The U.S. Army
Helicopter Structural Integrity Program

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1. Introduction

a. The Helicopter Structural Integrity Program (HSIP) was born of a need to clarify the engineering logic, gleaned from experience and lessons-learned, to insure structural safety, efficiency and durability. These qualities are addressed and rationally maintained through each phase of a U.S. Army helicopter weapon system from initial conceptual design studies to full field utilization of the aircraft (a so called "cradle to grave" concept).

b. A major theme of the HSIP is an understanding and appreciation of risk and the probability and consequences of failure. Helicopters in particular are subjected to a large variety and magnitude of repeated loads. The spectrum of flying conditions generating the loads is broad. The sensitivity of most structural materials to repeated loads varies greatly. The industries' techniques to account for these variables have been empirical in nature and not consistently applied. The HSIP will demand a more probabilistic approach to risk and will demand that the conservatism approved as reasonable and rational is consistently applied throughout the life cycle of the aircraft.

c. Another purpose of HSIP is to insure that the structures engineer's responsibilities for the structural safety, efficiency and durability of the aircraft are clearly defined at every step in the life of the fleet. Too often, in the past, the structures engineer's activities have ebbed and flowed in his efforts to insure structural integrity was being properly addressed. Initially he gets deeply involved in defining structural design criteria and making sure the design gets off to a good start. He then verifies by analysis and test that the design has a high probability of achieving its acceptable level of integrity. He then fades out of the picture until something nasty occurs which he must try to resolve. He has lost his team membership. HSIP will insure he gets back on the team with a clear charter for participation with Manufacturing, Maintenance and Logistic Engineering.

d. HSIP owes a great debt of gratitude to the U.S. Air Force's Aircraft Structural Integrity Program (ASIP) which led the way in clarifying and defining rules for maintaining structural integrity in fixed wing aircraft. HSIP builds on ASIP for the unique challenges of helicopters and rotary wing aircraft in general. Although HSIP preceded the new Total Quality Management (TQM) concept of weapon systems design and development, it is uncanny how well HSIP supplements and complements the Taguchi concepts of team effort, robustness and probabilistic methods to guarantee integrity.

e. This paper uses certain words and phrases in the American idiom that need clarification up front to enhance reader understanding of what the author is trying to convey:

1. Structural integrity means structural safety, efficiency (light weight) and durability (resistance to all environmental attack whether natural or man made).

2. Structure - Any component of the aircraft that carries primary flying or ground loads. [(HSIP does not address engines, transmissions or gear boxes. These items are usually treated as unique systems. The engine has its' own Engine Structural Integrity Program (ENSIP)].

3. Flight Safety Part - Any part, assembly, or installation whose failure, malfunction or absence could cause loss of or serious damage to the aircraft, and or serious injury or death to the occupants.

4. Safe Life - The life of a part in flight hours at which the beginning of failure is anticipated.

5. Defect (damage) tolerant - A part which has a degree of tolerance to structural degradation precipitated by a defect in manufacture or usage. (Ballistic tolerance is a separate consideration).

6. On-condition part - A part with a substantiated tolerance to a defect(s). The tolerance is utilized through proper maintenance procedures to permit the part to be retired on the basis of a readily detectable degradation.

f. Major steps in the successful evolution of an aircraft as a military weapon are as follows:

Structural design criteria

Initial design

Design substantiation (qualification)

Fabrication (manufacturing)

Field maintenance of structural integrity

The influence of HSIP on these steps will be discussed in the following paragraphs. In addition, the unique aspects of metals vs resin matrix fibrous composites in the structural integrity arena will be discussed. Finally the HSIP format and conclusions will be addressed.

2. Structural Design Criteria

The military customer wants an aircraft that doesn't break. One that will faithfully perform its mission under all kinds of adverse conditions. One that will get him there and back through a gauntlet of enemy threats. If worse comes to worse and he crashes, one that is forgiving and permits him to fly another day. Structure is a necessary weight and cost penalty required to hold the vehicle together so the soldier can perform his mission. (The structures engineer is never popular and is a hero only in his own mind's eye).

Since future wars are expected to be brief and intense, the aircraft weapon system will spend most (and hopefully all) of its life as a peacetime training vehicle for the real thing. It, therefore, must be low cost, easy to maintain and present little maintenance burden. To paraphrase a famous pugilist, "it must float like a butterfly, sting like a bee, and be cheap".

The military procuring agency specifies certain performance requirements as minimums of acceptability. One basic criterion is that the aircraft shall not bend or break due to the imposition of one loading application. The one-time loading application must have a very low probability of being exceeded in the life of the fleet. The magnitude of acceptable design limit loads is established empirically from experience gained over the past 80 years on many different aircraft. Additional conservatisms are added in the form of factors of safety and minimum margins of safety.

Another basic criterion is that the helicopter and its components shall not be sensitive to the effect of repeated loads. This sensitivity is commonly called fatigue.

The airframe made up of fuselage, empennage and landing gear is treated much the same way as its fixed wing counterpart. Criteria are defined similar to the Air Force ASIP standards except that safe life requirements will be required in combination with a purely damage tolerant design criterion.

