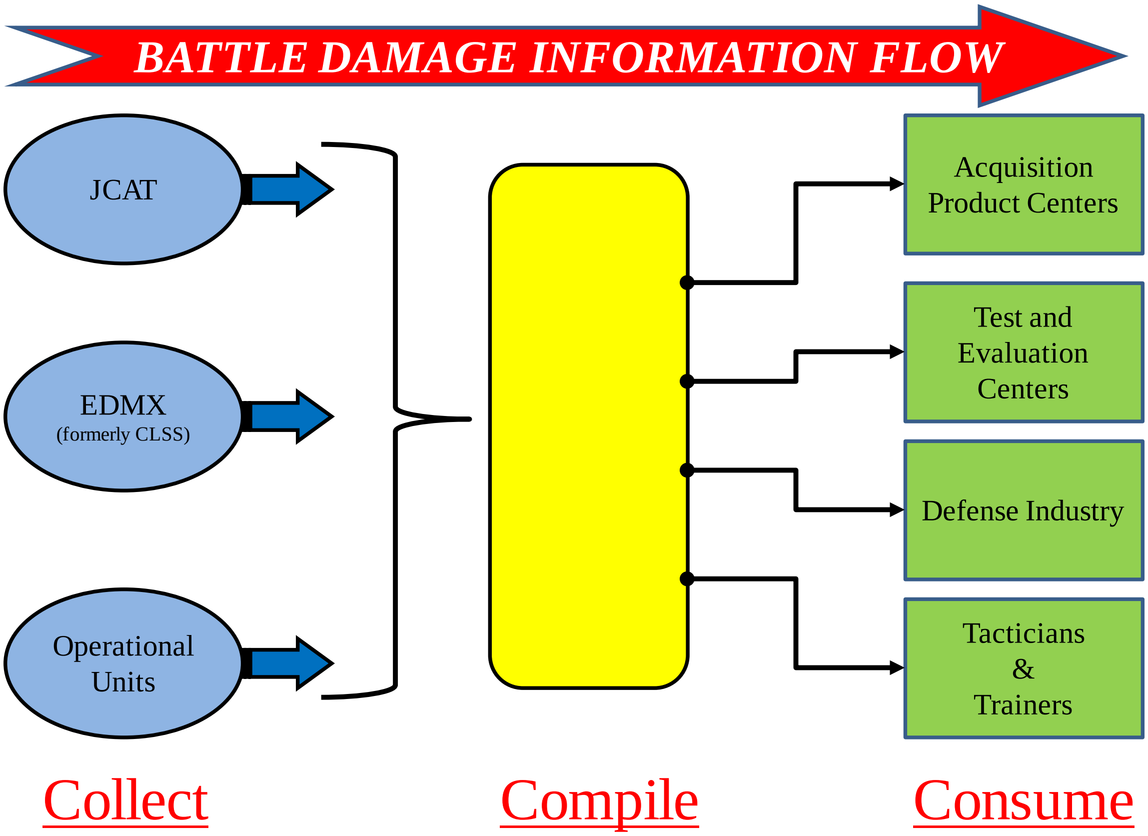


Figure 2-6: Battle Damage Information Flow

III. Methodology

In principle, the research methodology in this document is quite straightforward. Battle damage data, provided by SURVIAC (and other sources) to the Institute for Defense Analysis (IDA), is readily available. Furthermore, IDA has already invested significant resources to the process of scrutinizing the data. Not only is the data available its validity is widely respected within the larger aircraft survivability community. Therefore, step one is to mine the fixed-wing dataset available to identify battle damage trends. The approach involves looking at the battle damage from two perspectives. Perspective one looks at battle damage based on the aircraft involved in a particular combat event. The second perspective looks at battle damage based on the threat type involved in the same combat events as in perspective one. Concentrations of incidents from either one of these perspectives (or both), in theory, highlights fertile areas in which analysis is warranted. The second step requires crosschecking specific incidents against a second (or potentially a third) database to get as much detail as possible about the event. Finally, having identified battle damage trends and obtained situational awareness about specific events, the author makes recommendations to improve aircraft survivability. The following sections provide details about the three databases used and about the process used to further refine the scope of this research.

3.1 Information Databases

The primary objective of this thesis, as outlined in section 1.2, is to increase combat survivability of fixed-wing aircraft and thereby save lives. Therefore, it is necessary to examine aircraft damages and losses attributed to combat; determine aircraft susceptibility and vulnerability concerns; identify combat damage/loss trends; and make recommendations that accomplish the stated objectives. To this end, this document utilizes three databases. The databases are as follows: "Study on Rotorcraft Survivability"; Reliability and Maintainability Maintenance Information System (REMIS); and Combat Damage Incident Reporting System (CDIRS). It is important to note that the rotorcraft study mentioned and CDIRS are somewhat interrelated. SURVIAC, as the single DoD agency responsible for managing aircraft battle damage data, provided the bulk of the material used to produce the rotorcraft study. Meanwhile, CDIRS is a relatively new tool, also managed by SURVIAC, used to facilitate collection of current and future battle damage. In essence, the rotorcraft survivability study represents a historic composite of aircraft battle damage from various sources and CDIRS enables its users to conduct similar studies now and into the future.

As part of the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009, Public Law 110-417, Congress commissioned Institute for Defense Analyses (IDA) to produce a study on DoD rotorcraft survivability. IDA is a non-profit corporation that operates three federally funded research and development centers to provide objective analyses of national security issues, particularly those requiring scientific and technical expertise, and conduct related research on other national challenges [18]. The scope of this study was broad and included all rotorcraft losses during the OEF/OIF timeframe defined as October 2001 to December 2008. The analysis was supported by review of combat data reports from SEA era and by Class A mishap reports from 1985-2008. The study distinguishes aircraft losses from fatalities associated with aircraft losses. The reasoning for this approach is to identify potential solutions with the type of loss (airframe or personnel) they intend to prevent. Because the overall timeframe included in the study was so protracted (1962 to present), losses were subdivided into three categories: Combat Hostile Action—hostile fire involved; Combat Non-Hostile Action—hostile fire not involved; and Non-Combat—mishap outside of combat zone.

The study found that in OEF/OIF, for rotary-wing aircraft, the contemporary combat hostile action loss rate was six times better than SEA. Specifically, helicopter losses due to small arms fire was significantly less. However, Man Portable Air Defense Systems (MANPADS) and rocket propelled grenades (RPGs)/rockets account for 70 percent of rotary-wing combat hostile action losses. The study goes on to compare the hostile action and non-hostile action rates and indicates that both regimes are fertile areas for improving the survivability of rotary-wing aircraft. From a hostile fire perspective, the study found that rotary-wing aircraft are especially vulnerable to threats from MANPADS and RPGs. Therefore, to reduce combat hostile action losses the recommendation was made to increase investment in technologies that will improve situational awareness; detect and defeat guided and unguided threats; and enhance damage tolerance [19].

The premise of the argument that spawned the rotorcraft survivability study was that, compared to fixed-wing aircraft, rotorcraft survivability improvements were lagging. Therefore, to determine whether the premise was true or false, it was necessary to study fixed-wing losses from the same time. Because of this requirement, the survivability community at large considers the rotorcraft survivability study to be the most comprehensive single source of aircraft battle damage statistics to date, both fixed-wing and rotorcraft. Consequently, this thesis will rely heavily on the fixed-wing data presented in the "Study on Rotorcraft Survivability." Chapter 4 further discusses the details from the cited study, with regard to fixed-wing aircraft. The primary focus of the rotorcraft study, as the name implies, is improvements to rotorcraft survivability. Conversely, the focus of this thesis is improving fixed-wing aircraft survivability, which "spins" the point of view. This approach provides a fresh analytical perspective that is especially useful when dealing with a well-known database. Thus, the author is able to scrutinize and evaluate the data set with an open mind.

Evidence of this fresh perspective is the revolutionary approach of using typical maintenance databases, such as Reliability and Maintainability Maintenance Information System (REMIS), to validate the battle damage database. Air Force Technical Order (TO) 00-20-2, section 2-2.1 states that the purpose of REMIS is [to] accumulate data and provide information necessary to support the Air Force equipment maintenance program outlined in Air Force Instruction (AFI) 21-101. REMIS provides accurate, near-real-time data accessibility to all levels of management [20]. Information captured in REMIS includes aircraft MDS, serial number (i.e. tail number), work unit code (WUC), how malfunctions were identified (how malfunction code), and discrepancy narratives. Of particular importance is the so-called how malfunction code. Aircraft battle damage carries a how malfunction code of 731. Therefore, REMIS can be data mined for all actions associated with how malfunction code 731 and, theoretically, the returns should be maintenance actions resulting from an aircraft battle damage incident. Note that the primary purpose of REMIS is to identify maintenance man-hour and material usage data—not necessarily to track battle damage trends. To better understand the interconnectedness of REMIS with the maintenance and sustainment functions see Figure 3-1. Ultimately, REMIS is a repository of maintenance related information used by various agencies to maintain and improve aircraft availability. However, when used properly REMIS can provide information, which validates battle damage reports and provides quantifiable mission impacts.

The third database used to crosscheck trends from the rotorcraft study is the Combat Damage Incident Reporting System (CDIRS). SURVIAC is the arm of JASPO tasked with cataloguing,

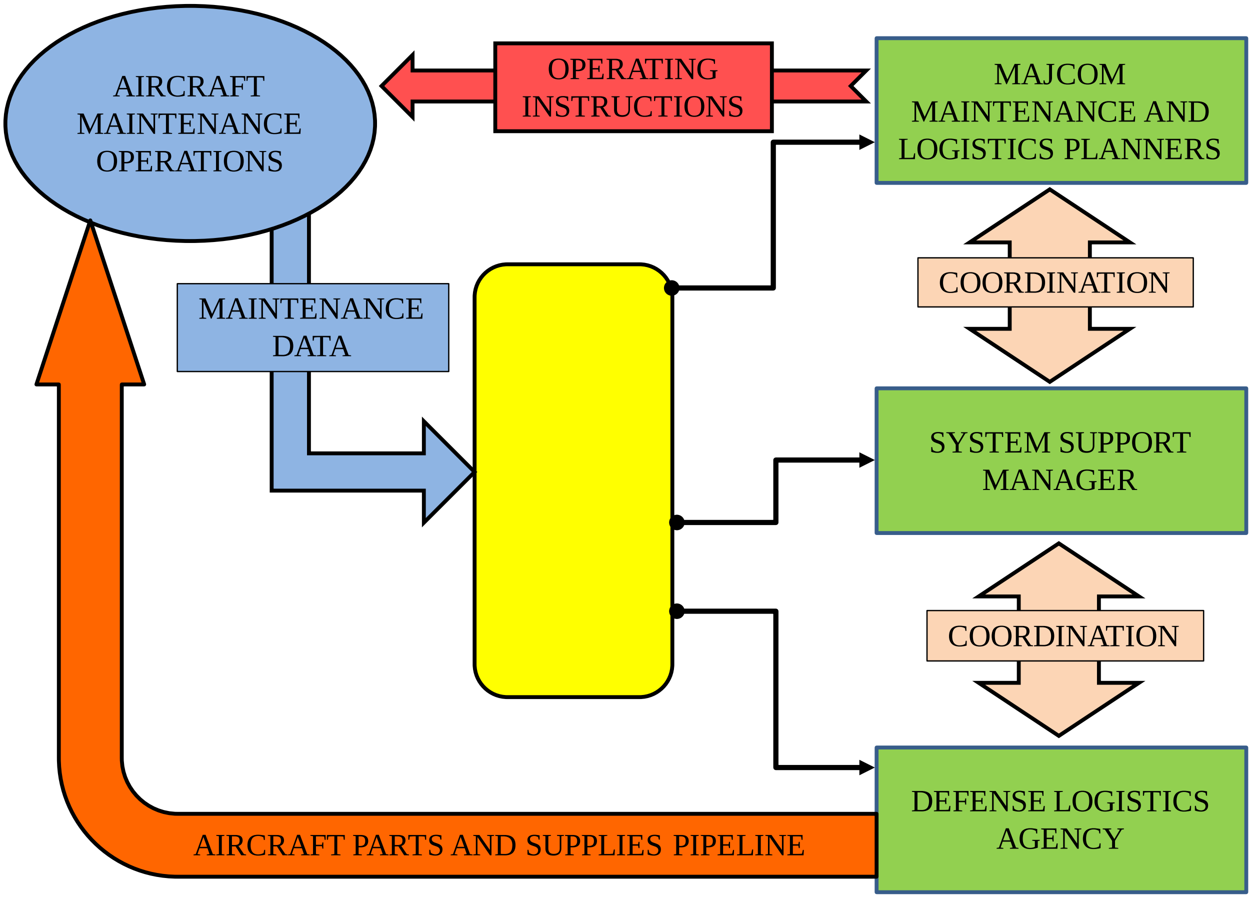


Figure 3-1: Aircraft Maintenance Data Flow

analyzing, and distributing battle damage information. Historically, operational USAF units captured the majority of battle damage information on Air Force Technical Order (AFTO) Form 97. Units then routed the paper AFTO 97 through the proper channels to SURVIAC located at Wright-Patterson Air Force Base, OH. Upon arrival, an analyst examined the document and captured pertinent information electronically. This process, though extremely important to the survivability community and still in use today, suffers from inefficiency. In June 2005, CDIRS was developed. Managed by SURVIAC, the Combat Damage Incident Reporting System (CDIRS) serves as a database for all combat damage incidents. CDIRS is a web-based interface designed to meet the needs of JCAT and ASDAT to distribute, store, edit, search, view, and discuss combat damage information within a centralized environment. Members of JCAT and the U.S. Army's Aircraft Shoot Down Assessment Team (ASDAT) input information gathered through on-site investigations of the actual battle damage. Information catalogued includes aircraft type, threat type, incident date, aircraft component damage, damage effects, etc. SURVIAC, in-turn, disseminates this information to tacticians and other users. After securing funds in the 2007 timeframe, SURVIAC upgraded CDIRS to allow a variety of aircraft survivability stakeholders to disseminate and analyze its data. The level of detail recorded about each incident is of high enough fidelity to warrant classification. Battle damage information prior to the implementation of CDIRS is not available through the web-based interface at this time. Fortunately, the personnel at SURVIAC have done yeoman's work ensuring the most comprehensive and useful database of battle damage is available to the survivability community. Because the scope of this analysis begins in 2001, CDIRS data is of limited value. However, if SURVIAC further institutionalizes its use, CDIRS will be an invaluable asset for the future of aircraft survivability.

3.2 Scope Refinement

Figure 3-2 shows the subdivision of rotary-wing and fixed-wing combat damage incidents from OEF and OIF. From this graphic, rotorcraft are an order of magnitude more likely to sustain combat damage than their fixed-wing counterparts working in the same area of responsibility. Therefore, further examination of rotorcraft survivability would seem to be in order. This fact is precisely why Congress commissioned IDA to perform the "Study of

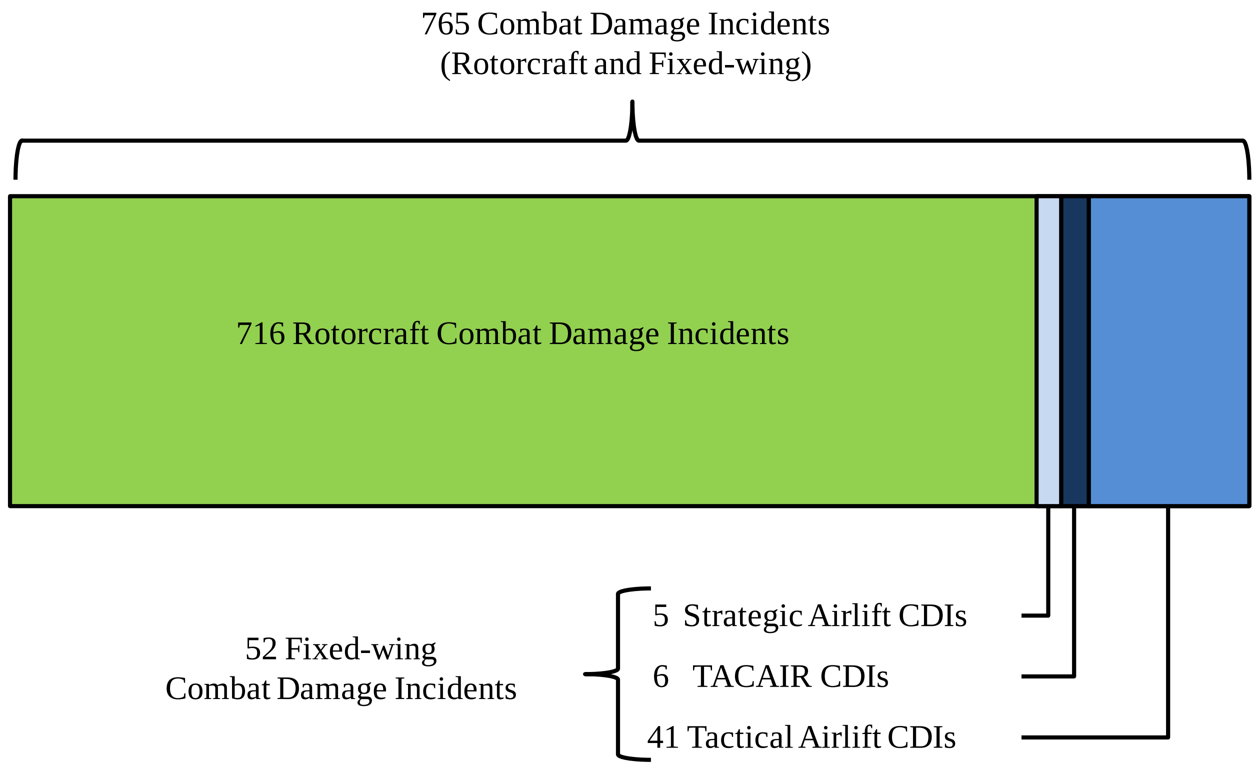


Figure 3-2: Aircraft Battle Damage Subdivisions

Rotorcraft Survivability" from which a significant portion of the data presented in this document is sourced. Since IDA conducted a thorough study of rotorcraft survivability, the author chose to explore fixed-wing survivability. The task is daunting. There are entire organizations whose sole purpose is the analysis of combat data, albeit with different goals. It was necessary; therefore, to refine the scope of this thesis into something more manageable within a finite timeframe. For this task, the author examines the rotorcraft study to identify potential areas on which to focus. Since the subject of this document is fixed-wing aircraft survivability, the initial step was to extract all relevant fixed-wing data. The resulting subset of information was broken into the following aircraft categories: Tactical fighter aircraft (TACAIR), Tactical Airlift, and Strategic Airlift. Figure 3-2 contains a graphic, which illustrates how the aircraft battle damage compilation was subdivided. For the purposes of this study, TACAIR is any aircraft that carries an F or A designator (e.g. F-16, A-10, etc.) Tactical airlift is any aircraft whose primary mission involves intra-theater airlift. Such aircraft tend to be multiengine turboprop powered cargo aircraft (e.g. C-23, C-130, etc.) Finally, strategic airlift is any aircraft whose primary function is global mobility (e.g. C-17, C-5, commercial airliners, etc.) For consistency, the definition of these categories closely resembles the definitions found in the rotorcraft study. The rotorcraft survivability study also includes damages and losses as a result of mishaps and indirect fire incidents. Mishaps are events, which result in a loss or damaged aircraft and are not a result of enemy fire. Indirect fire incidents are events where an aircraft is damaged or lost because of enemy fire while on the ground (e.g. during a mortar attack). This research does not present these two categories of damage. These categories are important. Indirect fire and mishap damage certainly affect a unit's ability to generate and sustain airpower. For this study; however, the goal is to produce recommendations that increase aircraft survivability during combat operations. Therefore, recommendations stemming from this research, which increases survivability during combat operations will likely have a positive outcome relative to these omitted categories.

