OVERVIEW OF ROTORCRAFT STRUCTURAL INTEGRITY - WHERE HAVE WE BEEN AND WHERE ARE WE GOING? [i]

Dr. Daniel P. Schrage
Professor and Director,
Center of Excellence in Rotorcraft Technology (CERT)
Co-Director, Aerospace Systems Design Laboratory (ASDL)
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

Rotorcraft are complex, but versatile machines that perform a variety of civil and military missions, thereby making fleet usage often difficult to track. While the fixed wing community has moved from a safe-life (1950s) to failsafe (1960s) to damage tolerant (1970s) structural design philosophy for most of the entire aircraft, many rotorcraft dynamic component lives are still calculated using a safe-life design approach. This fairly conservative approach is principally due to the uncertainty in usage and rotor loads prediction and measurement in both the low speed and high speed flight regime. Military helicopters in the past have included ballistic damage tolerant and failsafe design approaches, and new military rotorcraft developments, such as the V-22 Tilt Rotor Aircraft (Osprey) and the RAH-66 Conventional Helicopter (Comanche), are taking more of an overall damage tolerant and failsafe approach. It is, however, extremely difficult today, if not impossible, to substantiate and validate the entire aircraft using only a damage tolerant approach. Therefore, a piecemeal structural design philosophy is still being used for most rotorcraft. Active research and engineering assessments (at a fairly low level) have been ongoing in the U.S. to move to a more integrated structural design philosophy. Army, Air Force, Navy, NASA and the FAA have all had small efforts. The Army has initiated a reliability-based approach for integration into a Helicopter Structural Integrity Program (HSIP), similar to the Air Force's fixed wing Aircraft Structural Integrity Program (ASIP). The Air Force has supported efforts to apply the fixed wing damage tolerance approach (ASIP) to its special operations helicopters. The Navy has developed a structural monitoring system based on the regime recognition concept for fatigue tracking of individual dynamic components. NASA has continued a low level effort to develop fracture mechanics databases for metals and composites, applicable to rotorcraft. The FAA is requiring movement to a damage tolerant approach and has initiated a low level Research Proposal Initiative (RPI) entitled: Rotorcraft Structural Integrity and Safety Issues (now called Aging Rotorcraft).

This paper will review some of these ongoing efforts, as well as discuss where it appears "rotorcraft structural integrity" is going based on recent emphasis on affordability and the advent of enabling technologies, such as Health Usage Monitoring Systems (HUMS).

Overview of Aircraft Structural Integrity

Design criteria, along with mode of failure, and allowables data for sizing aircraft structures is summarized in Figure 1 [Ref. 1]. Even though a large portion of a modern aircraft is made up of composite structure most of the design criteria is

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still based on the experience and databases developed for metallic structures. The bulk of static and fatigue strength properties are identified through stess-strain and alternating stress - time (cycles) relationships as illustrated in Figure 2 [Ref. 2]. While both fixed and rotary wing aircraft must be designed for a combination of static and fatigue loadings, rotorcraft are much more fatigue design critical as will be explained in the next section.

Aircraft design, development, and certification in a generic sense is illustrated in Figure 3 [Ref. 1]. The total fatigue design philosophy must account for both safe life and fail safe design considerations, with damage tolerance being a subset of fail safe design. *Safe Life* means that the structure has been evaluated to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks. *Fail Safe* means that the structure has been evaluated to assure that catastrophic failure is not probable after fatigue failure or obvious partial failure of a single, principal structural element. *Damage Tolerance* means that the structure has been evaluated to ensure that should serious fatigue, corrosion, or accidental damage occur within the operational life of the aircraft, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected [Ref. 3].