The dynamic systems, including rotors, drive systems, and upper controls tend to be very sensitive to repeated loads. The spectrum of repeated loads imposed on the components is very broad including maneuvering and high vibratory loads. The U.S. Army recognizes that it may not be possible to demand dynamic systems that will last the life of the fleet without replacement. They do require a life high enough to minimize maintenance and logistics headaches. The minimum life required is usually in the order of 5000 flight hours.

3. Initial Design

The designer of modern day military helicopters is faced with a myriad of demands for utilization, protection and support of his vehicle. Within the constraints of these operational demands, he and the stress engineer work together to derive a load carrying system with optimum structural efficiency, safety and durability.

His initial efforts are to transmit design limit loads statically throughout the aircraft for minimum weight. He then evaluates his design for sensitivity to repeated loads concentrating on localized areas of load transfer or stress concentration. He compares these "hot spots", in terms of stresses related to normally expected operating conditions and to normalized fatigue strength data. His objective at this stage of design is to maintain a margin between anticipated frequently applied loads and the endurance limit of the selected material. (See Figure 1). Essentially he is hoping for a part insensitive to repeated loads - i.e., an unlimited life part. The weight penalty imposed on the component to compensate the design for the effect of repeated loads is small and rarely approaches 10% of the total weight of the part. However, initially designing helicopter dynamic components to be adequately resistant to the effects of repeated loads is the designer's and stress man's greatest challenge and requires a detailed understanding of strain flow and concentrations throughout the structure.

At this stage in the development of dynamic components expected to be Flight Safety Parts (FSP) the designer will be required to design for a degree of defect tolerance (i.e. damage tolerance) using the precepts of MIL-STD-1530 for metals and references 10 and 13 for composites. This inherent capability may be utilized in the final design substantiation step to qualify the part as a damage tolerant part leading to on-condition maintenance in the future. An additional beneficial aspect of this initial design effort could be the removal of the component from the FSP ranks with additional cost benefits. (FSP is discussed in more detail in paragraph 5 - Fabrication and Reference 8). At the end of this step fabrication of full scale test and flight hardware begins. It is interesting to note that whatever weight penalty the part imposes on the aircraft is fixed at this point.

4. Design Substantiation (Qualification)

The flight hardware is put through a rigorous analytical and test program to verify the static strength and resistance to repeated loads of each component.

Because it is anticipated that future helicopters will continue to include Flight Safety Parts (FSP), the U.S. Army's HSIP will emphasize conservative, low risk, requirements for their utilization. FSP may be qualified as "safe life" parts which rely on removal from service before a predicted failure can occur. Since fatigue strength and applied loads may be highly variable, a safe life assigned to a part must include a definition of the probability of failure at a life less than defined [1] Considering the number of FSP that may be exposed to failure in the life of the fleet, a probability of component failure must be low enough to predict less than one failure in the fleet life. The general equation defining this requirement is $(1 - .9_x) N < 1$. X is the number of nines probability that the selected life of a component will be exceeded. N is the number of FSP that may be exposed to failure in the life of the fleet. Various schemes are used in the helicopter industry to account for variability in fatigue strength and applied repeated loads. The schemes are empirical in nature and vary from one manufacturer to another. Application of these conservatisms are to a large extent left to the judgment of the designer. Occasionally conservatism is reduced on parts particularly sensitive to repeated loads thereby trading failure risk against cost or logistics considerations. The trade may be appropriate but it is sometimes conducted unilaterally rather than from a bipartisan basis. When a fatigue life is computed which is less than the specified requirement it indicates that the designer and stress man have failed to anticipate the sensitivity of the component to repeated loads and the component should be redesigned. Redesigning to improve component fatigue life costs little if any weight, but will cost time and money. If maintenance and logistics considerations can stand a low "safe life" part it could be temporarily used in the system. Conservatism (risk) should <u>never</u> be compromised.

The HSIP may not specify a procedure for defining safe life risk but it will require that flight loads test data be collected sufficient to evaluate loads variability in a probabilistic manner. The testing will be more extensive than past strain surveys with variables such as repeated data points, turbulence, and pilot techniques evaluated. Current practice in acquiring flight loads information is to fly a large number of individual maneuvers which start and stop in level flight. This methodology is appropriate for commercial helicopters, but it should be examined critically for modern military helicopters in which many maneuvers are strung together during high intensity usage. The current methodology does not capture some of the maneuver-to-maneuver transition loads which in some cases can be higher than the individual maneuver loads. HSIP will offer an alternative of assembling several discrete missions e.g., air-to-air combat, nap-of-the-earth (NOE) flying and performing the flight load surveys on those entire missions. The fatigue analysis would then combine the damage rates for those missions according to prescribed mission usage spectra.

The HSIP will also address fatigue strength definition in more detail. It will require in addition to the conventional constant load testing, spectrum testing late in the design development to evaluate Minor's hypothesis. The spectrum is to be as representative of actual usage as possible. Minor's hypothesis is usually defined as $\Sigma\left(\frac{n_1}{N_1} ---- \frac{n_r}{N_r}\right) = 1 =$ failure, where n_1 is the number of load applications at load level 1 and N_1 is number of applications of load level 1 to failure. It is very simple to use and has universal acceptance. There are flaws in it which could cause unconservative results. For FSP these flaws must be accounted for.