IV. Results and Analysis

For clarification, combat hostile action damage and combat hostile action losses are incidents that occur as a direct result of hostile fire, while engaged in a prescribed mission. It bears repeating that mishaps and/or indirect fire damage is not included in these numbers. In this context, battle damage and combat damage incidents (CDIs) are synonymous. However, this is not always the case. The latter part of this section discusses, in detail, the definition of battle damage. The discussion intends to highlight the nuance between battle damage and combat damage.

The initial scope of the research presented in this document was broad. This was intentional due to the relatively small fixed-wing aircraft battle damage sample size. The hope was to present research that identifies a particular vulnerability and highlights potential material solutions. During the course of this research; however, the findings indicated something more dubious. There were inconsistencies in the research databases. As a result, the analysis focus evolved to include the following questions: how is aircraft battle damage reported in the USAF and where is the system broken? To begin answering this and other questions posed, this chapter presents aircraft battle damage data from OEF and OIF in two clusters. The first cluster is "aircraft-centric." In this cluster, the reader will find loss, damage, and casualty data associated with particular aircraft. The purpose is to identify trends, which may be isolated to an aircraft family or shared across all fixed-wing aircraft. The second cluster is "threat-centric." In this cluster, the same loss, damage, and casualty data presented in cluster one is associated with the threat that caused it. Keep in mind the data presented is a snapshot in time, (2002- 2010). These dates correspond to the dataset from SURVIAC (and to a lesser extent other sources), analyzed by IDA, and presented in the "Study of Rotorcraft Survivability."

4.1 "Aircraft-centric" Battle Damage Cluster

Figure 4-1 shows a breakout of all fixed-wing combat losses and damages reported for the period studied. As of October 2010, three fixed-wing aircraft were lost because of hostile fire in OEF and OIF. All three aircraft losses were TACAIR assets including: (1) A-10, (1) F-15, and (1) F/A-18 [19]. Losses account for approximately ten percent of all fixed-wing combat incidents, but due to the relatively small numbers involved, very little trend analysis is possible.

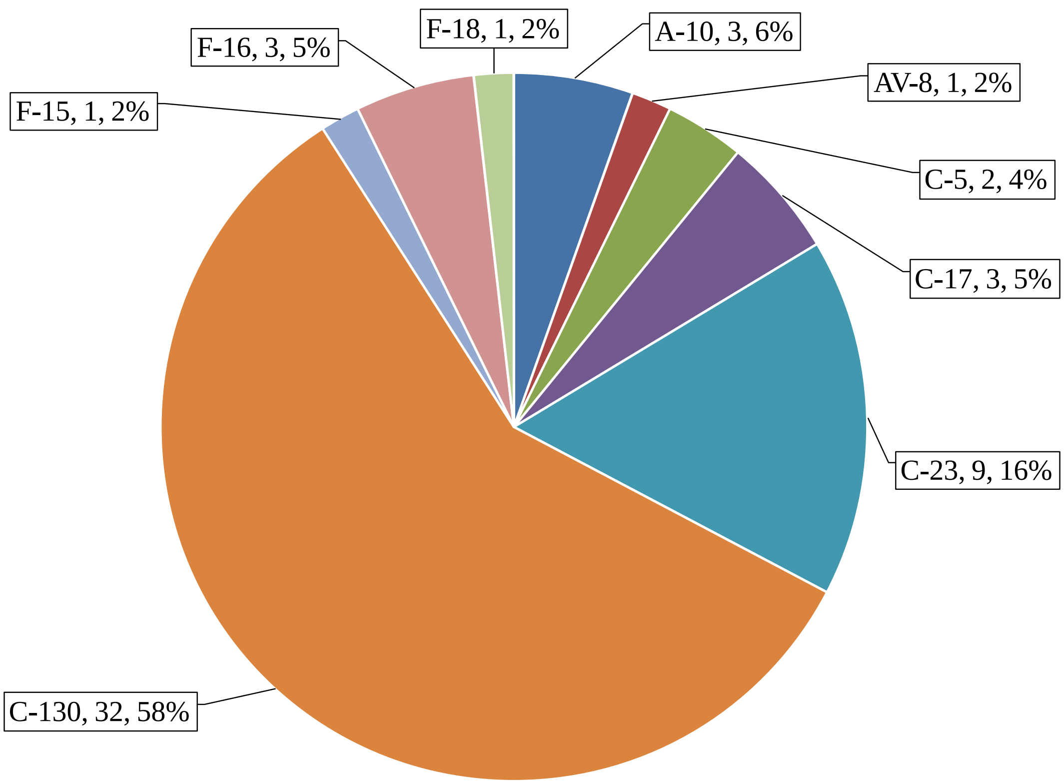


Figure 4-1: Aircraft Combat Loss and Damage Incidents, based on rotorcraft study data [19]

Therefore, to further refine the analysis this study removed the loss data. Figure 4-2 contains battle damage events with respect to the aircraft involved. Shown in this figure, in OEF and OIF combined, operators have reported fifty-two combat damage incidents (CDIs). Of these fifty-

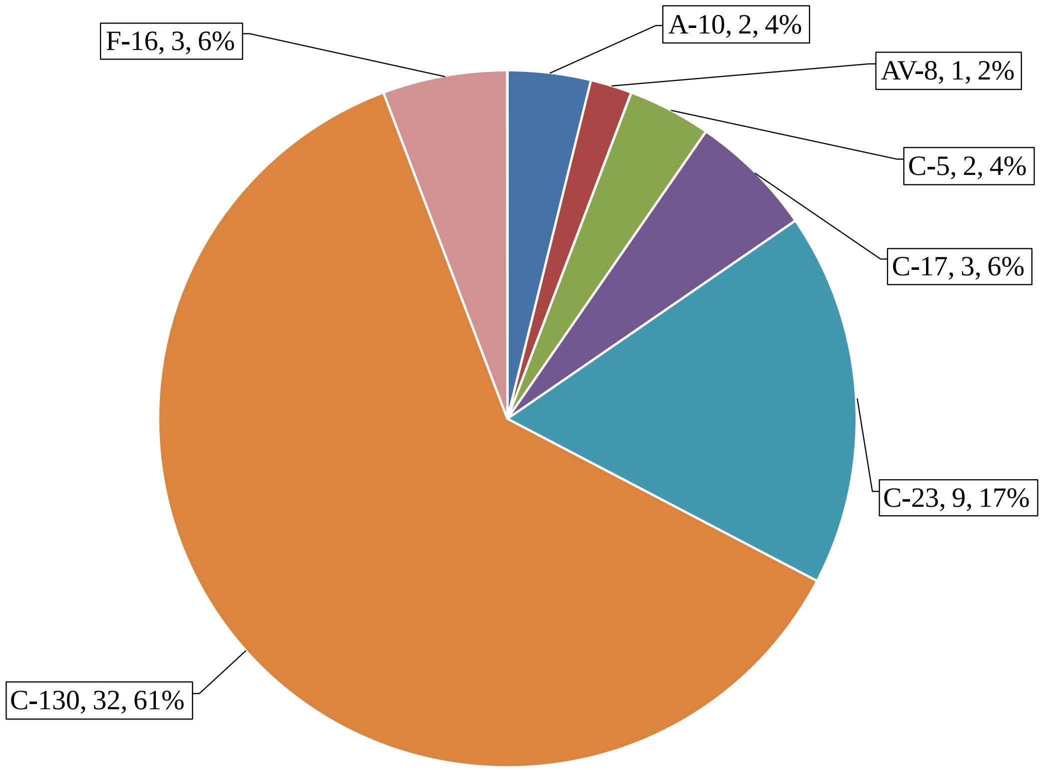


Figure 4-2: Aircraft Combat Damage Incidents only, based on rotorcraft study data [19]

two events, eight involved TACAIR assets, while the remaining forty-six events involved airlift assets. In terms of percentages, airlift CDIs represent eighty-eight percent of all CDIs reported. Furthermore, the family of aircraft with the highest concentration of damage events is the C-130 Hercules (and its variants). The rotorcraft study recorded thirty-two C-130 CDIs, which represents approximately sixty-one percent of all CDIs and fully seventy percent of airlift specific CDIs. The aircraft with the next highest concentration of CDIs is the C-23 Sherpa, which is also tactical airlift aircraft operated by the United States Army. CDIs reported for the C-23 account for seventeen percent of all damage events [19].

An important aspect of examining historical combat data is to determine the human impact of combat damage or loss occurrences. Figure 4-3 is a composite of all casualties incurred during a combat hostile action event (i.e. aircraft damage or loss.) The chart segregates casualties by the

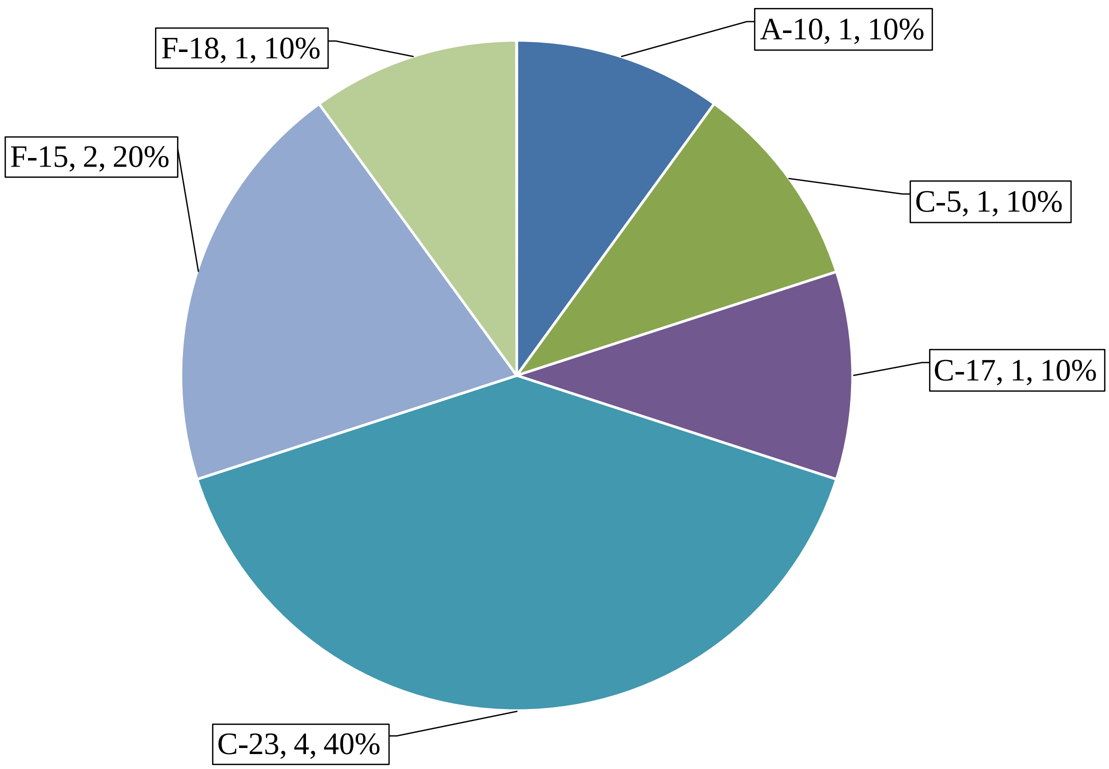


Figure 4-3: Casualties Associated with Combat Incidents, based on rotorcraft study data [19]

aircraft in which the person was flying at the time of the event. The F-15E is an all-weather strike fighter with a crew of two people. The USAF incurred two fatalities during the loss of a single F-15E Strike Eagle. Additionally, the pilot of a single-seat Navy F/A-18 Hornet was lost. Although the aircraft was lost, the pilot of a single-seat A-10 Thunderbolt II escaped from a crippled aircraft with injuries. In total, out of the three combat losses, three aircrew members died and one was injured. As illustrated by the A-10 example, injuries may be associated with aircraft losses. Injuries are also possible during damage only incidents. As of this writing, assessors have reported seven injuries associated with combat damage incidents. One injury, discussed previously, was associated with an aircraft loss, and six injuries have been associated with CDIs. The aircraft with the highest concentration of injuries is the C-23 with four. The C-17 Globemaster III and the C-5 Galaxy, both strategic airlift aircraft, each have one injury associated with their respective CDIs [19]. Again, the relatively small number of injuries prohibits meaningful trend analysis. However, from a survivability perspective, this is an excellent problem to have.

4.2 "Threat-centric" Battle Damage Cluster

Threat definition is a primary tenant of aircraft survivability. Thus, in order to protect man and material system engineers must first identify the most relevant threat. In the previous section aircraft battle damage data was presented from an aircraft perspective. This section, beginning with Figure 4-4, breaks down the same events illustrated in Figure 4-1 with respect to the threat that caused them. Of the fifty-five total fixed-wing combat damage incidents reported, seventy-three percent results from small arms or automatic weapons (SA/AWs). These [SA/AWs] by far represent the most common threat to fixed-wing aircraft affecting approximately forty aircraft.

The next largest threat categories are blast or explosion and infrared (IR) surface-to-air missiles (SAMs). These two categories each affected three aircraft, which represents approximately five percent of the total CDIs, respectively [19].

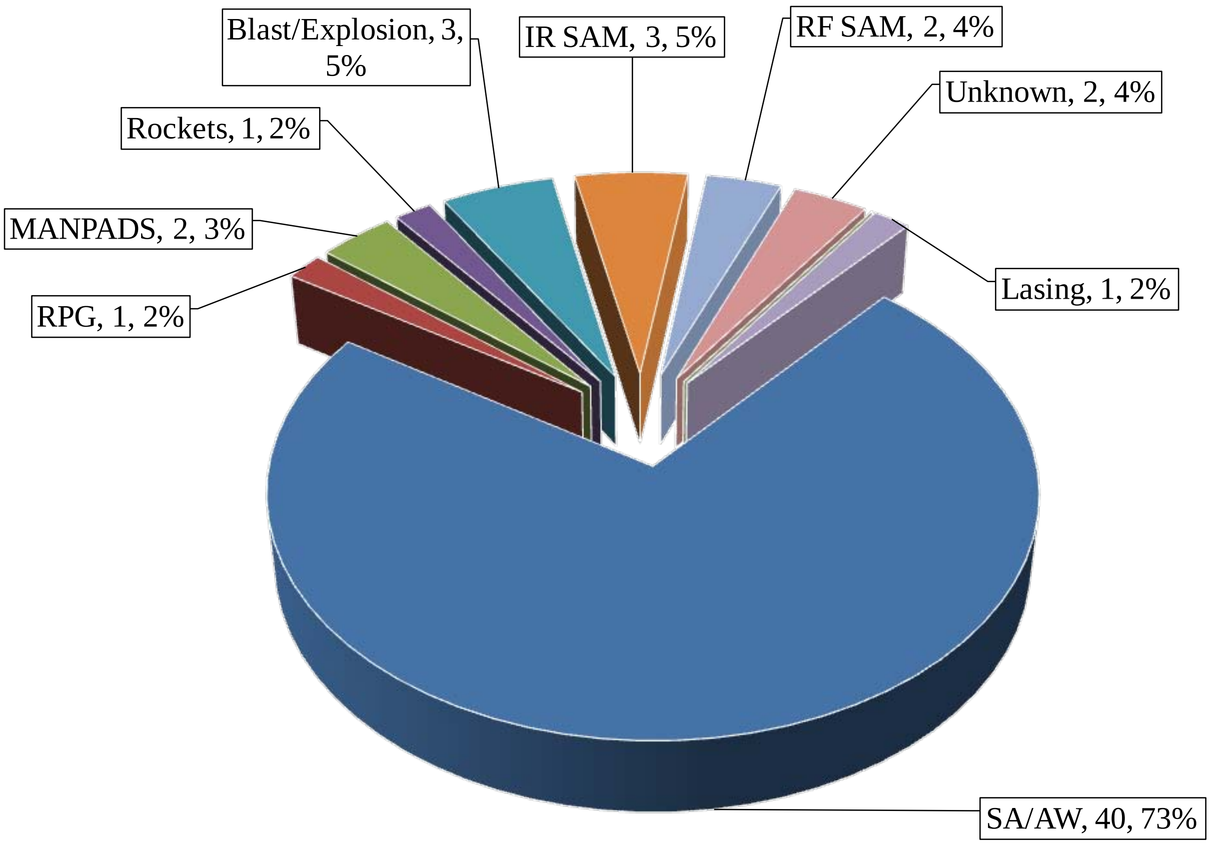


Figure 4-4: Loss and Damage Incidents by Threat Category, based on rotorcraft study data [19]

