1.1 Historical Perspective on Structural Integrity in the USAF

The current design philosophy of U.S. Air Force aircraft has come about through a long series of evolutionary advances. Each advance followed the identification of a problem area that the then-current design criteria did not envision or comprehend. The changes in design philosophy also followed the advances in materials usage, from wood and fabric of the Wright Brothers era, to the all-metal (predominately aluminum) aircraft of World War II.

The early fabric-covered aircraft from the Wright Brothers era used spans, ribs and bulkheads of wood and laminated wood for the main load-carrying structural members. Professor Nicholas Hoff [1955] documented the fact that "the Wright Brothers performed a stress analysis of their first power machine and conducted static tests far in excess of the load that is required of it in flight."

This systematic, strength-based approach so dominated the early design methodology that it was used as the primary method for the next 50 years. Of special interest from a materials viewpoint, the selection of wood as the main structural material was based on technology of the day. Wood also has a very high fatigue strength compared to its tensile strength and is remarkably insensitive to notches.

With the continual development of higher performance aircraft, both in speed and maneuvering capabilities, through the twenties and early thirties, it was clear that the fabric-skinned aircraft were out of their element. This ushered in the age of aluminum as the primary aircraft structural material. The early aluminum aircraft fared well from a structural standpoint, due in part to designer's conservative nature associated with using a new material. The yeoman work done by the C-47 in WWII (military designation for the DC-3) attests to the success of the Wright's concept of strength-based design methods.

After WWII, the first major new Air Force aircraft design was the all-jet-powered B-47. This was a swept-wing, medium-range, strategic bomber which, in the 1950s, was a lynchpin in the post-WWII "Cold War" strategy of "massive nuclear retaliation." Aircraft production of the three models totaled 2,041 by three different manufacturers: Boeing, Douglas, and Lockheed [Negaard, 1980]. No aircraft usage life was predicted for the B-47, although the calendar phase-out was set for 1965.

The growth in aircraft gross weight and engine thrust are documented from the various models in Table 1.1.1. Many performance-oriented changes required structural strengthening and equipment changes, as well as additional fuel capacity to increase the range. The original B-47 was designed as a high-altitude bomber. However, in the last half of 1957, the Strategic Air Command, with Air Proving Ground approval, began using the bomber extensively at low altitudes. One of the low-level missions included a "structure-wrenching" low-altitude bombing system maneuver (LABS) for delivery of nuclear weapons [Patchin, 1959]. It was also called a toss-bomb maneuver and incorporated a strenuous "pop-up" bombing run. The mission training was typically performed at altitudes under 1000 feet, which added increased load excursions due to atmospheric turbulence, coupled with the increased refueling requirements and the unique load cycles imposed by that maneuver. The B-47 fleet had markedly changed the expected loading spectrum.

Table 1.1.1. B-47 Aircraft Production Models

Model	Gross Weight (Lbs.)	Thrust per Engine (Lbs.)	Thrust Growth Versions
B-47A	125,000	4,000	5,200
B-47B	185,000	5,800	5,800
B-47E	206,700	6,000	

Complicating Issues: water injection takeoffs, 17% increase in takeoff power
JATO rocket-assisted takeoff mechanisms
"LAB" Maneuvers (Toss bomb arc)

The history of the Air Force Structural Integrity Program (ASIP) started with the B-47. Fortunately, the AF Flight Dynamics Laboratory (now AFRL/VA) documented these beginnings through an Aeronautical Structures IAC report compiled by Gordon Negaard [1980]. Much of this historical synopsis was gleaned from that report.

On March 13, 1958, two B-47Bs broke up in flight in separate incidents. The first was a B-47B, which disintegrated at 15,000 feet with the initial failure occurring on the lower wing skin at Butt Line 45 – the aircraft had 2,070 hours. The second aircraft, a TB-47B, was at 23,000 feet when the lower wing skin failed at Butt Line 35 – this aircraft had 2,418 hours total flight time.

The investigations on these accidents were still underway when three more in-flight accidents occurred. A B-47E disintegrated in midair with only 1,129 hours, another B-47E exploded at 13,000 feet with only 1,265 hours, and yet another B-47E failed shortly after takeoff with a total aircraft flight time of 1,419 hours.