In addition to more stringent flight loads testing and fatigue strength definition, HSIP will require a clear understanding of the variability of aircraft mission spectra. The Army basically issues one mixed usage spectrum against which the fatigue design is qualified. It is deterministic in nature and although conservatively derived it has no statistical foundation. As a reliability based fatigue methodology is approached, the Army will perform a much deeper review of how aircraft are intended to be used. HSIP will discuss methods to statistically isolate aircraft which will spend their lives in basic flight training, and aircraft which will spend their lives in NOE or air-to-air combat training. This should result in a number of likely usage spectra and their likely distribution. The usage spectrum with the appropriate probability of occurrence would be defined for contractural life requirements.

Although safe life design is acceptable, damage tolerant design from an economically reasonable <u>safe life base</u> will be encouraged. Since low risk safe life implies throwing away a lot of "perfectly good" parts, the cost of instituting inspection procedures or monitoring systems might justify qualification as a damage tolerant part. Full qualification implies that the initial detectable failure is clearly compatible with the inspection procedure; (the probability of detection should also be evaluated)[2] and the rate of degradation to point of limit load failure is clearly defined. A highly reliable damage tolerant system might justify proceeding to an on-condition system (paragraph 6).

New damage tolerant features are not as attractive for helicopters as they are for fixed wing aircraft for the following reasons:

a. A damage tolerant design must have a long safe life to initial failure in order for the part to be viable from a logistics cost standpoint.

b. Some Flight Safety Parts have several fatigue failure modes. It is unlikely that a damage tolerant feature can be developed to cover all failure modes.

c. Because of the monolythic nature and sensitivity to high frequency vibratory loads of some FSP, the inspection or detection method may have to be sophisticated and applied frequently or monitored constantly.

The conclusion here is that FSP will need to develop both safe lives and defect (damage) tolerant features in order to utilize the most efficient and economical maintenance procedures.

When a helicopter system is finally fully qualified by analysis and test; when strain survey data, full scale strength data, design mission spectra, and Minor's hypothesis are conservatively combined; when damage tolerant characteristics are fully utilized, a few Flight Safety Parts will have failed to meet basic design requirements. The computed life of the part will be less than acceptable. At this point in systems development the rules of conservatism and risk level set down by HSIP must not be compromised. It must be accepted that the designer has failed, the part is deficient, it is too sensitive to repeated loads and inadequate for use in the weapon system. A design change must be initiated immediately to bring the part up to the HSIP and systems specification standards. (Temporary work arounds can usually be approved to minimize mission impact). "Making do" with deficient parts increases the risk of eventual accidents or maintenance and logistics headaches.

[1] A large amount of activity is being devoted to the question of quantifying conservatism in computing safe fatigue life (or put another way, answering the question how safe is safe?) See references 1,5,6 and 7. Reference 1 describes a simplified methodology which was used to substantiate fatigue conservatisms in qualifying the Chinook CH-47C to the satisfaction of the manufacturer and military customer. Appendix A graphically illustrates the method used. (See Figure 2).

5. Fabrication

HSIP is a major link in Total Quality Management (TQM) Concurrent Engineering. Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. HSIP will insure that the quality of the components used in full scale tests and analysis to verify the design are fabricated for production to the same (or better) structural standards.

During the qualification program manufacturing methods for production are being developed. A pit-fall often develops at this point that can compromise the results and conclusions reached during qualification. Highly loaded, fatigue critical Flight Safety Parts are sensitive to variation in fabrication methods. Often the test components used to establish fatigue strength of the part are made in a prototype experimental shop using fabrication procedures inappropriate for large scale production.

HSIP will require that fabrication processes be fully qualified at each step in system development and effect of process changes be fully analyzed and tested. If a process is deliberately omitted from a test component as a conservatism (e.g. shot peening), added test components including the process will be required. However tightly process specifications are written the fatigue strength distributions of the same part from two vendors are not likely to be identical. That may become especially important with composites. HSIP will address the minimum testing requirements for multi-source components.

Flight Safety Parts will have several critical fabrication characteristics identified which, because of their critical effect on structural integrity, cannot be altered during manufacturing. Any alteration found necessary will require a special engineering study conducted jointly by the manufacturer and government engineering.

6. Field Maintenance of Structural Integrity

A tendency in the past has been for the Structures Design Engineer to relax after he had substantiated the structural integrity of his aircraft. He left it to the Maintenance Engineer and Logistics Engineer to carry on and insure proper care was taken of the aircraft in the field. The insidious effects of repeated loads, both amplitude and frequency and environmental attack both natural and man made were not evaluated on a continuous basis. In essence, the critical components are never fully qualified and must be continually evaluated for structural safety and efficiency the entire life of the system.

In the spirit of Total Quality Management, the structures engineer, maintenance engineer and logistics engineer will work as a team under HSIP aegis[3].

A Flight Safety Parts Surveillance program will be required on all systems. It will bring back from the field selected components for inspection and test of anomolies. The anomolies may be induced by field usage or uncovered as the result of a manufacturing defect. Structural implications of manufacturing process changes to new parts will also be evaluated through this program. The effect on structural safety and efficiency will be defined and proper precautions taken. The precautions could include reduced safe life, increased inspection procedures, redesign, or elimination of the cause of the anomaly.