To clarify, blast or explosion is essentially a catchall category for damage because of improvised explosive devices, flak from a secondary explosions, etc. The way blast/explosion differs from indirect fire incidents (which are not included in this analysis) is blast damage occurs while in the process of accomplishing an intended mission. This figure is particularly interesting because it includes, among others, a threat to aircraft that most people are unaware even exists—the threat of counter-air IEDs. One of the more poignant findings from the rotorcraft study highlights the need for flexibility when dealing with an asymmetric threat. The study states:

> *Improvised Explosive Devices (IEDs) caught most unaware during OEF/OIF. Although they have been around since explosives have been invented, the enemy's innovative use of triggering devices and concealment has made this an effective weapon. Since we will never be able to predict all the innovative ways an enemy will be able to attack us, the best solution will be to have the capability to react quickly to new asymmetrical threats. This can be accomplished by maintaining a robust S&T community with the expertise to understand and quickly develop counters to threats as they appear. Just as importantly, we must maintain the ability to investigate and understand what is causing our rotorcraft combat losses and feed this information back to the acquisition community via the intelligence community and in-country assessment teams.* [19]

For consistency between the "threat-centric" data set and "aircraft-centric" data set presented earlier in this chapter, Figure 4-5 provides threat data associated with damage only events. SA/AWs are, by far, the most prevalent threat and account for seventy-seven percent of all damage only incidents. The remaining twenty-three percent of the total damage incidents were inflicted by the following threat categories: (1) RPG, (2) MANPADS, (2) SAMs, (2) unknown threats, (3) Blast/Explosion, (1) rocket, and (1) lasing [19]. Note that the data set utilized from the "Study on Rotorcraft Survivability" breaks individual CDIs down by aircraft system damaged during the reported event. In the lasing incident, an aircrew member suffered eye damage. In the context of the study, aircrews are aircraft systems. Therefore, a laser eye injury suffered by an aircrew member is a CDI. Also, note there are two CDIs for which there was not enough forensic evidence for the assessor to precisely identify the threat. Together, these two

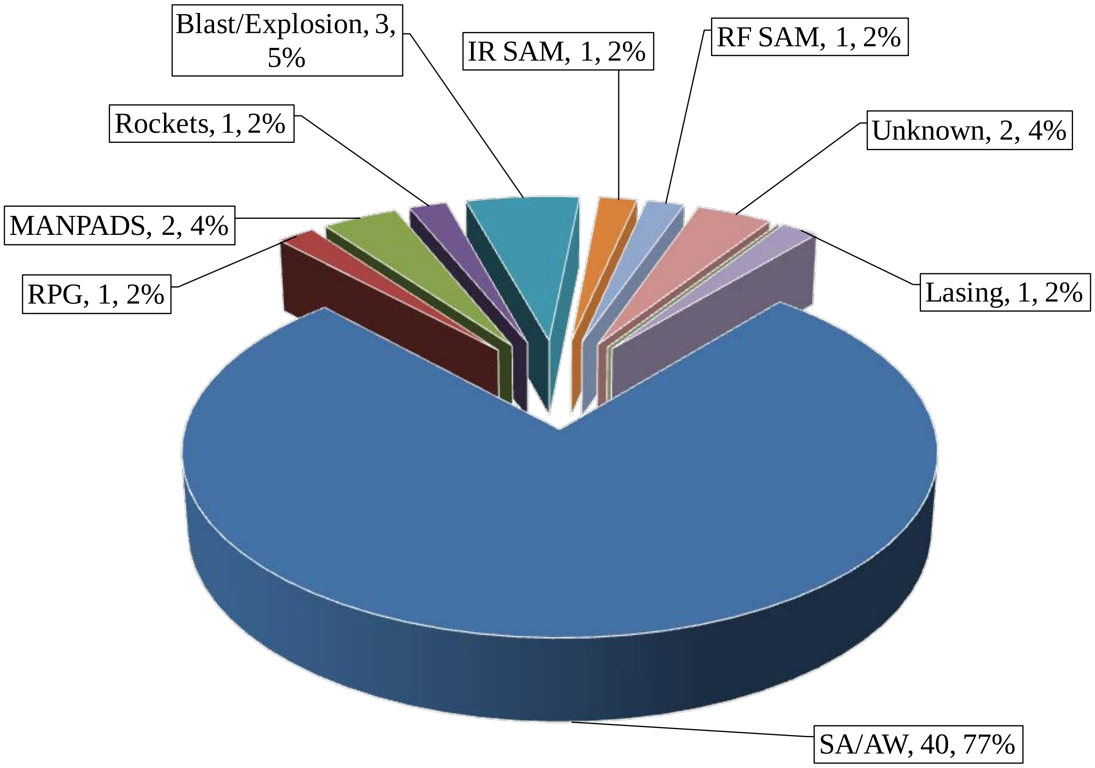


Figure 4-5: Damage Only Incidents by Threat Category, based on rotorcraft study data [19]

categories are relevant because the fixed-wing damage sample size is relatively small. Thus, inclusion or exclusion of these data points can skew the conclusions that may be drawn. In the interest of full disclosure, the author feels compelled to leave these data points in the data set and to let the readers draw their own conclusions about their relevance. Interestingly, the relatively small number of aircraft losses has virtually no effect on the threat environment definition. An observer can see this by comparing Figure 4-4 with Figure 4-5. Both figures present the same information except the latter does not include combat losses. In either case, SA/AWs remain the most prolific threat.

Continuing with the format set forth at the beginning of this chapter, Figure 4-6 illustrates casualties and their associated threat category. Similar to the aircraft-centric data (Figure 4-3), the threat-centric data (Figure 4-6) does not identify glaring trends with respect to casualties alone.

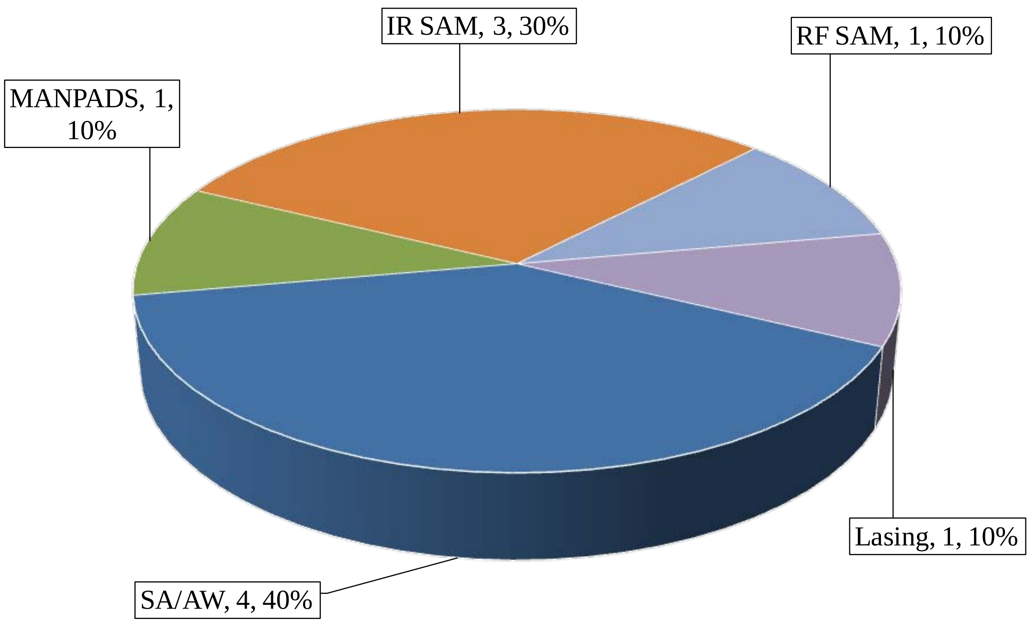


Figure 4-6: Casualties by Threat Category, based on rotorcraft study data [19]

4.3 Interim Data Summary

At this point, a minor digression is required. Unwittingly, with regard to the three incidents of blast damage from Figure 4-5, further investigation revealed another dimension to the combat damage reporting dynamic—mishaps reported as combat damage incidents. All three cases of blast damage involved F-16CJs in OIF. On three separate occasions ammunition from each of the F-16CJs’ 20mm cannon exploded next to the aircraft while strafing during close-air support missions. Further investigation determined the cause to be corroded ordinance [19]. Therefore, to remain consistent with the definitions outlined in the rotorcraft study from which this data was taken and the premise that only combat hostile action data will be presented, these three incidents of blast damage are removed. Figures 4-7 and 4-8 contain the corrected data with the blast events removed. The corrected aircraft-centric combat damage with the mishap blasts removed is in Figure 4-7. Similarly, Figure 4-8 contains the corrected threat-centric data. Compared to the information originally presented (Figure 4-2 and Figure 4-5) it can be seen that the impact of removing blast (F-16) damage had little effect on the overall trends.

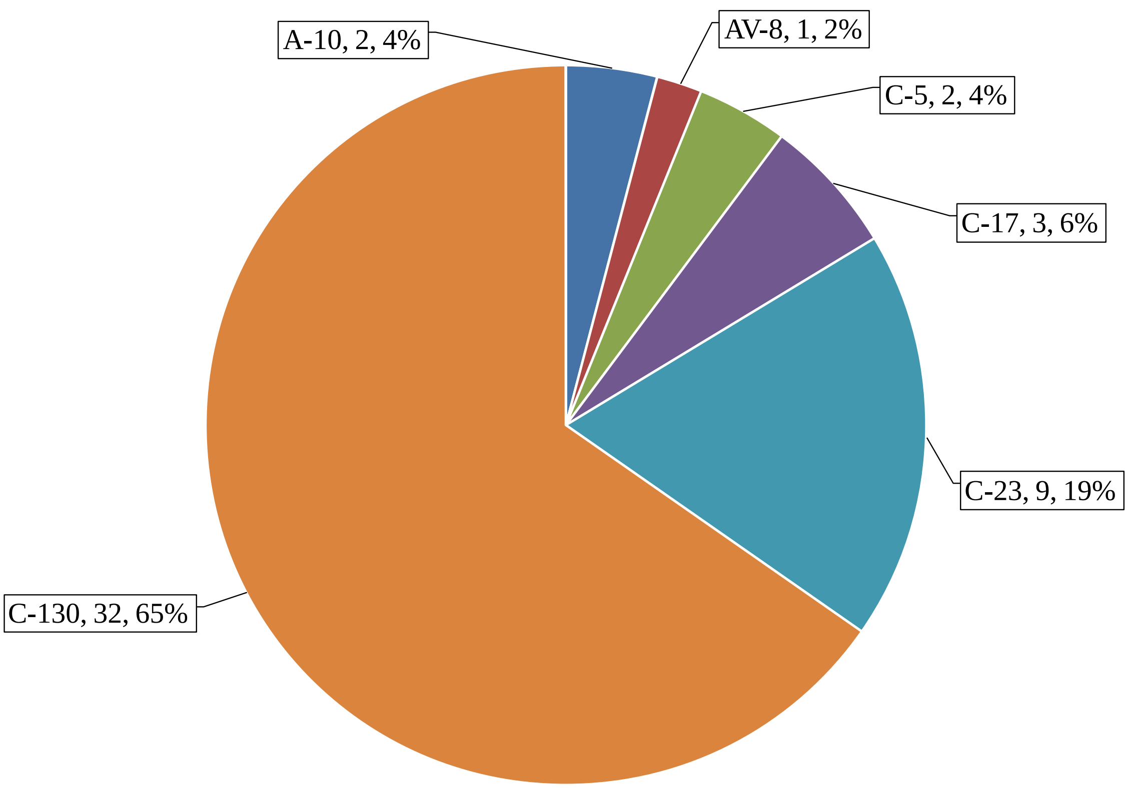


Figure 4-7: Aircraft Combat Damage Incidents (corrected)

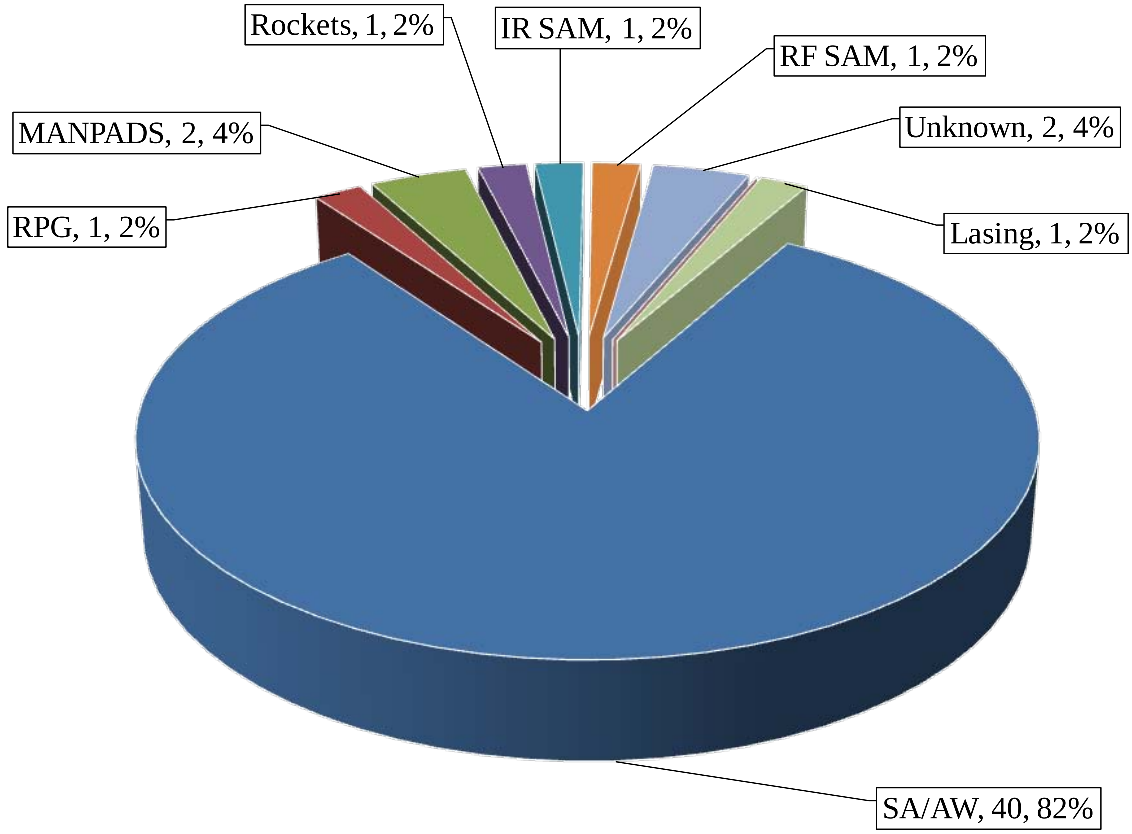


Figure 4-8: Damage Only Incidents, by Threat Category (corrected)

The following is a brief summary of the battle damage data presented to this point. All three aircraft losses and two damages out of the fifty-five total events have been attributed to SAMs. SAMs also account for 100% of all fixed-wing aircraft fatalities in OEF and OIF. Without question, SAMs represent the most lethal threat to fixed wing aircraft to date in OEF/OIF. While SAMs are the most lethal threat, SA/AWs are by far the most commonly encountered. In the data from this chapter, a second fact is also readily apparent. Tactical airlift aircraft are the most likely aircraft to sustain combat damage. Currently, there are only two fixed-wing, tactical airlift families of aircraft reported to have sustained combat damage. They are the C-130 Hercules and the C-23 Sherpa. Figure 4-9 shows the distribution of threat types associated with CDIs against tactical airlift assets. Analysis shows that of the forty tactical airlift aircraft CDIs reported, assessors attribute ninety-two percent to SA/AWs. Moreover, if the five percent of CDIs attributed to an "unknown" threat—which is strongly suspected to be SA/AWs—is added, SA/AWs account for ninety-five percent of all tactical airlift CDIs.