The immensity of the problem with the B-47 fleet caused massive infusion of personnel and funding to uncover the origins of fatigue failures and prepare and apply "fixes" for them. Technologies had to be developed to define the loads environment that the aircraft saw: number of takeoffs, landings, high-"g" pullups, rolling pullups, low-attitude maneuvers, and gust/turbulent weather loading.

A test spectrum of the applied loads had to be devised which matched the actual usage as closely as possible. The decision was made to run three concurrent fatigue test programs at Boeing Wichita, Douglas Tulsa, and at the NACA laboratory in Langley, Virginia. After about one month of testing, the Boeing test aircraft failed both fuselage upper longerons at Station 508 – one month later, the same fate occurred in the Douglas test aircraft.

Both the Boeing and Douglas test aircraft were repaired with improved longerons that had an additional reinforcement. Subsequently, lower wing failures occurred in all three aircraft and were repaired, then major fuselage cracking occurred and the cyclic testing stopped in February 1959.

The B-47 fatigue testing program accomplished a great deal towards identifying the problems associated with using a strength-based design criteria. It identified a series of very critical design areas on the B-47 which had to be repaired before release of the aircraft for full flight. It also served as a keystone for the fledgling Aircraft Structural Integrity Program (ASIP). This program was also aided by a policy directive by General Curtis LeMay, Air Force Vice Chief of Staff, which cut through the "red tape". This directive emphasized the importance of the structural integrity program and called for the complete and active support and cooperation of all Air Force elements [Negaard, 1980].

Throughout all the testing was an underlying learning experience for the Air Force structural engineers. A technical memorandum, WCLS-TM-58-4 [1958], set the baseline design requirements for fatigue life, expressed in flight hours and landings, for all Air Force aircraft that the program was to cover. A follow-on document to this memo entitled "ARDC-AMC Program Requirements for the Structural Integrity Program for High Performance Aircraft" dated 15 February 1959, delineated the breakout of responsibilities of eleven sub-program areas:

- Static test
- Flight load summary
- Fatigue test
- Low-altitude gust environment
- Mission profile data
- Interim service load
- VGH life history recording
- Eight-channel service load recording
- Sonic fatigue
- High-temperature structure
- Design criteria

General Curtis LeMay formally approved this joint command document and directed its "implementation on a priority basis." [Negaard, 1980].

The next several years saw minor changes in the basic ASIP document, but a major increase of supporting specifications were published to aid in the implementation. These included the Military Specification 8800 series of specifications that sought to clarify and document all aspects of the original ASIP guidelines. Table 1.1.2 lists the specifications of the MIL SPEC 8800 series that are most pertinent to the Damage Tolerance Design Handbook. Most were released 18 May 1960.

Table 1.1.2. Pertinent 8800 Series Specifications of 1960

Spec No.	Title
MIL-A-8860	Airplane Strength and Rigidity General Specification for
MIL-A-8861	Airplane Strength and Rigidity Flight Loads
MIL-A-8862	Airplane Strength and Rigidity Landing and Ground Handling Loads
MIL-A-8863	Airplane Strength and Rigidity Additional Loads for Carrier-Based Landplanes
MIL-A-8865	Airplane Strength and Rigidity Miscellaneous Loads
MIL-A-8866	Airplane Strength and Rigidity Reliability Requirements, Repeated Loads, and Fatigue
MIL-A-8867	Airplane Strength and Rigidity Ground Tests
MIL-A-8868	Airplane Strength and Rigidity Data and Reports
MIL-A-8869	Airplane Strength and Rigidity Special Weapons Effects
MIL-A-8870	Airplane Strength and Rigidity Vibration, Flutter, and Divergence
MIL-A-8871 (8 Oct. 1968)	Airplane Strength and Rigidity Flight and Ground Operations Tests

Even with the added attention on fatigue design issues, the learning process had many hesitations. During the full-scale fatigue test of the F-105D at Wright Field, the main wing carry-through frame at fuselage station (F.S.) 442 failed at less than 20% of one lifetime [Brammer, 1963]. After review of the data and the load spectrum, a replacement fuselage with specially-machined attachment lugs to reduce the stress concentration was inserted and the testing continued with a much-reduced load spectrum. This frame subsequently failed at 4653 flight hours, or 116% of one lifetime (the testing requirement was for four lifetimes.) A much beefier, five-piece frame was then inserted into the test fuselage and the testing resumed. The finalizing structural failure was a crack that initiated in the turtledeck on the upper fuselage and fractured down to the lower longerons. It was an ignominious end to a troubled test series.