No matter how well disciplined the structural integrity program is, failures will occur in service. The HSIP will define procedures for evaluating the impact of these failures on the established safe life and damage tolerant maintenance program for the failed component. An interim safe life will be computed using actual failure data and non failure data in terms of component flight hours, and Weibull probabilistic methods (Ref 11). A "Weibull" life will be computed which yields an expected failure of less than one during the remaining life of the fleet or the calendar time that the defective component is expected to be utilized in service. The basic rule, $(1 - .9_x)\ N < 1$ discussed in paragraph 4 will be applied. When prima facie evidence of root cause or causes of the failure are established the component will be redesigned and requalified as damage tolerant and/or safe life to the same standards described in paragraph 4. Reference 12 describes a successful redesign of a deficient helicopter safe life pitch link. In this case the part was protected from failure by a "Weibull" life computation. It was redesigned and fully qualified as a damage tolerant component.

A major contributor to the fatigue integrity of Flight Safety Parts is a precise definition of the spectrum of repeated loads to which each individual part will be exposed. During initial qualification a conservative hypothesized mission spectrum is used in fatigue life computations (reference paragraph 4). When a new aircraft is fielded the pilots and war games experts find new and unique things to do with the aircraft. Their perception is that they are flying "within the envelope" defined by the operator's handbook. They do not recognize, nor should they need to recognize, the potential for fatigue degradation due to their flying habits and practices. It is up to the Engineering, Maintenance and Logistics team to provide this structural safety at all times. The HSIP will require a continual assessment of mission spectrum changes and their effect on safe lives of critical components and subsequent changes in inspection procedures and frequencies[4]. The methodology for conducting this assessment may not be specified. However it is obvious that new weapon systems will require integrated prognostics systems to reasonably and realistically monitor aircraft usage. Ideally such systems can allow big savings if they can be used to determine aircraft specific retirement lives for critical components. Once the usage monitoring systems have matured to where they can display "effective flight time" it becomes logistically feasible to make retirement lives aircraft specific. Figure 3 is a road map of activities leading to a successful systems life cycle.

7. Metals vs Resin Matrix Fibrous Composites

The HSIP applies to all helicopters (and rotary wing vehicles) made of all state-of-the-art structural materials. It accounts for the difference in physical features of metals vs composites. In general and speaking empirically, structural metals are efficient transmitters of static loads but can be sensitive to repeated loads if proper care in design is not taken. Metals are not sensitive to environmental degradation if properly protected. Fibrous composites are efficient transmitters of static loads especially if the complex strain distribution between fibers and matrix is clearly understood in transition areas. Composites are relatively less sensitive to repeated loads. However, composites are sensitive to temperature and moisture and their mechanical properties can suffer in natural ambient conditions. The HSIP program recognizes these advantages and disadvantages and insures that risks are properly assessed and conservatisms are not excessively imposed in the utilization of these structural materials. A major factor in the safe life and damage tolerance of composite components is a definition of the initiation of a significant failure. In order to capitalize on the potential weight benefits of composites it will be necessary to quantify the level of acceptable safe "damage" that composites tend to display early in their exposure to repeated loads[9].

Another factor that tends to penalize composites is the tendency to stack conservatisms during the static analysis. Very conservative limit loads, conserative temperatures and moisture levels are combined with high factors of safety and damage knockdown factors to establish static strength margins. The HSIP probabilistic concepts discussed in paragraph 4 can be applied to insure a more realistic conservatism is established.

8. Organization and Documentation

The U.S. Army will take the lead in documenting the Helicopter Structural Integrity Program. The task has fallen to the Army's Engineering Directorate within the Aviation Systems Command (AVSCOM) in St. Louis, Missouri. The initial step will be an Army regulation requiring that a standard be published. Then a standard will be prepared and finally detailed specifications will either be revised or created anew. Figure 4 describes the specification tree and a description of contents. Figure 5 is a publication schedule. Because of the long gestation time of military specifications, several key criteria will be published as AVSCOM Aeronautical Design Standards (ADS) and later incorporated into specifications.

9. CONCLUSIONS

The Helicopter Structural Integrity Program (HSIP) is a viable program which is being incorporated on new and redesigned U.S. Army helicopters. It will be formally published in official military standards and specifications in the near future. It promises to provide a clear basis for structural safety, efficiency and durability of helicopters.

When the time comes for joint international ventures in helicopter design, qualification and maintenance, the U.S. Army will be able to offer a comprehensive plan for consideration.