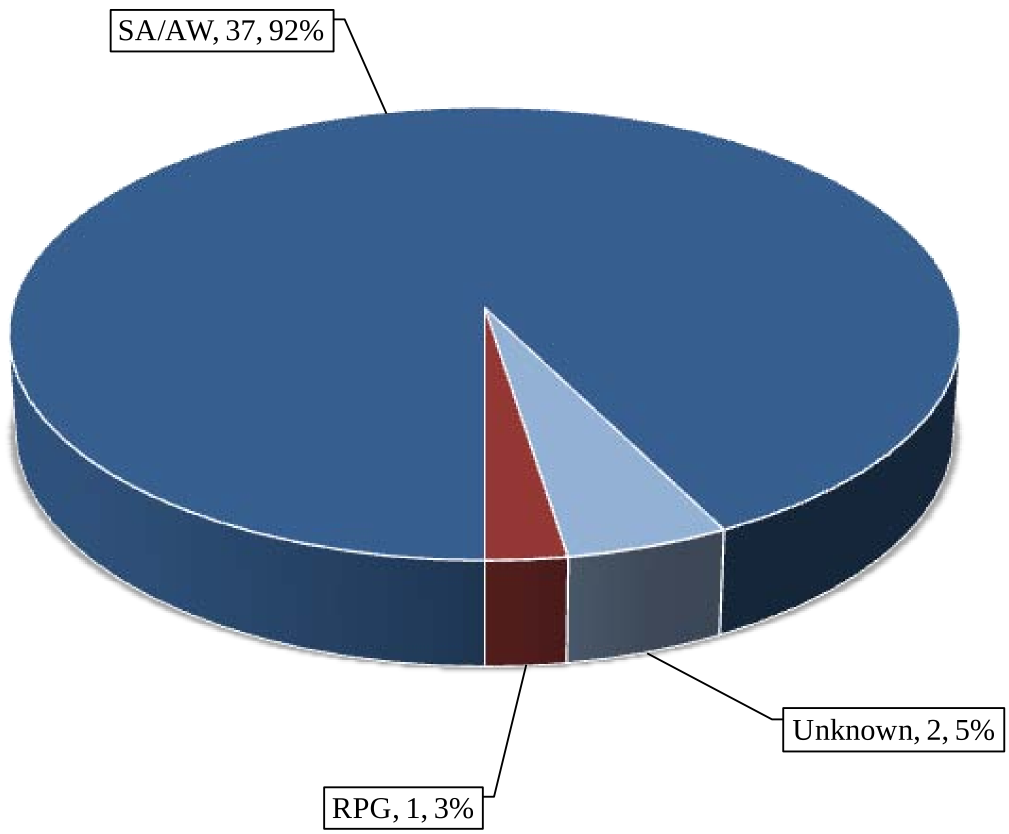


Figure 4-9: Tactical Airlift Combat Damage Incidents by Threat Category

4.4 Data Verification

In the previous section, why present the uncorrected data at all? There are two primary reasons for this approach. One, the F-16CJ blast damage example highlights the struggle to gather data, which can be trusted to portray an accurate description of the threat environment. Two, it also provides justification to scrutinize the dataset further. As mentioned previously, the survivability community considers the rotorcraft survivability study to be the most comprehensive report of aircraft battle damage information *reported* to SURVIAC. This fact is without question. However, what if operational units are not reporting all combat damage incidents? Unreported damage could potentially skew the threat picture and mask trends in such a relatively small data set. In turn, leaders at all levels may be unaware of the true risk to man and materiel. In theater, commanders may make operational decisions using false assumptions. Meanwhile, material leaders may focus resources on efforts to counter what may not be the prevailing threat. Therefore, it is imperative to validate the data presented to SURVIAC and reported in the rotorcraft study.

Since the single highest CDI rate involves the C-130, the effort to validate the combat data begins there. The C-130 sustainment program office provided a report of aircraft battle damage incidents recorded in REMIS under "How Malfunction" code 731. The REMIS report contains over 200 separate entries associated with 96 aircraft. To be clear, this is not to say that there were over 200 CDIs. Detailed examination determined the majority of the REMIS entries were not related to combat damage. For example, there were entries for benign maintenance issues such as static in communications equipment or typical tire wear. Therefore, the author conducted analysis on the REMIS report entries to separate definitive combat damage from typical maintenance actions. The analysis segregated entries, for example, which contain in their narrative verbiage such as "…aircraft has battle damage…" or "…bullet hole…" from entries that were more ambiguous. Once separated, the author crosschecked the aircraft from the REMIS report identified to have definitive battle damage with the database from SURVIAC associated with the "Study of Rotorcraft Survivability." Interestingly, the REMIS database did not capture several aircraft identified with battle damage in the rotorcraft study database. This is not surprising considering the intent of REMIS is not to capture battle damage statistics. However, the intent of the SURVIAC database used in the rotorcraft study *is* to capture such statistics. Therefore, it is extremely interesting that ten legitimate reports of C-130 battle damage captured in REMIS were unaccounted for in the rotorcraft study data from the same timeframe. These ten examples confirm the suspicion that combat damage incidents were going unreported to SURVIAC.

4.5 Discrepancy Analysis

Knowing that CDIs are going unreported, the obvious question that arises is, how and why are units failing to report such important data? In order to begin answering this question, it is important to understand the process by which the users populate the databases involved. SURVIAC receives reports from JCAT, CLSS, and operational units. On the other hand, only aircraft maintenance/sustainment organizations populate REMIS. When deployed, the USAF typically assigns CLSS to a supporting maintenance group. Imbedded with day-to-day operations, CLSS is available to assess CDIs, make repairs, and report incidents accordingly. However, the overall AEF force structure of OEF and OIF did not incorporate CLSS teams. Their contribution to the war effort is mainly in response to requests for depot-level repair actions or manning assistance—essentially acting as a depot field team. Compounding this issue, in OEF and OIF JCAT was not part of the original AEF package and did not arrive in force until well after hostilities had begun. JCAT did not have a continuous presence in OIF until March 2004, roughly one year after the initial invasion. Similarly, JCAT did not arrive in OEF until October 2008, several years after the beginning of the war [38]. This fact opened the door for missed data. Because CLSS and JCAT (early on) were not in country, the responsibility to report CDIs to SURVIAC fell onto maintainers at the unit level.

In summary, the battle damage dataset is small and has some deficiencies, which needs to be reconciled. Therefore, in order to explain the discrepancy between the incidents of C-130 battle damage reported in REMIS and those reported in the "Study of Rotorcraft Survivability," the author examined the manner in which each database is populated. CLSS and JCAT were not integral to the overall AEF package in OEF and OIF from their inception. Thus, the responsibility to report battle damage fell upon maintenance units. Consequently, as the evidence has shown, maintenance organizations recorded some CDIs in REMIS as aircraft battle damage but did not report them to SURVIAC. This explains why IDA did not include these events in the rotorcraft study.

4.6 Maintenance Records and Requirements

The existence of the discrepancies would indicate, at first glance, that maintenance organizations are derelict in their duty. However, further examination of the technical orders (TO), which govern maintenance action documentation, highlights some shortcomings that may explain, at least to some extent, why some discrepancies exist. To begin, Air Force Instruction (AFI) 21-101, AIRCRAFT AND EQUIPMENT MAINTENANCE MANAGEMENT, establishes the requirement for the USAF ABDR program [37]. Additionally, AFI 21-101 lays the groundwork for reporting aircraft battle damage. Organizationally, the aircrew and maintenance debrief section falls under the purview of the aircraft maintenance squadron (AMXS). Refer to Figure 4-10 to better understand the construct of a typical Maintenance Group. The aircrew and maintenance debrief section, as the name would imply, is responsible for debriefing the aircrew following mission completion. If, during debriefing, the aircrew reports the possibility of battle damage, the aircraft is assigned landing status code five (Code 5) in the aircraft's AFTO FORM 781. If the aircrew does not report battle damage during debrief, it may be found during routine

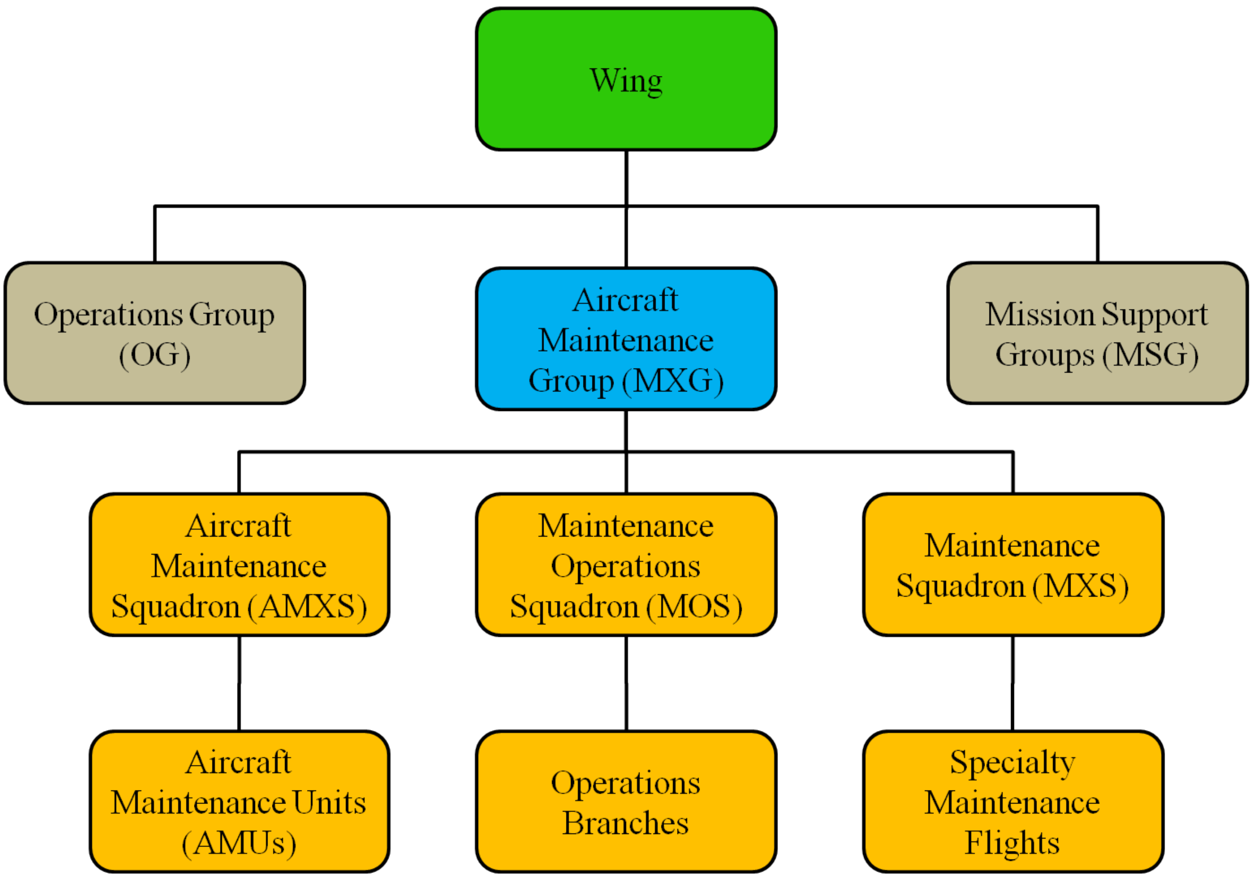


Figure 4-10: Notional Maintenance Group Organization

inspections. Typically, most maintenance discrepancies would spawn an AFTO FORM 781A, MAINTENANCE DISCREPANCY AND WORK DOCUMENT. However, in accordance with TO 00-20-1, AEROSPACE EQUIPMENT MAINTENANCE INSPECTION DOCUMENTATION, POLICIES, AND PROCEDURES, Section 5.9.1, battle damage discrepancies, "…will not be documented on the 781A. TO 1-1H-39, GENERAL AIRCRAFT BATTLE DAMAGE REPAIR (ABDR) technical manual contains specific instructions on documenting aerospace vehicle battle damage repairs [21]." In theory, TO 00-20-1, Section 5.9.1 would prompt the maintenance organization to seek out TO 1-1H-39 for further instruction. In practice, maintenance personnel follow routines or established procedures designed to meet the intent of TO 00-20-1. Such routines would typically cause personnel assigned to maintenance organizations to consult TO 00-20-2, MAINTENANCE DATA DOCUMENTATION, for specific guidance on reporting maintenance actions. However, the only reference to battle damage in TO 00-20-2 is with respect to the so-called "How Malfunction" code [20]. There is no mention of TO 1-1H-39. Compounding this issue is the fact, until recently; the use of -39 series (ABDR) TOs was largely isolated to the CLSS. Consequently, CLSS personnel are well versed in battle damage reporting procedures. Maintainers outside of CLSS, however, virtually never reference -39 series TOs. Thus, when battle damage is encountered maintenance personnel are ill prepared for the unique documentation requirements.

Clearly, assessors are reporting battle damage as confirmed by its existence in the SURVIAC database, corroborated in REMIS, and vice versa. In REMIS, a technician applies a single How Malfunction code to all maintenance actions performed at a given time. For example, if a bullet hole repair was performed at the same time as some other routine maintenance, the routine maintenance action would also receive How Malfunction code 731 (battle damage). This is completely in line with TO 00-20-2 and explains the large number of non-combat related entries under this code. Continuing with this hypothetical scenario, assume that the technician consults TO 00-20-1 and follows the guidance to refer to TO 1-1H-39. There the technician will find the definition of battle damage and its documentation process. The definition is as follows:

> *"Battle damage is defined as any damage and/or malfunction, typically caused by munitions or their effects whether self-inflicted or resulting from enemy or friendly fire or by ground mishap, encountered during combat operations* [21]*."*

It is important to note this is the only definition of battle damage found while conducting research for this thesis. The intent of this definition is to provide flexibility to commanders by authorizing the use of ABDR techniques for a wide range of issues, which may arise during combat—not simply to repair damage incurred by hostile fire. More simply, readers may interpret this definition of battle damage as essentially any damage encountered during combat operations. For example, if an aircraft strikes a piece of aerospace ground equipment while taxiing for a combat mission, by definition the result of this mishap is battle damage. From the perspective of a survivability analyst, the very broad definition of battle damage becomes confusing, especially when little or no detail is available about a reported event. To be clear, all of the CDIs reported in the rotorcraft study easily conform to the USAF definition of battle damage. However, as illustrated previously by the categorization of the F-16CJ blast damages as CDIs, an analyst looking to make aircraft more survivable in a hostile environment would have to be particularly diligent when making recommendations based on a given data set. The rotorcraft study addresses this factor by further defining combat damage incidents in the following manner: Combat Hostile Action—hostile fire involved; Combat Non-Hostile Action—hostile fire not involved; and Non-Combat—mishap outside of combat zone. These definitions, in conjunction with the premise this document does not report mishaps, support the argument to omit the three blast CDIs.

4.7 Field-level Repair Options

The previous section discusses the documentation requirements for maintenance actions. It also discusses areas with shortcomings that explain how and why battle damage may go unreported (to SURVIAC). Nevertheless, there are other reasons that may explain why the unreported incidents of battle damage identified in this document have gone unreported. One reason centers on the repair options available to field-level maintenance organizations.

When maintenance personnel identify aircraft damage or malfunctions, regardless of cause, they begin the process of determining what corrective actions are required to return the aircraft to operational status. Figure 4-11 illustrates the notional damage resolution flow that a technician may follow. In this example, a technician examines the issue and references a myriad of repair manuals known as technical orders (TOs). Virtually every weapon system operated by the USAF has TOs governing standard repair and maintenance. Within these TOs, guidelines can be found which tell a technician important details such as how much damage is acceptable without performing a repair, maximum repairable damage for a system, standardized repairs, etc. Once the technician assesses the damage or malfunction and identifies the applicable repair, he/she executes the corrective action.

To fully understand this process, consider the following scenario. During a routine inspection, a technician finds a half-inch diameter hole in a wing trailing edge panel. The technician notes the flaw in the aircraft forms and proceeds to coordinate with the necessary specialists to further assess the hole. The specialists take detailed measurements of the hole and

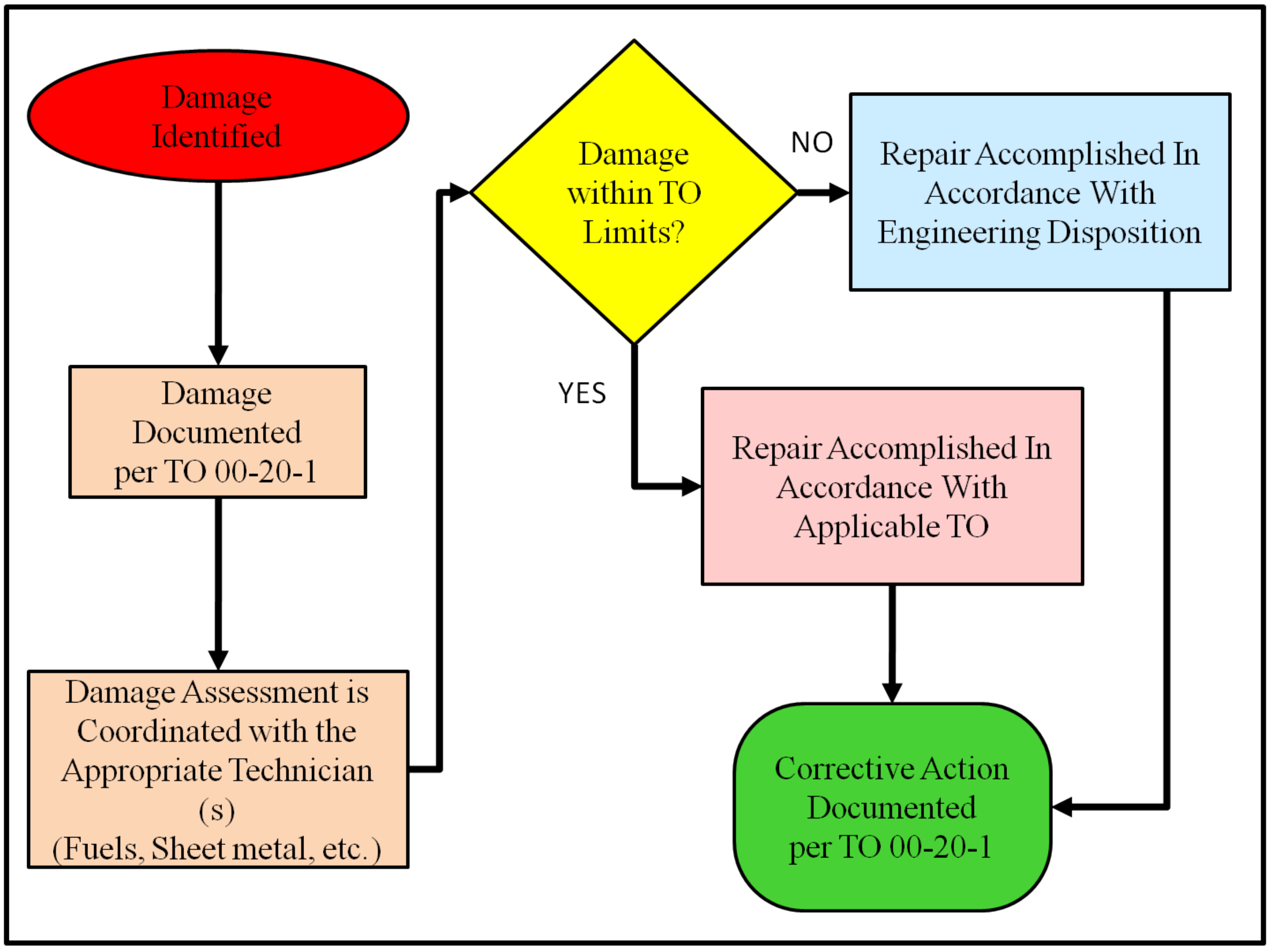


Figure 4-11: Notional Damage Resolution Flow

identify its exact location. The specialists then consult the appropriate repair manual for the damaged component. The author assumes, in this hypothetical scenario, in the repair manual holes up to one inch in diameter are repairable by applying a simple sheet metal patch. After installation of the specified patch, a technician updates the aircraft maintenance records and returns the aircraft to service. Revisiting this scenario, assume small arms fire caused the same half-inch diameter hole. Because the repair is within the limitations of the repair manual, a technician may follow the exact same process as illustrated in the previous scenario, including final documentation. This is because there is nothing in the standard repair manual to instruct a technician that battle damage has additional reporting requirements. At no time during this process was the technician obligated to search for guidance from the -39 series (ABDR) TOs. Therefore, it is possible that in this hypothetical scenario the maintenance organization would not report the small arms (battle) damage to SURVIAC.