From Reference 1 characteristics of the *Fail Safe* philosophy are:

- Structure has capability to contain fatigue or other types of damage
- Requires:
  - Multiplicity of structural members
  - Load transfer capability between members
  - Tear resistant material properties
  - Slow crack propagation properties
- Inspection controls
- Fatigue is *maintenance problem*

Characteristics of the *Safe Life* philosophy from Reference 1 are:

- Structure resists damaging effects of variable load environment
- Requires knowledge of :
  - Environment
  - Fatigue performance
  - Fatigue damage accumulation
- Limit to service life
- Fatigue is *safety problem*

Progressive failure of a structural element is illustrated in Figure 4 [Ref. 1]. Fatigue is a progressive failure mechanism and material degradation initiates with the first cycle. The degradation/damage accumulation progresses until a finite crack is nucleated, then the crack propagates until the failure process culminates in a complete failure of the structure. As illustrated in Figure 4, the total life, from the first cycle to the complete failure, can be divided into three stages:

(1) Initial life interval during which a complete failure can occur only when the applied load exceeds the design ultimate strength, i.e., time to initiate a crack which will tend to reduce the design ultimate strength capability. This time interval is usually defined as the fatigue life or the *Safe Life* interval.
(2) Life interval, after *Safe Life* interval, during which a complete failure will occur even when the applied load is below the ultimate design load and the strength reduction, due to a small crack, is a function of the material fracture toughness properties.
(3) Final life interval, during which a complete failure wil occur even when the applied load is below the ultimate design load and the strength reduction is a function of the material fracture toughness properties and area reduction due to a growing crack.

(2) and (3) combine to form a time interval which may be called the *Fail Safe* life. The length of this life is a function of the residual strength reduction rate, crack propagation rate and the fail-safe design criteria which llimits the residual strength to the limit load established by the certifying agency. The *Fail Safe* life corresponds to the time interval between inspections. This means that a crack which may initiate after an inspection should not propagate to a critical length; that is , the residual strength should not decrease below the *Fail Safe* design load before the next inspection, during which the crack should be detectable [Ref.1].

Structures which exhibit a very short *Fail Safe* life interval and where structural redundancy cannot be practically provided (which for fixed wing aircraft might be the nose and main landing gears) are usually designated as *Safe*

Life structures. Rotorcraft, due to their dynamic and mechanical complexity, have a number of additional items, such as main rotor and tail rotor shafts and pitch links and transmission drive train components. On the other hand, structures which have a finite *Fail Safe* life, and usually contain strutural reduncancy such as wing skin-stringers for fixed wing aircraft and composite rotor blades for rotorcraft (one reason composites where introduced early on rotorcraft). *An optimum fatigue design should exhibit a high reliability Safe Life for the purpose of aircraft availability and economical operation and a reasonably long Fail Safe life for safety, and to a certain extent economical operation by minimizing the inspection frequency.* [Ref. 1]

In summary, it can be seen that fatigue performance is a multi-variate phenomenon and requires a concurrent engineering and integrated product/process development (IPPD) approach. The design criteria must be pointed towards controlling the many features of design and manufacturing affecting the realization of fatigue performance. Design planning and execution, manufacturing quality control, analysis, test demonstration, inspection, and service monitoring of the aircraft experience and usage provide means to produce or maintain a high level of fatigue performance. [Ref. 1]

Introduction to the Rotorcraft Problem

While rotorcraft are extremely versatile machines and have a variety of civil and military applications, they are extremely complex machines to design, analyze, build and certificate. The multidisciplinary complexity of rotorcraft is illustrated in Figure 5. The fact that rotorcraft have virtually six degrees of freedom maneuverability capability in low speed provides incomparable agility in this regime (to fixed wing aircraft), but complicates flight envelope definition and provides an extremely complex multidisciplinary environment and unique interactions with the environment (terrain, earth boundary layer turbulence, wake induced from obstacles,etc.). In low speed flight the vortices shed from each blade interact with the next blade and the rotor wake below the rotor interacts with the airframe and the surrounding environment. In high speed flight the differential velocities seen across the rotor disk by the advancing and retreating blades cut across the subsonic flow regime and deep into transonic flow. The faster the helicopter goes the more the retreating blade is stalled, as the velocity differential between forward flight and rotor rotational speed approaches zero and causes it to operate at higher and higher local blade angles of attack. This flow environment is further illustrated in Figure 6 and shows that the tip of the retreating blade is stalled and that further inboard reverse flow (trailing edge to leading edge) is encountered. On the contrary, the advancing blade is operating at very small local angles of attack(even negative) and the tip is experiencing extreme compressiblity effects with a resultant drag rise. To keep the rotor from rolling to the left (due to the asymmetric lift distribution) most of the lift on the advancing side cannot be used and the working section of a rotor in forward flight is mostly the forward and aft sections.