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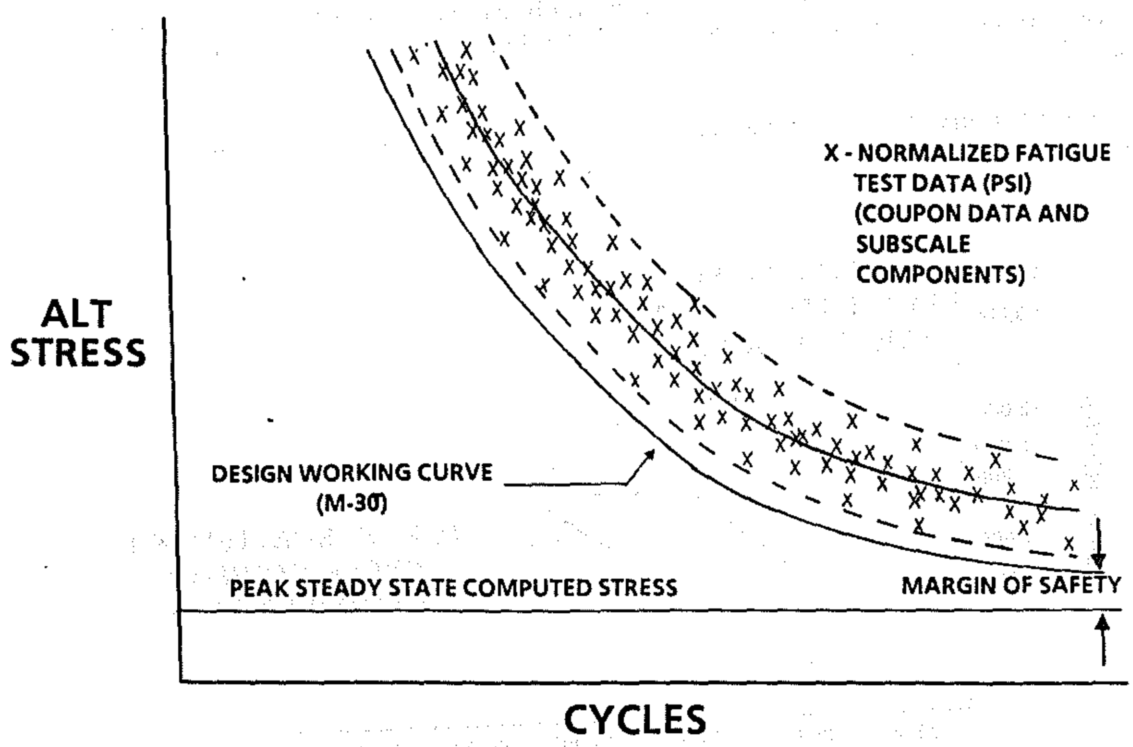

FIGURE 1. FLIGHT SAFETY PARTS INITIAL DESIGN

In this example, a safe life of 2800 flight hr was computed for a particular component using top of scatter loads data points from the Flight Loads Survey flight test program on the CH-47C and a M-3 fatigue strength curve from the full scale component tests. Working backwards from a life of 2800 hr and using all measured loads excursions from the flight test data, an equivalent fatigue endurance limit was established. Referring to the Weibull regression line for the part's fatigue strength variability, a probability value of .999993 was selected. The probability of the 2800 hr life being exceeded in operational use was attributed to be .999993.

Perhaps coincidentally, the CH-47C fleet has been free of serious fatigue failures in its rotor system. This is the stress man's conundrum.