An important underlying assumption is in the scenarios presented. These scenarios imply that a weapon system specific ABDR manual exists. Figure 4-12 shows the damaged vertical

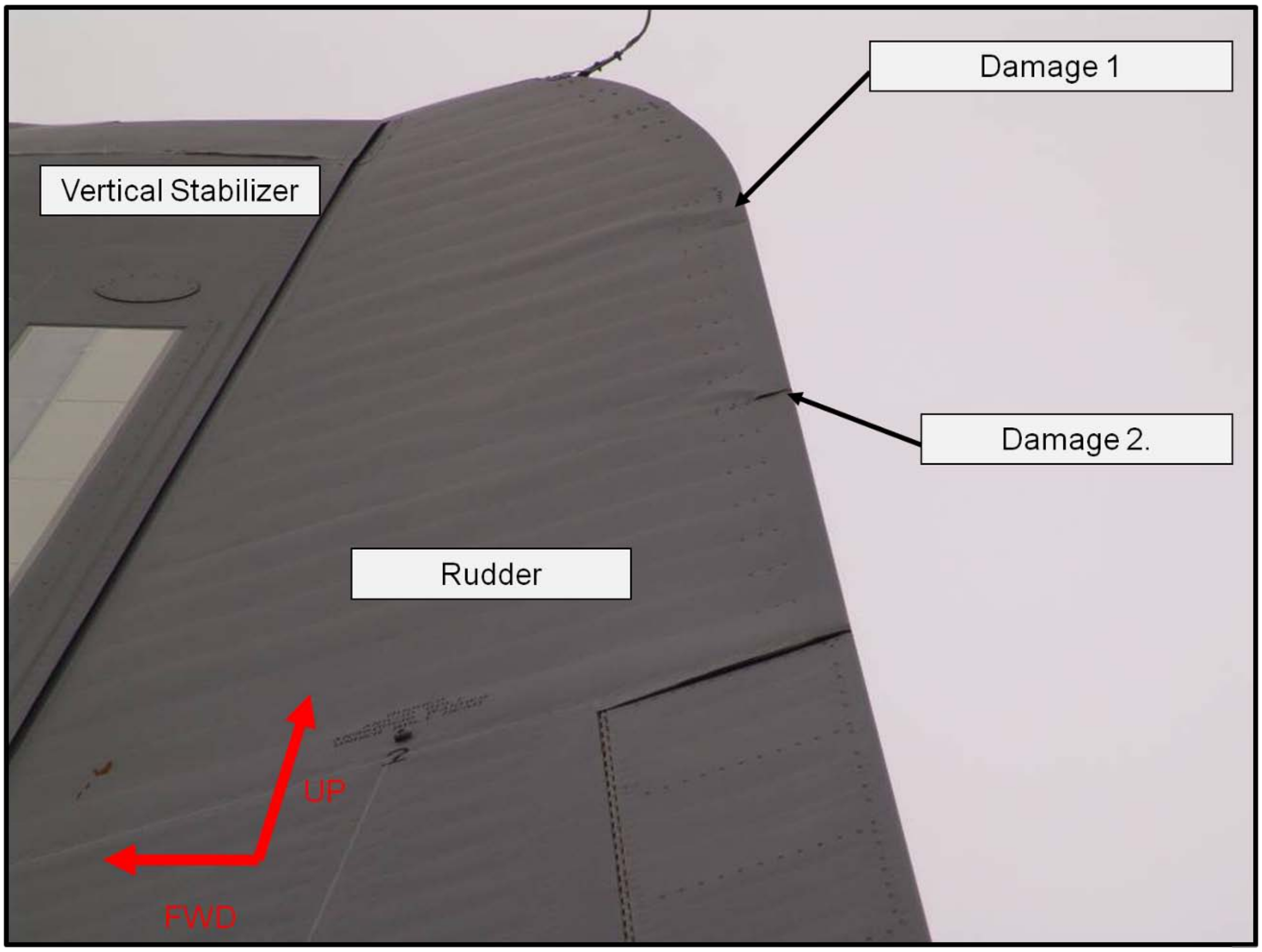


Figure 4-12: C-130J Vertical Stabilizer and Rudder Battle Damage, image courtesy of USAF C-130 Program Office [40]

stabilizer and rudder of a C-130J located at a deployed location. The standard structural repair manual has repairs that are applicable to this data. However, to accomplish the standard repair the rudder would likely need to be removed, disassembled (to some extent), and potentially rebalanced before being reinstalled. Assuming the tools and materials are on hand at the time of the repair, this process would likely take twenty-four hours or more. Instead of attempting the standard repair, the maintenance unit decided to request technical assistance from the responsible engineering authority. Analysis of the damage and the resulting engineering disposition required three days. If an applicable C-130J ABDR TO is available and maintenance leadership so inclined, the damage can be temporarily repaired and the aircraft can return to service in a few hours. The C-130J does not have an applicable ABDR TO. This omission is a critical suitability issue that the USAF must address.

When aircraft damage or malfunctions exceed the limitations stipulated in applicable TOs, maintenance organizations must request technical assistance from the responsible engineering authority for the subject weapon system (or sub-system). In the USAF, TO 00-25-107, MAINTENANCE ASSISTANCE governs the process for most technical assistance requests (TARs) [22]. During this process, engineers or equipment specialists evaluate the problem, formulate the necessary solution, and then communicate this information to the field-level maintenance personnel. Assume, for example, the hypothetical trailing edge panel hole discussed earlier in this section measured one inch in diameter. An identical process would be followed—identify the problem, consult specialists, determine TO limitations, execute repair. Except, in this case, a one inch diameter hole exceeds the repair limits of the TO. Therefore, a TAR would be required to determine the necessary repair. At this time in the scenario, maintenance personnel would submit the request as outlined in TO 00-25-107 [22].

Following the process flow shown in Figure 4-13, a weapon system manager (SM) point of contact (POC) assigns the TAR to an engineer and he/she formulates a solution. At this time, it is important to understand the dynamics of a typical engineering division within an aircraft sustainment program office. The engineers that staff the engineering division of an aircraft program office are generally a mixture of DoD civilians, contractors, and active duty military. The USAF trains a percentage of military engineers within the engineering division, with the possible exception of avionics/electrical engineers, as aircraft battle damage repair engineers

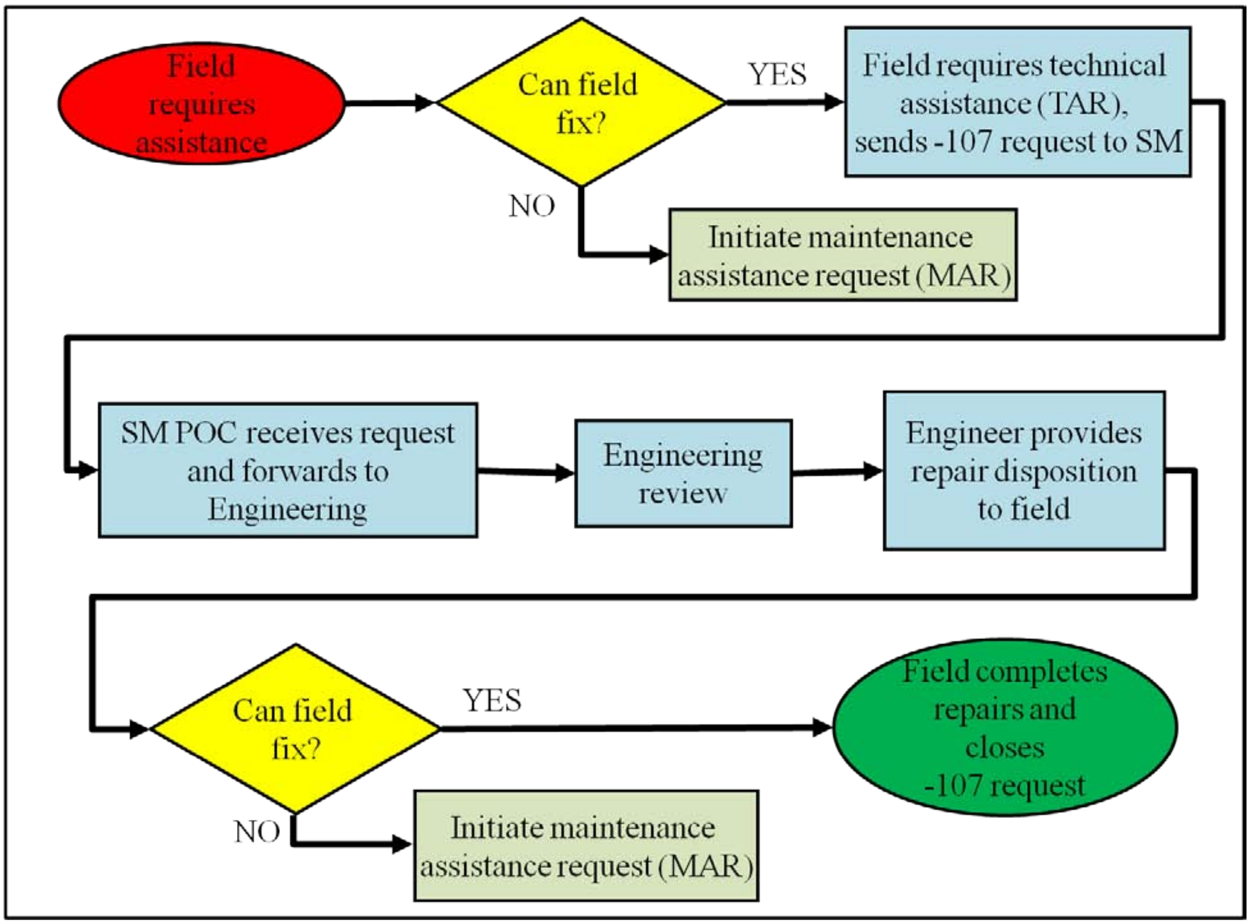


Figure 4-13: Technical Assistance Request (TAR) Flowchart

(ABDREs). The ABDRE curriculum includes many of the same classes required by CLSS. Thus, ABDREs are intimately familiar with the special requirements for reporting combat damage. The USAF also extends this training to civilian engineers in some cases; however, military engineers constitute the bulk of the ABDRE corps. In this hypothetical scenario, the SM POC may or may not assign the TAR addressing the one-inch diameter hole may to an engineer with ABDR training. If in the body of the TAR, the originator identifies the damage as battle damage and the engineer analyzing the damage is familiar with ABDR reporting, the repair disposition may include guidance on how to properly document the damage in accordance with TO 1-1H-39, however, there is no guarantee. If the originator does not identify the damage as battle damage or the engineer providing the repair disposition is not ABDR trained, it is highly unlikely that the engineer will provide documentation guidance.

In both the non-standard repair process and standardized repair process scenarios outlined above, maintenance personnel are at no time compelled to seek out TO 1-1H-39. Consequently, when the time comes to document the corrective actions executed to repair battle damage, if the technician does not follow the single line on the subject from TO 00-20-1, SURVIAC will not be notified. This crucial historical data will be lost.

These scenarios are not hypothetical. For example, C-130, tail number 82-00059 arrived at depot with a previously unreported lower wing surface repair. Depot engineers removed the repair and discovered an underlying hole suspected to be battle damage. No battle damage record was located for this action [39]. More definitively is the case of C-130, tail number 02-08155. On or around 16 April 2008 an aircraft sustained damage from "multiple low order weapon detonations" for an aircraft deployed in support of OIF, OEF, and Combined Joint Task Force Horn of Africa. Nowhere in the repair disposition is there mention of a requirement to report this incident to SURVIAC and, as a result, went unreported despite the fact that, in accordance with TO 1-1H-39, the damage clearly falls under the definition of battle damage. Another example of damage not being report due to the limitations of the governing policies involves C-130, tail number 90-00164. This aircraft received battle damage that technicians repaired in accordance with the C-130 ABDR manual at the direction of the responsible engineering authority. Nowhere in the repair disposition (Figure 4-14) or the C-130 ABDR repair manual is there a requirement to report the incident to SURVIAC [42]. Consequently, this incident is not in the SURVIAC database at the time of this writing.

To be clear, the purpose of this example is not to demonize the program office staff or the maintenance unit. There are many instances where the responsible engineering authority instructs maintenance personnel to report battle damage to SURVIAC. The purpose of this example is to illustrate that problems exist with the current reporting guidelines. Figure 4-15 shows an example of an engineering disposition including instruction to report the battle damage to SURVIAC via an AFTO Form 97. In this case, technicians used the standard repair manual to repair battle damage, which the crew believed small arms caused.

Ultimately, technicians can go about repairing damage, including battle damage, in three distinct ways. They can install a repair with guidance from a standard repair manual for the damaged system. They can request special repair instructions from the responsible engineering authority. Or, if circumstances allow, they can install temporary aircraft battle damage repairs (ABDR) with guidance from an applicable ABDR manual. Of these repair options, the general ABDR technical order is the only manual that mentions unique battle damage reporting instructions.

PART 1: REQUEST

GENERAL INFORMATION

[redacted]	DATE OF REQUEST 23 Jul 2007 1121	TYPE OF REQUEST C-130 TAR	SERIAL/TAIL NUMBER 9000164
CURRENT LOCATION (DISREGARD IF CLASSIFIED)	[redacted]		
[redacted]	ALTERNATE EMAIL FOR NOTIFICATION	EMAIL FOR NOTIFICATION OF SUBMISSION	[redacted]

AIRCRAFT MAINTENANCE AND AVAILABILITY INFORMATION

[redacted]

AIRFRAME HOURS AT LAST ISO

DISCREPANCY INFORMATION

NOMENCLATURE Rudder	PART NUMBER 355720-1	NATIONAL STOCK NUMBER 1560-00-520-5101	DRAWING NUMBER
NUMBER END ITEMS 0	TECHNICAL ORDER 1C-130A-4-27-1	FIGURE 1	INDEX 5
AIRCRAFT COMPONENT Vertical Stabilizer	COMPONENT SERIAL NUMBER 5257	WUC 1431Q	ADDITIONAL TECHNICAL ORDER REFERENCE
SUBJECT OF DISCREPANCY Battle damage to vertical stabilizer		[redacted]	
ROUTE 107 THROUGH MAJCOM? No		MAJCOM COORDINATION N/A	

DESCRIPTION OF DISCREPANCY/RECOMMENDATIONS

Aircraft received ground battle damage from a mortar on the rudder assembly. Resulting in a 1" entry hole on the right side & a 1.5" exit hole out the left side. The location of the damaged area is the 13 (inner) & 11 (outer) panels on the left and right side of the rudder (1C-130A-3, Fig 55-50-01). At our location we have no provisions or supplies (weights) to perform the alternate scale balancing method after repair. Requesting permission to perform a Battle Damage Repair IAW 1C-130A-39, Fig 4-3 & 4-6.

PART 2: REPLY

SM/IM ALC POINT OF CONTACT

[redacted]

DISPOSITION

Inspect for internal damage and report any damage to WR-ALC Liaison Engineering. If there is no internal damage, repair with an aerodynamic patch IAW TO 1C-130A-39, Fig 9-4 (notes 15 and 22 are applicable). Patch IAW TO 1C1-30A-39, fig 4-7 at the entry and exit holes. The patches shall be the same size and thickness to assure rudder balance. Perform an operations check to assure that there is no systems damage. This is a temp repair for the subject aircraft. Contact Liaison Engineering during next ISO for further inspection/disposition.

AFTO 95

Annotate temp repair and follow-up action in the aircraft forms.

AFTO 103

DISPOSITION ATTACHMENTS

[redacted]

ANALYSIS

ANALYSIS ATTACHMENTS

None uploaded.