Rotorcraft have properly been called "aeroelastic machines" and this is illustrated by the interdisciplinary interactions for the main lifting rotor in Figure 7. In addition to the complex aerodynamics discussed in the preceding paragraph substantial dynamics (both structural and kinematic) are also involved. Structural dynamics, associated with high aspect ratio blades coupled with a complex drive system and a relative soft fuselage (due to cutouts for doors, etc.), are strongly coupled with the complex aerodynamics. Tranformations between rotating and dynamics components and the fact that the flight controls are directly coupled in both the stationary and rotating environment provide substantial kinematics complexity. All of this complexity is illustrated by a number of feedback loops in Figure 7.

For all the complexity that rotorcraft entail they are truly elegant machines in that they provide six degrees of freedom control in hover, low speed flight (all directions), and forward flight with only two devices (lifting rotor and engine) and are the most agile machines, in terms of turning rate, as illustrated in Figure 8. The ability to turn 80 degrees per second without altitude loss is remarkable, but readily realized in most rotorcraft in low speed flight.

Review of Past and Evolving Rotorcraft Structural Design Philosophies

This section will review some of the various efforts in the U.S. to improve rotorcraft structural integrity.

U.S. Army. While a safe life structural design philosophy has served the helicopter industry well during its early years of development, there has been a continuing interest since the mid 1970s in trying to replace it with a less conservative, more affordable approach based on damage tolerant and/or failsafe approaches. Following the major Army helicopter development programs of the 1970s (UTTAS-UH-60 Black Hawk; AAH- AH-64 Apache) the American Helicopter Society (AHS) hosted a Specialists' Meeting on Helicopter Fatigue Methodology [Ref.4]. A highlight of this Meeting was the presentation of the manufacturers' (U.S. and Europe) fatigue methodology based on a calculated fatigue life of a hypothetical helicopter component. Using various treatments of the same basic data, the seven companies calculated fatigue lives for the same component (a pitch link) with variations from a low predicted life of 745 hours to a life in excess of 1,000,000 hours. While all predicted lives could be considered conservative, the sensitivity of calculated fatigue life to minute variations in critical values of the parameters indicated that any arbitrarily selected schedule or technique may produce a highly erroneous estimate of fatigue life. Subsequent to this Specialists Meeting the Structures and Materials Panel of the Advisory Group for Aerospace Research and Development (AGARD) published a Helicopter Fatigue Design Guide [Ref.5] and a follow-up AHS Helicopter Fatigue Specialists' Meeting was held in 1984. [Ref. 6]

Following these meetings the Army pushed for a reliabliity-based approach and developed Aeronautical Design Standard (ADS)-29: Structural Design Criteria For Rotary Wing Aircraft [Ref.7], which specified combined minimum fatigue strength, severe loads, and severe usage with Miner's cumulative damage theory to compute fatigue lives with a remote probability of failure. The objective of the Army approach is to quantify this remote probability of failure with the goal of achieving a one in a million failure which means a reliability of 0.999999 (six nines). The rationale for this approach is that Army operates a fleet of over 6000 helicopters. Each of these rotorcraft has on the order of 100 flight critical components. In general, the airframes have been kept in service much longer than originally anticipated, while many critical parts are replaced at predetermined intervals. Still, at any one time, almost one million of these components are in service and they must serve their function safety. For this reason, the Army and its rotorcraft contractors aim to design and operate these components with a risk of failure of roughly one in a million, or a reliability of six nines. [Ref.8]

Later in the 1980s the Army initiated an Army Helicopter Structural Integrity Program (HSIP) to incorportate this approach [Ref.9]. Rationale for this initiative was that current (then) rotorcraft design and development specifications were outdated and require extensive revision to keep pace with emerging technologies. It recommended that the Army establish overall statistical reliability as a design goal, since it was felt that a *statistically based design requirement is compatible with any chosen design methodology*, and it would provide the Army with a means to establish, evaluate, and substantiate structural integrity. An alternative to either safe-life or damage-tolerant design was proposed as the total life approach, which was intended to marry the two concepts. The proposed total life methodology is illustrated in Figure 9 and was developed for metallic structures. It was intended to encompass both the time to crack initiation size and the time to propagate the crack to failure. The requirements for crack initiation would guarantee durability while the requirement for crack growth would imply a damage-tolerant design. The time to crack initiation could be determined by a local strain-life approach which bounds the fatigue life for each selected maximun load value. The local strain-life approach would mimic a safe-life design by utilizing a strain-life curve and a cumulative damage algorithm such as the Palmgren-Miner rule. For the crack propagation portion of the total life approach, the crack growth for metallic structure can be predicted by various models relating crack growth rates and the stress intensity factors. [Ref.9]