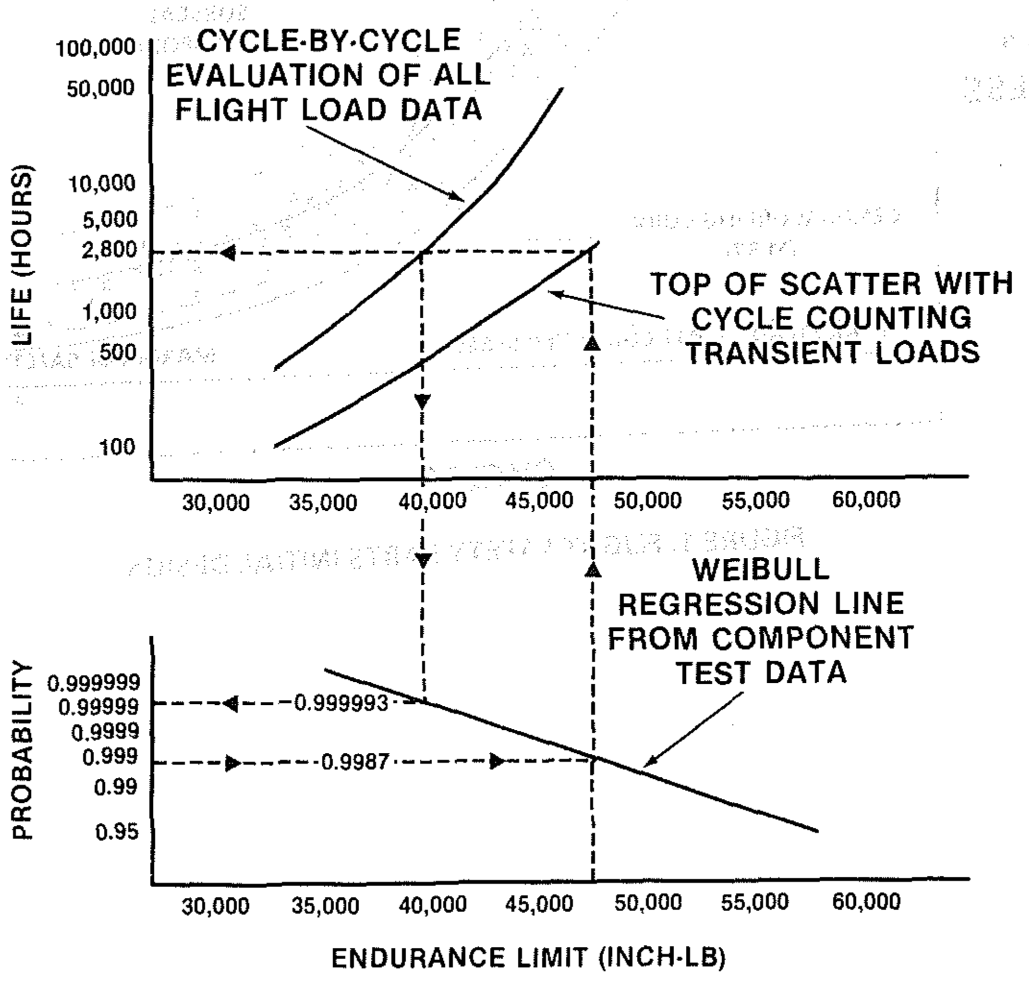

FIGURE 2. PROBABILITY OF EXCEEDANCE OF COMPONENT LIFE

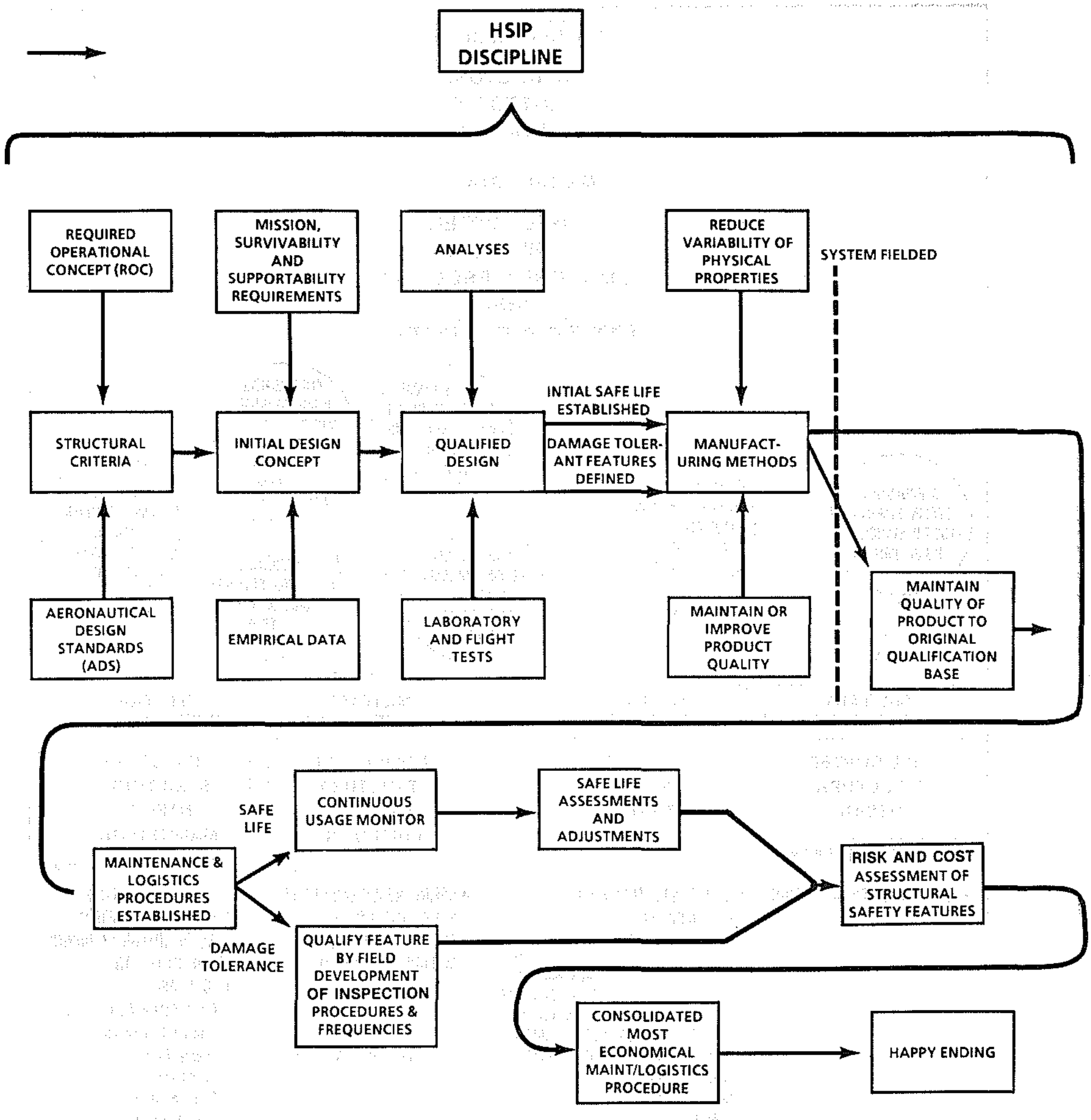

FIGURE 3. COMPONENT LIFE CYCLE

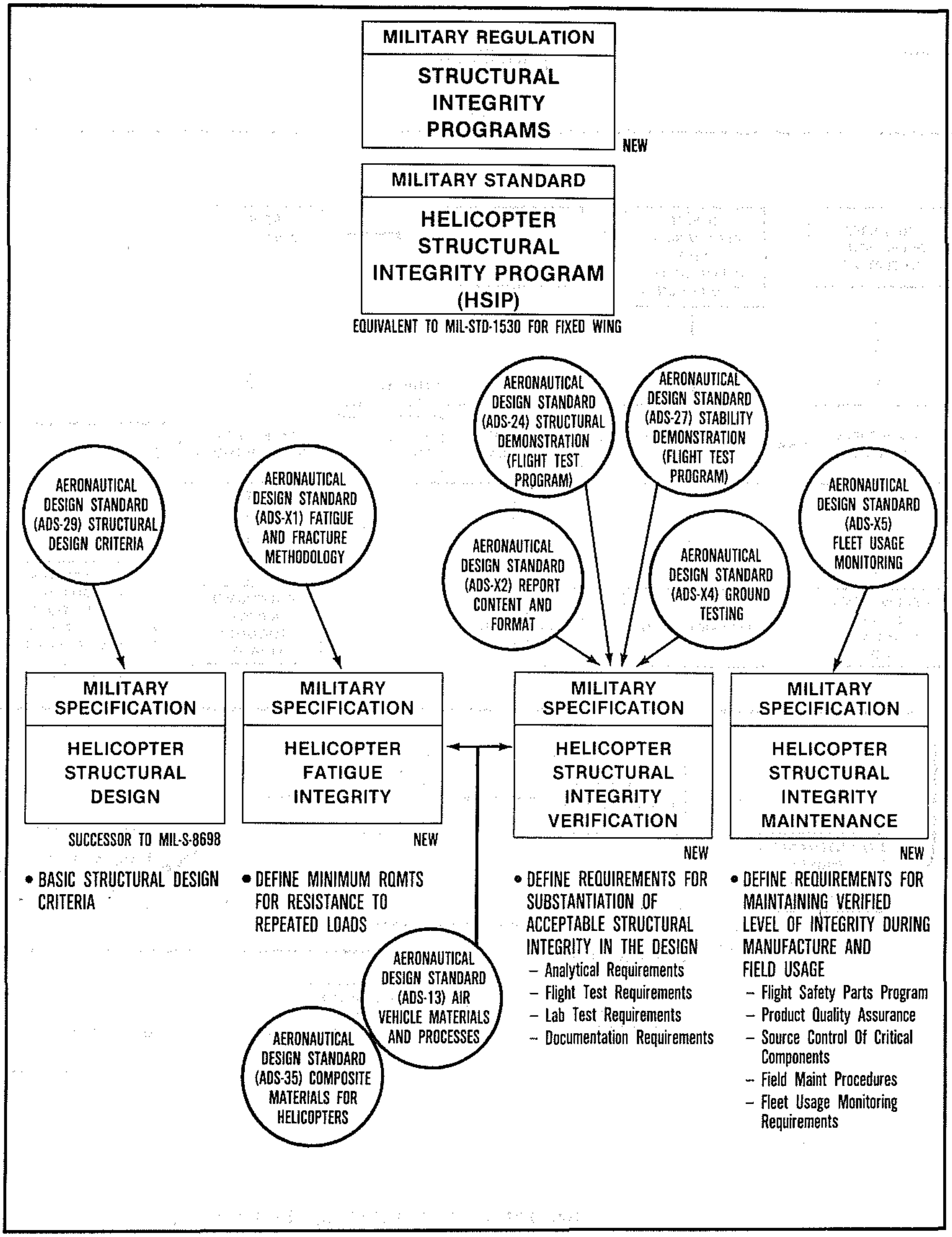
MILITARY REGULATION
STRUCTURAL INTEGRITY PROGRAMS
NEW
MILITARY STANDARD
HELICOPTER STRUCTURAL INTEGRITY PROGRAM (HSIP)
EQUIVALENT TO MIL-STD-1530 FOR FIXED WING
AERONAUTICAL DESIGN STANDARD (ADS-24) STRUCTURAL DEMONSTRATION (FLIGHT TEST PROGRAM)
AERONAUTICAL DESIGN STANDARD (ADS-27) STABILITY DEMONSTRATION (FLIGHT TEST PROGRAM)
AERONAUTICAL DESIGN STANDARD (ADS-29) STRUCTURAL DESIGN CRITERIA
AERONAUTICAL DESIGN STANDARD (ADS-X1) FATIGUE AND FRACTURE METHODOLOGY
AERONAUTICAL DESIGN STANDARD (ADS-X2) REPORT CONTENT AND FORMAT
AERONAUTICAL DESIGN STANDARD (ADS-X4) GROUND TESTING
AERONAUTICAL DESIGN STANDARD (ADS-X5) FLEET USAGE MONITORING
MILITARY SPECIFICATION
HELICOPTER STRUCTURAL DESIGN