IAW T.O. 00-25-107 WHEN DISPOSITIONED AND APPROVED BY SM/IM ALC POC'S AUTHORIZATION IS GIVEN TO PERFORM DISPOSITION INSTRUCTIONS

[redacted]

Figure 4-14: Example Technical Assistance Request (TAR) Identifying Aircraft Battle Damage. Note: blacked-out areas mask specific aircraft data and engineer identity. Highlighted areas show specific ABDR manual references. Image courtesy of USAF C-130 Program Office [40]

PART 1: REQUEST

GENERAL INFORMATION

[redacted]	DATE OF REQUEST 06 Dec 2005 1256	TYPE OF REQUEST C-130 TAR	SERIAL/TAIL NUMBER 6201835
CURRENT LOCATION (DISREGARD IF CLASSIFIED) Balad AB Iraq	[redacted]		
[redacted]			

AIRCRAFT MAINTENANCE AND AVAILABILITY INFORMATION

[redacted]

AIRFRAME HOURS AT LAST ISO

DISCREPANCY INFORMATION

NOMENCLATURE	PART NUMBER	NATIONAL STOCK NUMBER	DRAWING NUMBER
NUMBER END ITEMS 0	TECHNICAL ORDER	FIGURE	INDEX
AIRCRAFT COMPONENT Right Outer Wing	COMPONENT SERIAL NUMBER 8020058	WUC	ADDITIONAL TECHNICAL ORDER REFERENCE
SUBJECT OF DISCREPANCY #2 #4 Fuel Tank Battle Damage		[redacted]	
ROUTE 107 THROUGH MAJCOM? No		MAJCOM COORDINATION N/A	

DESCRIPTION OF DISCREPANCY/RECOMMENDATIONS

While on climb-out from Balad AB Iraq aircraft 62-1835 sustained small arms damage to the #4 main fuel tank lower surface and the #2 main fuel tank lower surface, see attached photos.

Both fuel tanks were punctured causing fuel to leak in flight. The internal condition of the tanks is unknown at this time. No ballistic exit damage is evident. We have no fuel cell repair capability or equipment at Balad AB and limited structural repair capability.

[redacted]

You are authorized to repair as described above with the following exception.

1. Use TO 1C-130A-3, Fig 57-50-08, to lay out your fastener pattern for both damages.
2. At OWS 58, install your scab patches as stated above (.100" each) in place of repair members 4 & 5, fig 57-50-08.
3. At OWS 434, install scab patch in place of repair members 4 & 5, Fig 57-50-08.
4. Install with 5/32 dia. Jo-bolts instead of Hi-Locs and seal per above the repair fig.
5. The intent is to be able to permanently repair this damage per Fig 57-50-08. Therefore, every effort must be made to assure the pattern is intact for later R&R at home station.
6. This aircraft is cleared for unrestricted flight with the above repairs.
7. Due to confined space and riser height repair fig. 57-50-08 can not be accomplished for the damage at OWS434. It is likely that a UDLM will be required at Robins.
8. Contact the engineer [redacted] final disposition once the internal damage has been identified.
9. Accomplish AFTO Form 97, Aerospace Vehicle Battle damage Incident debrief assessment and repair record

AFTO 95
Annotate temp repairs in the aircraft forms. Delayed discrepancy, repair at home station prior to next flight.

AFTO 103

DISPOSITION ATTACHMENTS
None uploaded.

ANALYSIS

ANALYSIS ATTACHMENTS
None uploaded.

IAW T.O. 00-25-107 WHEN DISPOSITIONED AND APPROVED BY SM/IM ALC POC'S AUTHORIZATION IS GIVEN TO PERFORM DISPOSITION INSTRUCTIONS

[redacted]

Figure 4-15: Example Battle Damage Technical Assistance Request (TAR) with Reporting Instructions. Note: blacked-out areas mask specific aircraft data and engineer identity. Highlighted areas show specific C-130 manual references. Image courtesy of USAF C-130 Program Office [40]

4.8 Tactical Airlift Case Study

Before proceeding, it is important to recall some important details from the information presented thus far. Chapter four begins by presenting battle damage data from OEF and OIF. Analysis shows a concentration of battle damage in the tactical airlift family of aircraft. Analysis also shows tactical airlift aircraft are susceptible and passengers are vulnerable to small arms. Further investigation revealed the existence of battle damage in maintenance records, for which battle damage records do not account. Further investigation reveals shortcomings in the process by which maintenance organizations report battle damage. In light of these discrepancies, the first reaction may be to discount the data presented altogether. Such a reaction would be foolhardy. For the purpose of continued analysis, assume that the trends identified in the combat damage data reported to SURVIAC and presented by IDA in the "Study on Rotorcraft Survivability," remain to be true despite being somewhat incomplete. REMIS data from the C-130 program office, which overwhelmingly indicates SA/AW as the primary threat, supports this assumption. Therefore, in the following section, the author examines tactical airlift aircraft to identify survivability concerns.

One of the fundamental questions posed in Section 2 was how system program offices incorporate current battle damage statistics into the acquisitions process. To explore this question it is first important to understand how requirements are developed. One way program offices develop requirements based on maintenance records and identified maintenance trends. For example, if the system program office (SPO) identifies the mean time between failures for a particular component is too short and its impact to operational capability is too high, they may redesign or otherwise improve the component. This requires the SPO to come up with viable solutions, cost estimates, and determine the most effective course of action. Another way requirements are developed is in response to an urgent needs statement from users involved in combat. Of course, SPOs give such requirements high priority.

The C-23 Sherpa (Figure 4-16) is the military version of the Shorts 330/360 regional airliner. It operates in the intra-theater (tactical) airlift role. Originally operated by the military's transportation command, the USAF primarily flew the C-23 throughout Europe. Its users are capable of outfitting the C-23 for various missions. It is capable of carrying up to 30 passengers when operators install airline-style seats or it can be loaded with pallets and containers.

Figure 4-16: C-23 Sherpa, courtesy of Alaska National Guard [23]

Additionally, operators can configure the aircraft for medical evacuation and transportation duties. The Sherpa is capable of operating from short, austere runways and capable of performing airdrops. The DoD procured C-23s as Shorts airliners. Contractors then modify the airplanes with additional equipment not found on the civilian aircraft. In March of 2005, the U.S. Army awarded M7 Aerospace a contract for C-23 life cycle support. Under this contract, M7 Aerospace provides all services required to keep C-23s operational [24].

As seen from the data presented, fixed-wing tactical airlift aircraft are highly susceptible to SA/AWs. In the case of the C-23 Sherpa, little protection for passengers is offered against such threats as evident by the rate of injuries associated with this aircraft. In response to this fact, the U.S. Army produced an urgent needs statement requesting additional protection from the effects of SA/AW threats. In response, M7 Aerospace developed a solution and the U.S. Army subsequently provided authorization to incorporate ballistic protection on C-23s [24]. In this regard, the U.S. Army C-23 Sherpa program; therefore, is an example of how the DoD acquisitions community, in concert with their contract support organizations, responds to urgent requests.

Designed and built in the 1950's the venerable C-130 Hercules (Figure 4-17) performs the intra-theater (tactical) airlift mission. The aircraft is capable of operations from unimproved runways and is capable of air dropping troops and equipment. The DoD has developed specialized versions of the aircraft over more than four decades of service. Variants of the C-130 are capable of performing a wide range of missions including: Antarctic resupply, aeromedical evacuation, weather reconnaissance, aerial firefighting, air-to-air refueling, close air support and intelligence surveillance and reconnaissance. In its most basic form, the C-130 has a large fuselage area that can accommodate a plethora of cargo from vehicles and troops to helicopters. The USAF has made continuous improvements over the C-130s lifespan. More powerful

Figure 4-17: C-130 Hercules, image courtesy of USAF [5]

engines, increased fuel capacity, and other improvements have increased its flying performance and capabilities.

In February 1999, the C-130J entered service with the USAF [26]. The "J model," as it is typically referred to, only shares approximately thirty percent of its features with so-called "legacy" C-130 models. Most of the commonality between the J model and its predecessors is in the basic airframe. That is not to say that the airframe structure is a carryover—quite the contrary. For example, Lockheed replaced several metallic structures such as trailing edge panels and control surfaces with composites. Externally the J model may look like its legacy brethren, but the similarities essentially end there. Differences include digital avionics, two-person cockpit (down from four), Rolls-Royce engines, and, most obvious to the casual observer, six-blade propellers.

In May 1995, DOT&E designated the C-130J for LFT&E oversight. Specific areas of interest included: wing dry bays, propellers, wing fuel tanks, engines, and engine nacelles. Subsequent tests on these areas identified significant vulnerabilities to ballistic threats. One may split the nature of these vulnerabilities into two categories: hydrodynamic ram effects and fire effects (see Sections 4.10.2.1 and 4.10.2.2 for more detail on these subjects). With regard to dry bay fires, the DOT&E FY1999 annual report for the C-130J stated:

> *Ballistic testing of the C-130J wing dry bays has shown them to be extremely vulnerable to realistic threats, however at the same time, although not planned for production design, gas generators (SPGG) have proven to be highly effective in extinguishing fuel fires resulting from ballistic impact* [27].

And,

> *Preliminary results of LFT&E indicate that identified C-130J wing dry bays are vulnerable to expected threats and that an SPGG system could be designed to effectively extinguish ballistically induced dry bay fuel fires. Careful consideration should be given to installing SPGGs for dry bay protection to reduce identified vulnerabilities* [27]"

The following year, the FY2000 annual report states:

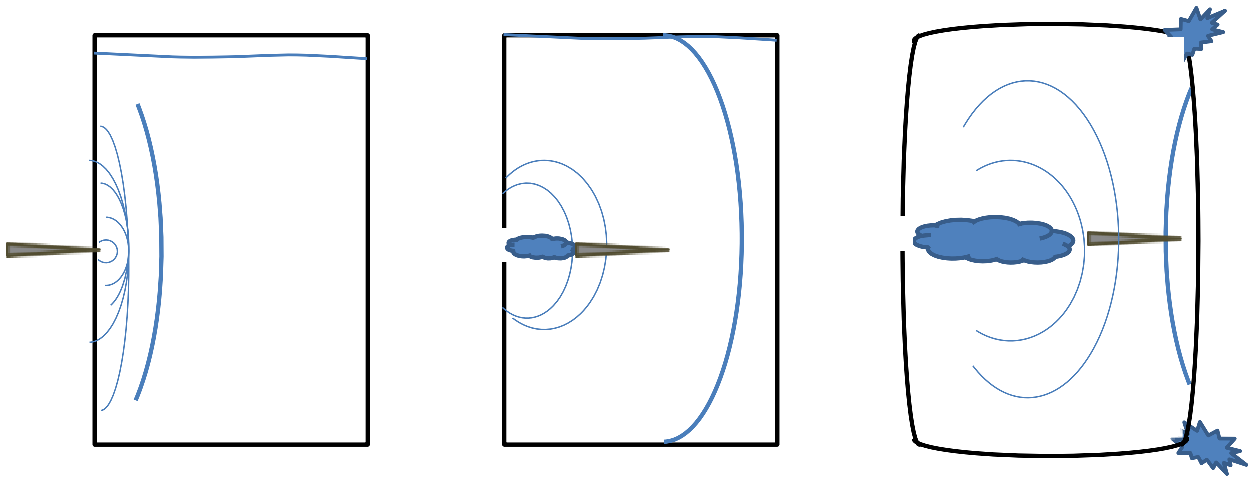
> *I continue to be concerned about the potential vulnerability of this aircraft to fire and explosion from impacts into the wing dry bays and several other large presented areas of the aircraft. We have had extensive discussions with the Air Force and the Under Secretary of Defense (A, T&L) on this issue and we have*

reached agreement that this is indeed a vulnerability which the Air Force must fix [28].

This level of involvement marked a key opportunity to take the necessary steps to resolve such a critical vulnerability. Unfortunately, the FY2009 annual report indicates that dry bay suppression systems incapable of suppressing fires induced by representative threats tested. The same report also notes that the C-130J remains vulnerable to the effects of hydrodynamic ram. This is some ten years after DOT&E identified these (among other) vulnerabilities. The FY2009 report goes on to assess that the C-130J is not effective for worldwide operations in a non-permissive threat environment despite seeing deployments to the Air Force Central Command (AFCENT) area of responsibility (AOR). The program has had successes with regard to survivability improvements. For example, DOT&E grades the engine nacelle fire extinguishing system as highly effective. The propellers, questioned early in the program, were determined to have low vulnerability to the tested threats and the aircraft's overall vulnerability to MANPADS is low as well. These findings highlight two major damage mechanisms: hydrodynamic ram and fire/explosions. The following sections briefly introduce these topics.

Hydrodynamic ram is a phenomenon that occurs when a penetrator impacts a fluid filled chamber. The impact of the penetrator and its propagation cause the internal pressure of the fluid to increase, in many cases, dramatically. Two main factors cause this pressure increase. First, the penetrator transfers some

of its kinetic energy to the fluid forming a shockwave. Figure 4-18, phase one illustrates this event. The shockwave then travels relatively quickly through the fluid. The second factor increasing the fluid's internal pressure is cavitation. Figure 4-18 shows the cavitation beginning in phase 2. The penetrator causes cavitation when fluid displaces along its path. This



Phase 1—Strong Shock Forms

Phase 2—Weak Cavitation Wave Forms; Strong Shock Propagates

Phase 3—Strong Shock Impacts Vessel Wall; Cavitation Wave Propagates

Figure 4-18: Phases of Hydrodynamic Ram

displacement allows a cavity to form. Emanating from this cavity is yet another wave front—albeit slower and with a smaller pressure gradient. These pressure waves interact with the chamber walls and other structures along their pathways until they dissipate due to viscous forces or the pressure is relieved otherwise. In many cases, the pressure is relieved through the failure of one or more chamber walls. If those chamber walls happen to be the primary structural members of an aircraft, the results can be catastrophic. Options for the mitigation of hydrodynamic ram effects in aircraft structures (primarily those containing fuel) include controlling the volume of fuel held in a particular tank, lining the fuel tank with energy absorbing materials, and designing tanks such that sharp corners are minimized [6]. The C-130, including the J model, employs rubber fuel bladders in some of its fuel tanks. This is an example utilizing an energy absorbing material to mitigate the effects of hydrodynamic ram.

Explosions produce effects similar to those produced by hydrodynamic ram. Both involve significant pressure gradients without the means to adequately dissipate them. Explosions have three significant elements in common with fires. To exist, both require fuel, oxidizer, and a source of ignition. If any one of these three elements is missing, a fire or explosion cannot occur. The sequence of events following ignition can vary. One potential sequence of events involving fire is shown in Figure 4-19. In combat, a projectile entering an aircraft's fuel tank typically initiates ullage fires. The fire then burns until it consumes all oxygen or it is extinguished

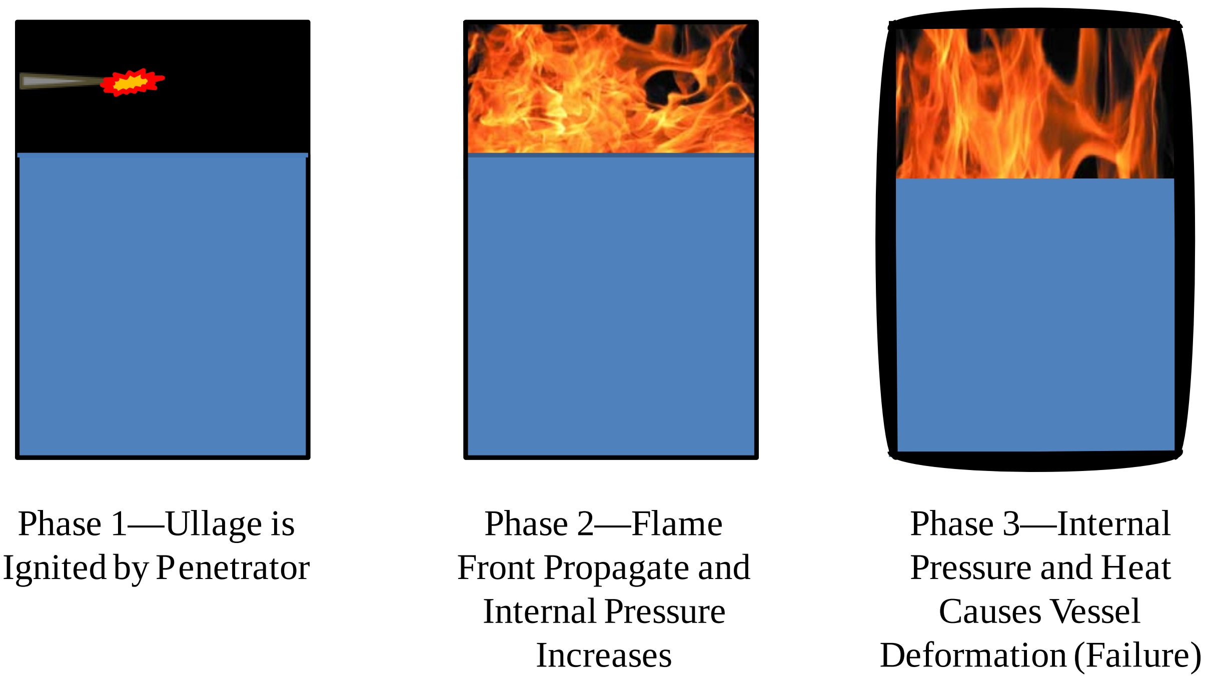


Figure 4-19: Phases of Fire Growth and Effects

otherwise. In some cases, it is possible for the ullage to explode. Should a fire occur, it is imperative that its duration is kept to a minimum. Otherwise, a fire or explosion will surely affect unprotected systems in the area. Fire, even if isolated to small areas, can destroy electrical wiring, actuators, hydraulic system components, flight controls, aircraft structure, etc.—all having potentially catastrophic consequences. Because the hazard of fire damage is not limited to military applications, the aerospace industry has developed a wide range of fire risk mitigation technologies. These technologies are based on the following principles: removal of the energy necessary to support combustion; interference with the combustion mixing process; dilution of the oxygen concentration; removal of fuel vapors; and breakdown of the long combustion chain reaction. Examples of technologies used to prevent or extinguish fires are: explosion suppressant foam (ESF), ballistic foam, fibrous flame suppressors, EXPLOSAFE™ (expanded aluminum flame arrestor), fuel tank inerting, and numerous extinguishing agents [6]. The C-130, including USAF J models, employs (ESF) and other technologies to prevent fires. ESF prevents the fuel vapors above liquid fuel (ullage) in fuel from igniting by arresting the flame front and isolating ignition sources. Figure 4-20 shows a technician installing ESF in a C-130 wing tank. Essentially, technicians fill every cubic inch of fuel volume with ESF. The technician in the inset photo of Figure 4-20 demonstrates the confined space requirements for ESF installation (note respirator and other personal protection equipment.