While the total life approach was proposed it has not been completely developed or implemented. Several studies have been undertaken to assess the viability of the reliability based approach and HSIP. A round robin approach involving industry and government was established by the American Helicopter Society (AHS) Subcommittee for Fatigue and Damage Tolerance to investigate reliability-based fatigue methodology. [Ref.8] The results from this round robin reaffirmed that much more work is needed before reliability-based fatigue design becomes standard industry practice [Ref. 8]. A loads analysis program based on CH-47D Chinook helicopter flight load surveys and structural demonstrations was conducted as part of the U.S. Army HSIP [Ref.10]. One objective of the HSIP was to monitor fatigue damage to critical components by measurements obtained on individual fleet aircraft. The goal of the loads study was to devise a method of obtaining all required fatigue loads without any measurements in rotating aircraft systems. Some difficultiess were encountered, but it was felt that with additional effort an acceptable solution for CH-47D and MH-47E model Chinook helicopters appears to be feasible. [Ref.10]

U.S. Air Force. The Air Force has contracted with Sikorsky Aircraft and the Georgia Tech Research Institute (GTRI) to evaluate the practicality of using the Air Force's Aircraft Structural Integrity Program (ASIP) damage-tolerant approach for its special operations helicopters (H-53 and H-60).

Sikorsky Aircraft entered a contract with the Warner Robins Air Logistics Center (WR-ALC) in the early 1980's to evaluate the applicability of damage tolerance for broad based force management of the H-53 cargo/transport helicopter rotor and dynamic structure [Ref.11]. Since WR-ALC manages their large inventory of fixed wing C-130's and C-141's and F-15's on a damage tolerance basis, it was logical to evaluate this approach for helicopter rotor and airframe structure. This work by Sikorsky indicated that damage tolerance design and management is feasible for helicopter airframes and some if not all rotor structure. It also indicated by 1990 that while significant progress was made, problems still exist in the basic technology which needs to be addressed before safe damage tolerance management can be realized. One significant problem identified was the legacy of safe life management in which a high degree of conservatism has been used in defining usage data and fatigue loading, which is not appropriate in damage tolerance. Key technical issues were identified for technology development [Ref.11] and are identified as follows:

Element	Recommended Action
•Flight Test Data Processing	•Complete Cycle Counting
•Flight Data Recorder	•Improved Usage and Loads Data
•Crack Propagation	•Small Cracks Data (.005-.020 inches) •Propagation Models •Threshold Scatter and Retardation Data
•NDI	•Applicability of Engine NDI to Helicopters
•Stress Analysis Verification	•Strain Surveys on Full Scale Parts (e.g. Main Rotor Head)
•Threaded Parts	•Improved Stress Analysis and Stress Intensity Models •Crak Propagation Verification Data
•Regime Sensitivity	•Critical Flight Regimes

Many of these development efforts have been supported and funded by the Air Force and since the late 1980's Sikorsky Aircraft and the Georgia Tech Research Institute (GTRI) have worked pretty much in partnership with the Air Force in moving helicopter damage tolerance assessment forward, at least for metallic components for fielded aircraft.