SUCCESSOR TO MIL-S-8698
• BASIC STRUCTURAL DESIGN CRITERIA
MILITARY SPECIFICATION
HELICOPTER FATIGUE INTEGRITY
NEW
• DEFINE MINIMUM RQMTS FOR RESISTANCE TO REPEATED LOADS
MILITARY SPECIFICATION
HELICOPTER STRUCTURAL INTEGRITY VERIFICATION
NEW
• DEFINE REQUIREMENTS FOR SUBSTANTIATION OF ACCEPTABLE STRUCTURAL INTEGRITY IN THE DESIGN
– Analytical Requirements
– Flight Test Requirements
– Lab Test Requirements
– Documentation Requirements
MILITARY SPECIFICATION
HELICOPTER STRUCTURAL INTEGRITY MAINTENANCE
NEW
• DEFINE REQUIREMENTS FOR MAINTAINING VERIFIED LEVEL OF INTEGRITY DURING MANUFACTURE AND FIELD USAGE
– Flight Safety Parts Program
– Product Quality Assurance
– Source Control Of Critical Components
– Field Maint Procedures
– Fleet Usage Monitoring Requirements
AERONAUTICAL DESIGN STANDARD (ADS-13) AIR VEHICLE MATERIALS AND PROCESSES
AERONAUTICAL DESIGN STANDARD (ADS-35) COMPOSITE MATERIALS FOR HELICOPTERS