In contrast, full-scale fatigue testing on the F-104G/MAP aircraft [Boensch, 1964] went through the entire four-lifetime test program with no major cracking observed (1963-1964). Following a fifth lifetime of 100% lateral gust loading, the airframe was cycled to 100% of the subsonic pull-up maneuver at 5 g's for an additional 775 cycles, at which time a catastrophic failure of the left wing occurred. The conclusions from the test were that the F-104G/MAP aircraft had adequate fatigue life without modification based on the usage spectrum tested.

On 12 June 1969, the definitive establishment document from ASIP occurred with the publication of Air Force Regulation 80-13. This document contained all the technical aspects of the ASIP programs, added a Phase VI on inspections, and assigned ASIP responsibilities to Headquarters USAF, Air Force Systems Command, Air Force Logistics Council and the using commands. It also included the implementation authority for the program.

On December 22, 1969, a catastrophic accident occurred when an F-111 lost a wing while on a training flight. Both pilots were killed and evidence pointed to the conclusion that they never had a chance to eject. The failure was found to originate at the lower wing pivot plate of this swing-wing fighter/bomber. The origin, shown in Figure 1.1.1 [Rudd, et al., 1979], occurred at a forging lap incorporated during the primary metal-working operation. Because of the proximity to a vertical reinforcement rib, it was not discovered in any of the production-level inspections.

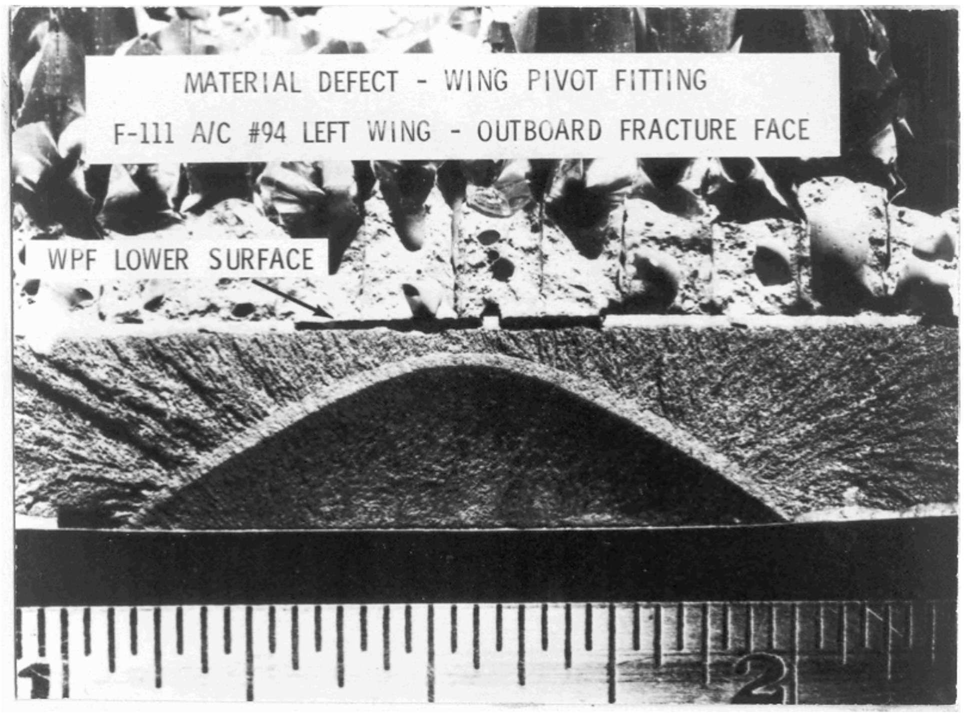

Figure 1.1.1. Origin of the F-111 Wing Defect [Rudd, et al., 1979]

This accident brought about the largest single material investigation ever, focused on D6AC steel. In addition to the database formed, a concept for releasing the aircraft for flight was based on a cold-proof test along with state-of-the-art NDI.