As part of the H-53 Damage Tolerance Assessment Program Sikorsky Aircraft developed and delivered to WR-ALC a general computer pocessor for damage tolerance assessment of helicopter structure. Basically this processor provided the databases and management software to generate usage load, and stress spectra; a crack model, and perform the crack propagation analysis. For the H-53 program the databases where constructed for this aircraft, but could be replaced with those for any other aircraft. Planned interfaces were with flight data recorder usage data and with improved flight test data. [Ref. 11]

GTRI has worked with WR-ALC and Sikorsky Aircraft over the past five years in an effort to improve this computational toolkit, now called Structual Integrity Computer Program (SICP) [Ref.12] and is illustrated in Figure 10. This program can now be used for both safe-life and fail-safe approaches for Force Management. It includes damage tolerance analysis of some critical MH-53J structural components and safe-life analysis of all MH-53J dynamic components. Crack initiation and crack growth analyses consider short crack and closure effects, complex geometries, and load spectrum effects. Fatigue analysis results for components were validated when possible by correlation with full scale test results. GTRI extended the capabilities of the basic SICP system to allow data from any flight test program to be rainflow cycle counted and to evaluate the effects of rainflow cycle counting on crack propagation life. Implementation of this capability also required the development of a flight loads translator, and modification of the spectrum generation software. GTRI modified the software to include variable loop counters and array dimensions that would allow more refined data to be used. Six new efforts currently on-going are: Incorporate Short Crack Model in SICP; Incorporate Top of Scatter Flight Loads Methods; Include a Flexible Flight Regime Substitution; Include a Robust Usage Spectrum Generator, Insure NASGRO-SICP Compatibility; and Include a Loads Prediction Code (CAMRAD-II). The basic SICP program is in place at WR-ALC and is intended to function either in a stand-alone mode or with other logistical programs that track parts and aircraft usage. [Ref.12]

U.S. Navy. The Navy has developed a structural usage monitoring system based on the regime recognition concept for fatigue tracking of individual dynamic components with the objectives of maximizing the safety, reliability, and readiness of the fleet in an environment of limited defense resources [Ref. 13]. The first Structural Data Recording Set (SDRS) was installed in the AH-1W Cobra fleet in February 1993. Fifty aircraft were equipped with SDRS and a total 3,400 flight hours of usage were required. Conclusions drawn from this Navy effort [Ref.13] were:

1. Helicopter component fatigue strength, usage, and component flight loads in each regime can be modeled with a three-parameter Weibull distribution.

2. The incremental joint probability density function of a component failure due to three independent variables (usage, load, and strength) can be numerically computed using Weibull distribution parameters and the expression of cumulative probability density function.

3. The reliability associated with each life can be accurately determined. The contribution of usage, load, and strength to six nines reliability can be identified.

4. The reliability associated with a life is a function of the approach with which it is determined. The differences in methodology could result in as much as two nines difference in reliability prediction.

5. Additional work in evaluating each of the variables is necessary if an acceptable reliability methodology is to be developed.

FAA. The FAA's position is that damage-tolerant design is the only practical way to decrease the number of accidents involving fatigue failures in civilian aircraft [Ref.14]. The FAA has also noted that if damage tolerance is only 50 percent effective, then the fatal fatigue accident rate would be reduced by one-half. In 1995 the FAA started a Research Project Intitiative (RPI) - Rotorcraft Structural Integrity and Safety Issues [Ref.15]. This RPI was composed of six tasks with the following industry sponsors:

1. *Rotorcraft Health Usage Monitoring Systems (HUMS) Operational Development -*

Bell Helicopter Textron, Inc. and Petroleum Helicopters, Inc.

2. *Teetering Rotor System Aircraft* - Robinson Helicopter

3. *Damage Tolerance Database and Application Methodology* - To Be Determined (TBD)

4. *Guidance Material for Replacing Existing Parts with Advanced Material Parts*- TBD

5.*Fly-By-Wire Certification Requirements* - TBD

6. *Crash Protection Airbag Application to Light Helicopters* - Simula/Sikorsky Aircraft

Results from the first task were reported by Bell Helicopter Textron at the 52nd AHS Annual Forum in Washington D.C [Ref.16]. Usage data, collected on a Bell Model 412 helicopter that was equipped with a commercially available HUMS and operated by Petroleum Helicopters Inc. (PHI) under an independent flight trial program, was used to evaluate two usage monitoring techniques, flight condition recognition (FCR) and flight load synthesis (FLS). For the selected components that were analyzed, the results of the evaluation indicated a potential for extending retirement lives. This was due to the damage accumulation rate for the FCR and FLS techniques being slower ("slow clock") than the current method of using actual flight hours as the basis for retirement times. Based on the mission flown for this aircraft, which is transporting workcrews to offshore oil platforms, the flight hours charged against retirement times could be reduced by 50% or greater. Thus the operator would gain a considerable payback in reduced maintenance costs due to extension of retirement intervals. [Ref.16]

The use of HUMS on rotorcraft is seen as an excellent opportunity to improve safety while at the same time save on operations and support cost. HUMS activities for rotorcraft are taking place around the world. In Britain the Civil Aeronautics Authority (CAA) has sponsored trials to prove the technology. North Sea helicopter operators are equipping fleets with HUMS and working groups have been active since 1986. Military applications for HUMS are also proceeding in the U.S. Navy and Army, and in the U.K. Ministry of Defense (MOD).