FIGURE 4

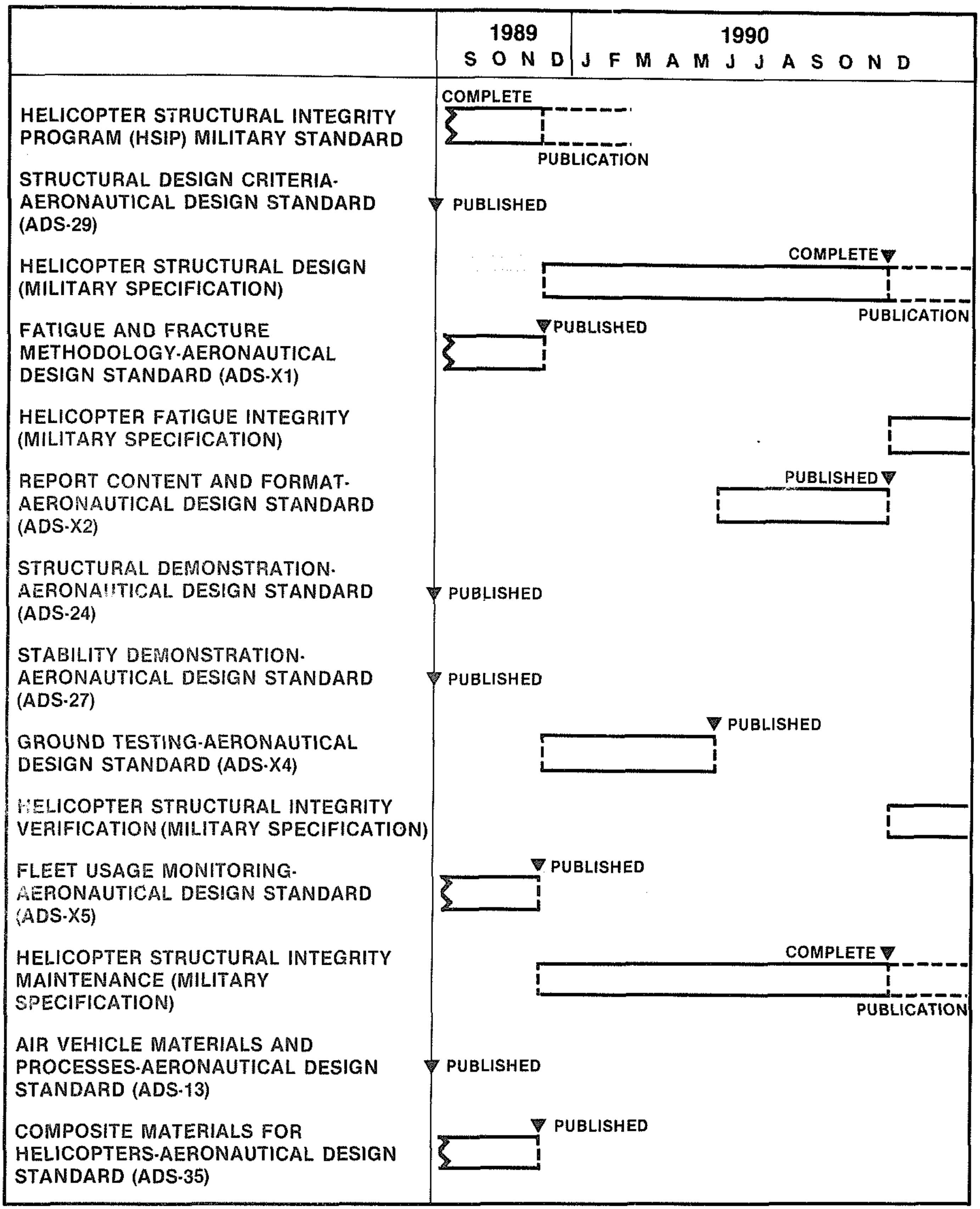

FIGURE 5. HSIP CALENDAR