A Scientific Advisory Board assembled for the F-111 investigation subsequently recommended that a damage-tolerant design methodology be used for all future weapons systems. In September 1972, these new design concepts were incorporated into an ASIP document, MIL-STD-1530, Aircraft Structural Integrity Program, Airplane Requirements. MIL-STD-1530 incorporated all the applicable prior documents and also instituted the requirement that each aircraft system have an ASIP force structural maintenance master plan that identifies inspection and modification requirements and estimates the economic life of the airframe. This version of the ASIP document was also the most specific; it called out the Service Life Requirements clearly, as shown in Table 1.1.3.

Table 1.1.3. Service Life Requirements from MIL-STD-1530 [1972]

	Years of Service	Flight Hours	Number of Flights	Landings[(1)]	Fuselage Pressurization
Fighter					
Air Superiority					
Long-Range	15	8,000	6,000	8,000	8,000
Short-Range	15	6,000	8,000	10,000	8,000
Ground Attack	15	8,000	8,000	10,000	8,000
Bomber	25	15,000	3,000	5,000	5,000
Tanker	25	20,000	5,000	7,500	7,500
Cargo[(2)]					
Medium and Heavy	25	50,000	12,500	25,000	15,000
Assault	25	15,000	12,500	20,000	15,000
Utility	25	25,000	15,000	20,000	20,000
AEW&C[(3)]	20	40,000	4,000	8,000	6,000
Trainer					
Primary	25	15,000	15,000	40,000	15,000
Navigational	25	25,000	6,000	10,000	7,500

This table constitutes minimum structural design criteria and should not be used to interpret operational use (such as hours per flight)
(1)Full stop landings are assumed equivalent to the number of flights. Remainder are touch and goes
(2)Includes STOL & VTOL
(3)Includes command post systems

This was a period of rapid growth in both technical concepts for materials understanding and the development of methodologies for implementing the ASIP program. The Military Specification, Airplane Damage Tolerance Requirements, MIL-A-83444 (USAF), was issued in July, 1974 and presented detailed damage tolerance requirements as a function of design concept and degree of inspectability. In 1975, MIL-STD-1530A was issued to update and revise the process. The fatigue and fracture control plan of MIL-STD-1530 was replaced by the damage tolerance control plan of MIL-A-83444 and a durability control plan. An added section on chemical/thermal environment required contractors to also include these concerns in their design. After the publication of MIL-STD-1530A, AF Reg. 80-13 was updated. Since the technical responsibilities were now expressed in MIL-STD-1530A, Reg. 80-13 concentrated on the overall policy and responsibilities of the appropriate commands with respect to establishing, implementing, and utilizing the ASIP programs.

In February 1985, the ASIP requirements of MIL-A-83444 were revised in format and updated in content in MIL-A-87221 (USAF), General Specifications for Aircraft Structures. MIL-A-87221 was directed at specific design requirements for aircraft systems and presented guidance for demonstrating that the requirements were met. MIL-A-87221 (USAF) was superseded in June 1990 by AFGS-87221A in which the same format for requirements and verification guidelines were retained.

As part of the overall government acquisition reform initiative, the ASIP requirements were interpreted as ASIP guidelines with the issuance in November 1996 of MIL-HDBK-1530, "General Guidelines for Aircraft Structural Integrity Program." Further, the latest version of the structural requirements and verification guidelines were stated in the Department of Defense

Joint Service Specification Guide: Aircraft Structures, JSSG-2006. This guide is intended for all DoD departments and agencies and is predicated on a performance-based, business-environment approach to product development. JSSG-2006 was first released 30 October 1998 and is an evolving document.

In this Damage Tolerance Design Handbook, specific references to design requirements and verification guidance are from JSSG-2006 [1998].