Royal Air Force (RAF) and Royal Australian Air Force (RAAF) operated C-130Js were not initially equipped with ESF. Tragically, insurgents in Iraq happened upon this vulnerability on 30 January 2005. On that day ten UK personnel lost their life when, after coming under attack by ground-to-air fire, the right hand fuel tank exploded. The explosion caused the outer wing to separate from the aircraft at which point the aircraft became uncontrollable [29]. By late 2008, the RAF had installed ESF on approximately three-quarters of their C-130 fleet. The RAAF, aware of the vulnerability, had already begun a project to retrofit ESF in its J models on 10 December 2004 [30]. In the U.S., the Assistant Secretary of the Air Force and DOT&E agreed to

Figure 4-20: C-130 ESF (image courtesy of USAF) [5]

execute a C-130J LFT&E program in 1998. This program identified the potential vulnerability represented by ballistic threats and as a result ordered LFT&E to conduct tests to evaluate the risks. Early analysis from 1999 confirmed vulnerability to representative threats [27].

Why was this vulnerability not identified earlier in the acquisition process? Lockheed-Martin initiated the C-130J program as a contractor funded development program in 1996. In 1999, the United Kingdom became the first customer for the J model and several other countries followed suit including Australia, Denmark, Italy, and Norway. The USAF also entered into the acquisition program and, as the largest operator, provided oversight of aircraft development. At the time, procurement was to proceed under a commercial acquisition strategy. According to the Defense Acquisition Guidebook (DAG), when using a commercial acquisition strategy it is incumbent upon the program manager to:

> *…pay particular attention to the intended product use environment and understand the extent to which this environment differs from (or is similar to) the commercial use environment. Subtle differences in product use can significantly impact system effectiveness, safety, reliability, and durability* [14].

Among other reasons, the USAF chose a commercial acquisition approach because the prime contractor, Lockheed-Martin, already expended significant development costs. As the program progressed and the government evaluated aircraft, it became clear that significant issues existed which made the C-130J unsuitable for its intended military mission. Consequently, the J model program had to incorporate upgrades, which the program phased in through the fall of 2000, to address more than 50 deficiencies. By incorporating these upgrades, the program evolved from a COTS program to a "modified COTS" program. Again, according to the DAG, *"…a 'modified COTS product'… by definition, is not a COTS product…* [14]." Therefore, efficiencies that may be gained by using a commercial acquisition strategy are if the product is modified to meet military operational safety, suitability, and effectiveness requirement. For example, the USAF developed the C-130E/H with full funding from its inception. Included in the development contract was complete ownership of engineering analysis, technical specifications, and engineering drawings for the resulting aircraft. Consequently, the DoD can make modifications during the life cycle of the aircraft to account for diminishing sources of supplies, evolving environmental legislation, modifications, etc. without the blessing of the original equipment manufacturer (OEM). The USAF did not procure a similar technical data package for the C-130J. As a result, to address the issues listed previously the USAF must either consult the OEM or embark on a costly reverse engineering process.

The USAF implemented a similar acquisition strategy for the purchase of the Joint Cargo Aircraft (JCA) the C-27J Spartan. The C-27J Spartan (Figure 4-21) was selected to fill the Joint Cargo Aircraft (JCA) requirement originally developed by the U.S. Army. The intent of this requirement was to have an aircraft capable of interoperating between heavy lift helicopters, such as the CH-47 Chinook, and larger intra-theater airlift aircraft such as the C-130 Hercules. Alenia designed the C-27J to operate from short, unimproved runways. It can carry three standard pallets, six airdrop bundles, up to 40 passengers, 26 paratroops, or 18 NATO standard litters. The Army transferred primary oversight of the program to the USAF in 2009. Full-rate production is scheduled for FY2011. Ballistic testing results presented in the FY2009 DOT&E annual report indicate the C-27J is vulnerable to dry bay fires in the wing leading and trailing

Figure 4-21: C-27J Spartan (JCA) [5]

edges. DOT&E expects the final LFT&E evaluation of the C-27J in FY2011. It will determine if the actions taken by the military adequately address the dry bay fire vulnerability [13]. Other survivability features of the C-27J include critical system redundancy (electrical, hydraulic, controls, etc.); damage tolerant structural design (including a three-spar wing structure), aircraft survivability equipment (ASE); and on-board inert gas generating system (OBIGGS) [31]. In general, aircraft use OBIGGS to mitigate the risk of ullage fires. As fuel is consumed, the empty space in the fuel tanks (ullage) is filled with an inert gas—typically nitrogen. This minimizes the development of highly volatile fuel vapors. OBIGGS is widely used throughout the civil and military aviation industry and is highly effective, if properly designed, at preventing ullage fires. Compared to ESF used in the C-130J, OBIGGS does not displace usable fuel capacity and the maintenance penalty is much lower. On the other hand, OBIGGS is expensive if not incorporated as part of the early aircraft design. For example, C-27J total life-cycle costs likely support the manufacturer's decision to install OBIGGS as part of its original configuration. Conversely, life-cycle costs do not support replacing ESF with OBIGGS on C-130J aircraft [33]. This is primarily because Lockheed-Martin did not install OBIGGS as original equipment on C-130s.

This chapter presents raw battle damage information from OEF and OIF. The data shows a definite concentration of aircraft battle damage associated with the tactical airlift mission. Furthermore, data shows the most persistent threat is certainly small arms. All of the tactical airlift aircraft operating in Iraq and Afghanistan share the same general performance and survivability features. They also share the same general vulnerability to fire damage and hydrodynamic ram effects. The fact they share similar battle damage statistics in OEF and OIF; therefore, is expected. The C-130 presence in the respective theaters of operation is considerably greater than the smaller C-23. This is the most likely explanation for the higher damage incident rate on the C-130. Due to the concentration of battle damage caused by ballistic threats, the author presented their associated damage mechanisms. This chapter also highlights fundamental flaws in the battle damage reporting process. The importance of correcting these flaws and ensuring the process is robust cannot be overstated. In the C-130, C-23, and C-27J cases, the Director of Operational Test & Evaluation uses actual combat damage reports produced by SURVIAC to determine live-fire test criteria. If the data presented to SURVIAC is incomplete, their analysts may draw conclusions, which are inconsistent with reality.

V. Conclusions/Recommendations

Aircraft safety has come a long way from the wood and fabric machines of World War I to the metal and composite workhorses of today. In parallel, aircraft combat survivability has improved. The fact that fixed-wing aircraft remain susceptible and vulnerable to existing threats is without question. These results provide the beginnings of a roadmap intended to the guide efforts, produce viable solutions, and the steer the concentration of resources. Take these results in context. It is important not to lose sight of the fact that the next war that is fought will likely be very different from the current wars. Surface-to-air missiles (SAMs) are the most lethal threat encountered in the modern battlespace. This fact remains largely unchanged since the war in Southeast Asia (SEA). In today's fight, fixed-wing aircraft are most widely exposed to small arms and automatic weapons (SA/AWs). As a subset of fixed-wing aircraft involved in combat in OEF and OIF, tactical airlift assets are the most susceptible to threats.

Fixed-wing aircraft remain vulnerable to the threat posed by surface-to-air missiles (SAMs). All losses, to date, incurred in OPERATION ENDURING FREEDOM (OEF) and OPERATION IRAQI FREEDOM (OIF) are because of engagements involving SAMs. The rapid establishment of air superiority in both of these operations is the reason for relatively low aircraft losses. In OEF, U.S. forces won air superiority quickly because years of civil war and the lack of a strong centralized government in Afghanistan prevented the establishment of an effective integrated air defense system (IADS) or defensive air arm. In Iraq, years of sanctions following OPERATION DESERT STORM prevented the reconstitution of their IADS. The Iraqi military either hid its operational fighters in hopes of a rapid coalition withdrawal or ferried them to neighboring countries for safekeeping. Consequently, the U.S. military once again established air superiority during the early days of OIF. Despite a relatively small number of SAM engagements, the military cannot ignore the losses. Hence, the defense industry should continue, its efforts to reduce susceptibility and vulnerability to this threat.

Eighty percent of all fixed-wing aircraft engagements involve SA/AWs. SA/AWs represent the most prevalent threat encountered in OEF and OIF, by far. In general, adversaries tend to guide SA/AWs visually or acoustically. Thus, to decrease susceptibility to this threat, technologies that enable nighttime operations and decrease an aircraft's acoustic signature are crucial. Other concepts of operations could involve high-altitude ingress to the target-landing zone, followed by a steep, low power (and therefore quiet) tactical approach. Tactics, techniques, and procedures (TTPs) are best left to the experts. However, some combination of these efforts could significantly reduce the combat damage incident rate. Fortunately, U.S. fixed-wing assets have proven, thus far, to be survivable against this threat. To continue this trend, the defense industry should direct efforts toward ensuring the tolerance level of aircraft systems to ballistic threats provide for sufficient margin of safety to account for potential threat evolution. For example, if the most common threat to an aircraft is, hypothetically, a 12.7 mm ballistic projectile and the systems are designed to be survivable at this level—is there adequate safety margin should the prevalent threat become a 20mm projectile? Of course, designers must balance the level of protection provided, current threats, and practical limitations. However, on future systems, designers could leverage technologies that enable tailoring the level of protection and, in some cases, retrofit them onto current systems. A simple example of this could be the installation of Kevlar™ under the cargo floor of a transport aircraft. Retrofitting these additional protection measures in practice is typically easier said than done. This is why it is critically important that the acquisitions community incorporate requirements for such capabilities early in the system design process. There is a saying in survivability, "If the new system is only as survivable as the system it is replacing, then it is no better than the old system [41]."

Ballistic projectiles like those fired from SA/AWs can cause the hydrodynamic ram phenomenon. The effects of hydrodynamic ram can be devastating to aircraft structures. At this time, the physics of hydrodynamic ram are prohibitively difficult to model; therefore, costly tests are usually involved to determine vulnerability. For this reason, significant effort should be concentrated on the characterization of this phenomenon; development of predictive models; and the development of materials and techniques that mitigate its effects. One possible mitigation technique is the application of an energy absorbing material, such as elastomeric polyurethane. This material can be sprayed or rolled onto the walls of a vessel and when impacted by a projectile, absorb the ensuing shock wave. Pairing this technology with other similar technologies like flexible bladders could potentially amplify their efficacy.

The potential for fire and/or explosions because of ballistic projectile impacts like those from SA/AWs present a significant risk. Aside from the obvious dangers associated with an explosion such as catastrophic structural failures, resultant fires have the potential to cause cascading series of subsequent failures. Some of these effects are rapid consumption of fluids like hydraulic fluid, engine oil, and fuel, which causes failure in the affected systems. Other consequences of lingering fires can include structural failures, mechanical system failures, and additional explosions. Therefore, research and development in fire detection, prevention, and extinguishing continue to be invaluable. Incorporation of these technologies early in the system design phase of a program, as always, is absolutely essential to produce the desired outcome.

Aside from the damage mechanisms listed, small arms have another critical factor—the work force required to repair damage. The military deploys with far less “excess” capacity than in previous conflicts. It is imperative; therefore, that an aircraft not only be survivable but also rapidly repairable. Institutionally, aircraft battle damage repair (ABDR) technology has remained relatively stagnant. However, ABDR continues to be a relevant skill to have available during conflict. In OEF and OIF, maintenance organizations and their leadership are reluctant to utilize these skills. This is mainly due to the misconception about the temporary nature of repairs installed in accordance with ABDR manuals. Granted, repairs installed per a weapon system ABDR manual have recurring inspection requirements and are, by definition, temporary. However, the USAF typically cycles aircraft, deployed to the OEF or OIF area of responsibility (AOR), back to their respective home stations on a regular basis. Today, deployed maintenance units enjoy ready communication with the engineering authority responsible for a weapon system. This allows for consultation with subject matter experts, which more often than not results in the removal of re-inspection requirements for temporary repairs. Upon return to home station, technicians may remove and replace temporary repairs with permanent repairs. Together, these factors—connectivity and aircraft rotation—actually makes the use of ABDR techniques more attractive because they typically require less time to install. Another reason leaders seem to not embrace ABDR is the fact that the wars in Afghanistan and Iraq have not been traditional wars of attrition. If an aircraft sustains significant damage and is going to require an inordinate effort to repair, then deployed units will request, and usually receive, a replacement aircraft. This may not always be the case. The USAF, in recent years, is relying heavily on its technological advantage to compensate for imbalances in sheer numbers. There is a tipping point at which one of the principles of war—mass—cannot not be achieved. Mass enables numerically smaller forces to achieve decisive results. Unless planners know the tipping point with the utmost certainty, retaining the ability to regenerate battle-damaged aircraft is a valuable insurance policy to ensure that the USAF maintains mass. To remain relevant and effective, ABDR techniques and materials must evolve along with the aircraft on which the USAF employs them. This is why one of the stated objectives of live fire test and evaluation (LFT&E) is to, "*Assess recoverability from battle damage and battle damage repair capabilities and issues* [14]."

Fixed-wing aircraft engaged in the tactical airlift mission expose themselves to hostile threats in OEF and OIF more than any other fixed-wing category. Ninety-five percent of all tactical airlift engagements involve an encounter with SA/AWs. Therefore, material leaders should aim considerable resources at assessing vulnerability, reducing vulnerability, and identifying technologies that reduce susceptibility of tactical airlift aircraft to SA/AW threats.

The highest concentration of injuries associated with a fixed-wing aircraft, as a result of a combat damage incident (CDI), occurred in the C-23 Sherpa. The C-23 is a relatively slow and low flying aircraft. Its tactical airlift mission makes it susceptible to threats close to the ground in hostile environments. Combat data indicates that, while the aircraft itself is survivable in this environment, the occupants are at risk. In response to this reality, the U.S. Army initiated a program to add ballistic protection to existing C-23s. M7 Aerospace completed the project, but information about its effectiveness in an operational environment was unavailable at the time of this writing. Considering the concentration of damage incidents within the tactical airlift category, the U.S. Army should consider a robust aircraft battle damage repair (ABDR) capability—if not already in place. The capability should include guidance for accurately assessing battle damage, unrepaired damage limitations, and expeditionary repair techniques. The USAF originally purchased the C-23 as a commercial derivative not intended to fly in non-permissive environments. Hence, the evolution of the C-23 mission warrants, at a minimum, a cursory re-investigation of survivability. Per the Defense Acquisition Guidebook, with regard to commercial derivatives, it is incumbent upon the weapon system program manager to ensure that the system co-evolves with essential changes to doctrine. Survivability with respect to SA/AWs and their effects are, obviously, the most pressing concern. Consequently, DOT&E should examine topics such as critical system redundancy; fire/explosion prevention and detection; fire suppression/extinguishing; and hydrodynamic ram effects.

The C-130 family of tactical airlift aircraft has sustained more battle damage in OEF and OIF than all other fixed-wing aircraft combined. As with the C-23, the tactical airlift mission requires the C-130 to fly close to the ground and relatively slow speeds. In Afghanistan, the terrain also plays a significant role. High peaks may flank landing zones near forward operating bases that the USAF services with C-130s. The combination of the slow and low flight requirement for landing and abundant hostile firing positions equates to a situation, which is akin to, proverbially shooting fish in a barrel. Impressively, there are no injuries associated with the reported incidents of combat damage. This is a testament to the efforts to provide ballistic protection for both the crew and cargo area. Nonetheless, it is crucial to constantly reevaluate the level of protection that systems provide against the potential evolution of the threat environment.

From an aircraft systems perspective, combat data indicates a relatively high survivability to the threats faced by the C-130. However, LFT&E of the C-130J, conducted during FY2008 indicated vulnerability to hydrodynamic ram and limited effectiveness of the dry bay fire suppression system. These vulnerabilities are not limited to J model versions. The structural characteristics that lend J models to being vulnerable to hydrodynamic ram and dry bay fires are virtually identical on legacy C-130s. Compounding the issue is the fact that SA/AWs can initiate hydrodynamic ram and dry bay fires. It is important; therefore, to continue efforts to reduce these risks.

The sheer volume of C-130 CDIs when compared to other MDSs highlights the need to have a robust ABDR program in place. In accordance with AFI 21-101, AIRCRAFT AND EQUIPMENT MAINTENANCE MANAGEMENT, Section 14.1, Air Force Materiel Command (AFMC) shall assume management responsibility for USAF ABDR Programs. Included in the AFI 21-101 directed responsibilities is the task to develop the capability to repair battle and crash damaged aircraft and to support the publication of weapon system specific ABDR TOs. With respect to legacy C-130s, TO 1C-130A-39 meets the ABDR TO requirement. This document covers USAF C-130E and C-130H aircraft. However, the legacy ABDR TO does not cover the C-130J. In this regard, AFMC is derelict in its responsibility. Not having a J model specific ABDR TO has had significant repercussions for deployed operations. For example, without an ABDR TO, technicians must repair battle damage in accordance with standard repair manuals or specific guidance from the responsible engineering authority via a technical assistance request. Both options typically have time penalties associated with them. Standard repairs typically involve time-consuming steps, such as corrosion prevention measures, which a technician may not omit without engineering authorization. Requesting repair procedures through the technical assistance process could potentially have a time penalty measured in days—not including the time required to actually install the repair. Alternatively, with an ABDR TO, technicians could quickly triage damage and make a realistic assessment of the level of effort needed to return the aircraft to at least some measure of mission capability. This capability is why ABDR is relevant, a force multiplier, and must be expanded to include the C-130J.

The threats encountered by C-130s in OEF and OIF tend to be, primarily, ballistic projectiles. This category of threat usually involves visually or acoustically acquiring and tracking of the target (C-130) followed by multiple shot engagements. To reduce susceptibility in this scenario it is necessary to employ technologies that decrease an aircraft's visual and acoustic signatures. Where applicable, operators should employ technologies such as the Joint Precision Air Drop System (JPADS). This technology increases the C-130's ability to standoff from a given threat environment and could therefore minimize threat exposure. Unfortunately, operators cannot always avoid threats. In these cases, it is imperative that aircraft systems be survivable to the level of threat encountered. DOT&E identified hydrodynamic ram and dry bay fire suppression as critical vulnerabilities for the C-130. Therefore, researches should focus resources to identify technologies to mitigate the risks associated with these vulnerabilities.

One procedure for mitigating the effects of hydrodynamic ram is to minimize fuel quantity held in each tank when the possibility of being exposed to a ballistic threat is high. Generally, this procedure increases the possibility of fire or explosion if hit. However, USAF C-130s are equipped with explosive suppressant foam (ESF) proven to be effective at preventing such events. Legacy C-130s also have the option of utilizing external fuel tanks. Operators can completely fill external fuel tanks to their capacity. If hit, the hydrodynamic ram effects are limited to the external fuel tank structure and, thus, are less likely to cause catastrophic failure of the wing. Strategically placed check valves prevent the total loss of fuel. Therefore, the combination of creative fuel load management with ESF may make the C-130 more survivable in a ballistic threat environment. With regard to the vulnerability associated with dry bay fires, engineers have made significant progress over the last decade of J model development. Planners should apply the lessons learned, where able, to the legacy fleet. The C-130 has proven itself a survivable platform in the current environment. However, significant shortcomings remain. Enemy tactics and weapons are constantly evolving. Therefore, it is vital that the USAF employ an agile scientific, engineering, and acquisitions community capable of predicting and if need be reacting to changing threats.

The C-27J is included in this analysis because it is the newest member of the tactical airlift family of aircraft. The C-27J will be performing similar missions to both the C-23 Sherpa and C-130 Hercules. When deployed, its mission profile will expose the C-27J to the same types of threats as other aircraft performing the tactical airlift mission. Therefore, its inclusion herein is both validated and relevant. Like the legacy C-130, Alenia designed the C-27J for the tactical airlift role. Like its larger brethren, the C-27J will have to mitigate the risks associated with flying low and slow in a hostile environment. Realizing this fact, DOT&E designated the C-27J for LFT&E oversight as a covered system. In the FY2009 DOT&E report, ballistic testing demonstrated that the C-27J wing was vulnerable to dry bay fire in the leading and trailing edges. The subsequent report for FY2010, states, "*The survivability of the JCA [C-27J] against the threats tested and analyzed is comparable to other military cargo aircraft* [34]." From this statement, one can infer that some of the limitations outlined elsewhere in this document are applicable. Thus, prior to entering combat it is imperative that the USAF take steps to mitigate the risks associated with the SA/AWs. This includes developing tactics, techniques, and procedures (TTPs) to avoid ballistic threats; protecting all crew and occupants from ballistic threats; taking steps to minimize ballistic projectile effects such as hydrodynamic ram and fire; and producing a robust ABDR manual and training program.

5.1 General Technical Order Change Recommendations to Improve the Battle Damage Reporting Process

Perhaps the most important outcome of this analysis is the identification of deficiencies in the process for reporting battle damage to SURVIAC. It is absolutely critical to the discipline of aircraft survivability to have timely, accurate, and actionable information about the threats being encountered in combat as well as the damage those threats are inflicting. Without the utmost confidence in the battle damage captured, the assumptions made to protect man and materiel, may drive analyst to faulty conclusions. Therefore, in order to correct the deficiencies identified in this document, which may have influenced units to not report battle damage to SURVIAC, the author recommends a series of changes to maintenance documentation procedures. This is a near-term solution. The intent of these changes is to direct entities that may encounter battle damage, or corrective actions thereto, to the SURVIAC reporting procedure found in TO 1-1H-39. The desired effect, therefore, is to ensure SURVIAC captures all battle damage incidents, regardless of what corrective action technicians take to repair them. These recommendations increase awareness of the unique reporting requirements of battle damage at unit level. Ideally, these unique requirements would be covered and emphasized during initial and recurring documentation training conducted by all involved parties. Changes to existing technical orders do not improve the speed or efficiency of the reporting process. To address these issues, the mid-term solution the author recommends involves the development of an "electronic AFTO Form 97." Maintenance organizations with connectivity will be able to quickly upload pertinent information, which will instantly available to analyst and other users. This will dramatically reduce the lag, which the current paper AFTO Form 97 process experiences. Both the near-term and mid-term changes will achieve the goal of improving the battle damage reporting process, but the long-term goal is making battle damage reporting no different from any other maintenance documentation. For this to occur, the author recommends incorporating battle damage reporting into existing maintenance data documentation resources such as REMIS.

The near-term recommendations consist mainly of verbiage additions and changes to technical orders already in existence. Maintenance documentation in the USAF is a robust institution. Rather than attempt a massive change, adapting ABDR documentation requirements to it is a more productive approach.

TO 1-1H-39 contains the authoritative definition of battle damage. It alone contains the information necessary to steer battle damage information to SURVIAC. However, the definition of battle damage, contained therein, is extremely wordy and confusing. The current definition of battle damage is as follows: "*Battle damage is defined as any damage and/or malfunction, typically caused by munitions or their effects whether self-inflicted or resulting from enemy or friendly fire or by ground mishap, encountered during combat operations* [21]." By this definition, essentially any damage or malfunction encountered during combat operations is battle damage. Consequently, commanders may use ABDR techniques to repair essentially any problem to which they are applicable. For example, while deployed, an aircraft tire fails and damages the adjacent landing gear door. In this case, a commander, at his/her discretion, may use ABDR techniques to repair the landing gear door. ABDR techniques are not applicable to the tire and, consequently, the commander cannot use them for its repair. The intent of this broad battle damage definition is to provide deployed Commanders rapid repair options, which maintain safety and effectiveness—regardless of what caused the damage. The unintended consequence of the wordy definition is that it makes it difficult for a technician to decide whether to send an AFTO 97 to SURVIAC or not. In this regard, the term battle damage may be too all encompassing. Therefore, to correct the deficiencies identified in TO 1-1H-39, the author recommends the following changes. In section 1 of TO 1-1H-39, the current verbiage states:

"*Battle damage is defined as any damage and/or malfunction, typically caused by munitions or their effects whether self-inflicted or resulting from enemy or friendly fire or by ground mishap, encountered during combat operations. Use of advanced weapons, along with…*[21]"

The author recommends amending the verbiage to state:

"*Battle damage is defined as damage sustained during combat operations. Battle damage may be broken into two categories—combat damage and mishap damage. Use of advanced…*"

This change accomplishes multiple things. It is concise and; therefore, less confusing. It removes any doubt that mishap damage can be considered battle damage if sustained during combat. It also maintains the flexibility commanders require for applying ABDR techniques to situations other than combat hostile fire damage.

TO 1-1H-39 also contains a decision matrix used to determine if an AFTO Form 97 is required to document a particular damage event. Similar to the battle damage definition, the decision matrix needs improvement. TO 1-1H-39 Section 1-12, Table 1-2, Note 2 states:

"*Combat damage includes all damages and malfunctions caused by munitions or their effects whether self-inflicted or resulting from enemy or friendly fire* [21]."

The goal of this note is to define combat damage so the technicians can in-turn, determine if their particular damage warrants an AFTO Form 97. The following change is a better alternative. Note 2 should read:

“*Combat damage includes all damages and malfunctions caused by munitions or their effects whether from enemy fire, friendly fire, or self-inflicted.*”

Similarly, the current verbiage of note 3 states**:**

“*Mishaps include such items as an aircraft coming in contact with vehicles, shelters, support equipment, etc, mid-air collisions, maintenance accidents, cash landings not resulting from combat damage, etc* [21].”

The recommended verbiage states:

“*Mishaps include damage and/or malfunctions not considered combat damage or normal wear such as: aircraft coming in contact with ground based objects, mid-air collisions, maintenance accidents, etc.*”

[Note: TO 1-1H-39, Section 1-12, has an error. It states, “Table 1-1 describes…” it should read, “Table 1-2…”]

The recommendations to TO 1-1H-39 intend to clarify instructions for reporting battle damage. However, these improvements are only helpful if a technician is steered to them in the first place. As shown in this thesis, there are chinks in the maintenance documentation chain when battle damage is involved. The problem begins in TO 00-20-1, AEROSPACE EQUIPMENT MAINTENANCE INSPECTION, DOCUMENTATION, POLICIES, AND PROCEDURES. TO 00-20-1 implements the documentation policies of AFI 21-101, AIRCRAFT AND EQUIPMENT MAINTENANCE MANAGEMENT. As such, it lays the foundation on which all requirements for reporting aircraft maintenance is built. In TO 00-20-1, battle damage is mentioned in three distinct locations: Appendix C, the acronym list; Appendix B, Applicable Technical Orders; and Section 5.9 where, correctly, the user is instructed to refer to TO 1-1H-39 for instructions on reporting battle damage [36]. However, TO 00-20-1 does not mention the special form used to report battle damage. Therefore, the following recommended additions to TO 00-20-1 will increase the probability that maintainers will capture battle damage appropriately. Section 3.1.1 of TO 00-20-1 provides a list of forms used to document maintenance discrepancies and corrective actions. Therefore, the recommended change inserts the AFTO Form 97 and 97A used to document battle damage and repairs, respectively. The verbiage is as follows:

"*3.1.1.4 AFTO FORM 97, AEROSPACE VEHICLE BATTLE DAMAGE INCIDENT DEBRIEF/ASSESSMENT RECORD*"

"*3.1.1.5 AFTO FORM 97A, AEROSPACE VEHICLE BATTLE DAMAGE ASSESSMENT/REPAIR RECORD*"

The point of the change is to make battle damage reporting as similar to other maintenance documentation acts as possible. Additionally, Section 3.11 of TO 00-20-1 addresses how to file the forms listed. Thus, the author recommends adding a note in this section, which directs the user to TO 1-1H-39 for specific documentation instructions. The verbiage states: "*AFTO Form 97/97A shall be filed IAW TO 1-1H-39.*"

Likewise, TO 00-20-2 MAINTENANCE DATA DOCUMENTATION requires revision. TO 00-20-2 intends to provide a better understanding of the objectives, scope, concept, and policy of Maintenance Data Documentation (MDD). TO 00-20-2 communicates greater detail about the specific systems used to capture maintenance data—in accordance with TO 00-20-1. Like TO 00-20-1, TO 00-20-2 there is only limited mention of battle damage. Specifically, TO 00-20-2 mentions battle damage in Appendix G, HOW MALFUNCTION CODES. There is no mention of TO 1-1H-39 whatsoever. Because TO 00-20-2 intends to provide a higher understanding of MDD, it is critical that the following addition be made. Section 4.22.1.7 should state:

"*4.22.1.7 HMC 731 (battle damage) will be used whenever a job involves corrective action as a result of battle damage as defined by TO 1-1H-39. Aircraft Battle Damage and Repair (ABDR) actions shall be documented IAW TO 1-1H-39.*"

The intent of this addition is to drive a technician to the unique reporting requirements of battle damage as explained in TO 1-1H-39.

The recommendations to this point mainly involve improvements to routine maintenance documentation processes. However, this thesis highlights the potential for battle damage to go unreported when technicians assistance seek from the responsible engineering authority. TO 00-25-107 MAINTENANCE ASSISTANCE**,** governs this process. Therefore, it is imperative that this technical order addresses the unique nature of battle damage and its required documentation. Hence, the author recommends the addition of the following to TO 00-25-107:

<FOLLOWING PARA 1.4 ADD>

NOTE
MAINTENANCE ASSISTANCE REQUESTS INVOLVING BATTLE DAMAGE SHALL BE DOCUMENTED IAW TO 1-1H-39.

5.2 Weapon System Specific ABDR Manual Revision Recommendations

The preceding recommendations address the deficiencies in general battle damage reporting policies. The recommendations to follow address deficiencies in weapon system specific repair manuals. Technicians use the two specific manuals listed for standard structural repairs and weapon system specific ABDR repairs. The structural repair manual is listed because the majority of battle damage will likely involve some form of structural damage. Therefore, to increase the probability that a technician records the subject battle damage appropriately, this is the most logical choice. The author also chose the weapon system specific ABDR manual because if a mechanical system is to be repaired using ABDR techniques technicians must reference it. Therefore, these two weapon system specific manuals will most often prompt the user to record battle damage accordingly. While the C-130 is the subject of the recommendations below, weapon system managers should explore similar amendments for all other combat aircraft.

The first recommendation involves the C-130 specific ABDR manual, TO 1C-130A-39. In this manual, there is no mention of the requirement to uniquely document battle damage. Therefore, the USAF should add the following statement to the foreword section, which already exists. The addition states: "*Battle damage shall be documented IAW TO 1-1H-39.*" Likewise, the USAF should add this statement to the foreword section of TO 1C-130A-3, the C-130 structural repair manual.

5.3 Mid-term Battle Damage Documentation Recommendations

While the recommendations set forth in Sections 1 and 2 of this chapter correct many of the deficiencies in the current battle damage reporting process, they are by no means a complete solution. For the mid-term, the battle damage reporting process as a whole needs evaluation. A simple, yet effective, solution for many of the battle damage reporting woes outlined within this thesis is wider adoption of the Combat Damage Incident Reporting System (CDIRS). SURVIAC developed CDIRS *for* SURVIAC [35]. Why then is CDIRS not the preferred battle damage input method for all Department of Defense (DoD) agencies—not just JCAT? Maintenance operations should institutionalize CDIRS for aircraft battle damage in the same way that they use other management information systems (MIS) for typical maintenance data. In essence, the CDIRS interface would become an electronic AFTO Form 97 except with considerably more functionality such as the ability to upload pictures. Paper AFTO Form 97s would still be available for organizations without the necessary connectivity. Commanders could also use a CDIRS AFTO Form 97 interface to access recent battle damage information and enable more responsive decisions In a rapidly evolving threat environment this capability is invaluable. The possibilities are endless. Most importantly, users will be able to upload higher fidelity information. Ultimately, the widespread use of CDIRS will improve the quality of battle damage analysis.

Developing the "CDIRS AFTO Form 97" interface is only the beginning. The system is useless if no one knows about it. Therefore, the USAF should update TOs 00-20-1, 00-20-2, and 1-1H-39, discussed previously, to reflect the existence of the CDIRS AFTO Form 97 and provide, at least, the same level of detail with regard to its importance and purpose as it provides on other systems. Finally, SURVIAC should populate the CDIRS database with historical data such as "The Study of Rotorcraft Survivability." Proper training, an electronic AFTO Form 97 interface, and ready access to invaluable historical data will prompt a quantum leap in survivability analysis. Lives will be saved as a result.

5.4 Long-term Battle Damage Documentation

Simply reporting combat damage incidents is not enough to improve aircraft survivability. The DoD must improve the quality of the reports. Therefore, battle damage reporting must be normalized across the DoD. To accomplish this goal, within the Air Force, it should staff maintenance operations with personnel trained to assess aircraft battle damage in a manner similar to the Joint Combat Assessment Team (JCAT). With these personnel in place, the level of fidelity reported for a combat damage incident will increase tremendously. Furthermore, the DoD should mandate these personnel are current and proficient in combat damage incident reporting prior to deploying. This all but guarantees qualified assessors are in place where and when battle damage occurs.

5.5 Conclusion

It bears repeating that war is the ultimate test of survivability. At this point in history, the agencies of the Department of Defense have proven themselves excellent students. In survivability, one cannot rest on the strengths of yesterday because an adversary is constantly looking for the weaknesses of tomorrow. Roughly a century after the implementation of fixed-wing aircraft as an instrument of war, ballistic projectiles remain a relevant threat. Therefore, the survivability community should focus significant research and development on the phenomena of hydrodynamic ram. The defense industry needs high-fidelity modeling tools; material solutions that can be easily retrofitted into existing weapon systems; and design guidelines for future systems that minimize the effects of hydrodynamic ram. Doing so ensures combat aircraft will be prepared for the survivability tests of the future.

When operating in a non-permissive threat environment, aircraft are going to sustain battle damage. Therefore, it is vital that the USAF retains a rigorous aircraft battle damage repair (ABDR) capability. The current ABDR trend introduces the potential for a critical vulnerability. The USAF is losing the experience and skills necessary to provide ABDR and when it is gone, it is lost forever. Furthermore, the dissolution of the Combat Logistics Support Squadron (CLSS) is completely contrary to the AEF vision. The USAF needs to completely reinvigorate its ABDR program and prepare for the battlefield of the future. Furthermore, the USAF needs to develop technologies that enable rapid and effective repair of stealthy materials, imbedded electronics and sensors, and modern aircraft structure. Assuming air superiority is going to be a given in future wars is reckless, indeed.

Last, but by no means least, when the current battles in OEF and OIF have gone cold and the next battle is begun, it is absolutely crucial that the USAF (and other DoD agencies) has in place the ability to accurately capture aircraft battle damage. If this is not accomplished—soon—the USAF runs the risk of missing relevant data that may result in unnecessary loss of life.

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14. ABSTRACT: The primary tenet of the aircraft survivability discipline is threat definition. In order to deliver relevant capabilities and protection to the warfighter it is imperative; therefore, to provide timely, accurate, and actionable threat data to the survivability community. In an attempt to identify the evolution of aircraft threats in today's combat environment, an analysis of fixed-wing aircraft battle damage was conducted. This analysis reports battle damage incidents from OPERATIONS ENDURING FREEDOM (OEF) and IRAQI FREEDOM (OIF). Additionally, reported damage incidents were then validated by crosschecking aircraft maintenance records from this period to eliminate non-hostile fire data points. This revolutionary approach uncovered discontinuities, which were further explored to identify their root cause. As a result, significant Air Force policy changes in the realm of battle damage reporting procedures were suggested. In the end, lives will be saved because the acquisition community at large will have valuable threat data in which they can be confident.

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