WHERE ARE WE GOING?

Safety and affordability are key drivers of where rotorcraft structural integrity is going? While safety has always been predominant NASA and FAA initiatives to drive safety to even higher levels will have a pronounced impact, especially on aging fielded helicopters. Affordability has always been the Achille's heel of rotorcraft and is now being addressed in the aggessive manner required. At the AHS 53 Forum three special sessions were incorporated to address affordability. Presentations from the special session addressing the operations and support aspect of affordability and the HUMS Session will be used to address where rotorcraft structural integrity is headed.

The current practice of limited life is illustrated in Figure 11 [Ref. 17], and illustrates how the different elements combine to produce a fatigue life, usually using Miner's Rule. While conservative fatigue lives are usually obtained, this practice still does not account for failures to presence of flaws and extreme usage. The presence of flaws is where *damage tolerance* methods promise design for flaws, evaluate for flaws, and inspect for flaws. Extreme usage can be addressed through usage monitoring to verify design usage, account for extreme usage, and provide for individual usage monitoring. [Ref.17]

Usage monitoring together with health monitoring forms the bulk of what is in a current state-of-the-art HUMS [Ref.18]. There are five categories of usage monitoring being discussed in most circles, namely (1) simple measurement of time in flight, hover etc, (2) flight regime recognition, (3) maneuver recognition, (4) loads synthesis, and (5) direct strain measurement. Only one of these, the first, is in service. The problem is that as one moves further and further away from the ideal (i.e. direct measurement) the usefulness of the technique diminishes in respect to the benefits that can be claimed. Everything must therefore be a compromise based on (a) system cost,(b) system maintainability, and (c) benefit in terms of life extensions gained [Ref. 18]. The potential benefit of usage monitoring is illustrated in Figure 12 [Ref. 19]. A distinction between predicted fleet *basic usage* and *advanced usage* can be made. *Basic usage* is defined in terms of parmeters such as flight hours, number of flights and engine starts. *Advanced usage* is based on a more rigorous determination of how the aircraft is being used on a real-time basis. *Advanced usage* requires that algorithms be developed to recognize how the aircraft is being used and to then predict how much component life was used. Thus it can be seen that *Advanced usage* allows determination of usage from mild to severe, while *basic usage* only provides a predicted usage and can be used to reduce maintenance costs, but not the risk of unexpected failures. [Ref.18]

Further discussion of the importance of regime recognition and simpler approaches which utilize fixed system statistics to predict fatigue damage are provided in Ref. 20. While at least two HUMS cost-benefit studies have been recently undertaken, the jury is still out on the conclusiveness of their results [Ref. 21]. Recent workshop results from the NASA/FAA Aviation Safety Investment Strategy Team (ASIST) has identified Rotorcraft HUMS as having the strongest potential for improving rotorcraft safety [Ref.22]. The bottom line which summarizes where safety level and affordability is driving rotorcraft structural integrity is illustrated in Figure 13 [Ref.17]. Reliability is plotted versus service time. This figure provides a good assessment of where rotorcraft structural integrity is headed. It is based on the hypothesis that damage tolerance design safegards against failures due to presence of flaws, while inspections are a very effective way to increase structures service life and reliability, i.e., to increase structures affordability. [Ref.17]

CONCLUSIONS

Ensuring rotorcraft structural integrity is extremely complex and not always appreciated, due to the relatively low static load flight envelope (~3gs) for helicopters, i.e. V-N diagram. However, the capability of rotorcraft to provide six degrees of maneuvering freedom in low speed flight make them the most agile (in terms of turning rate) of aircraft. This capability also makes defining flight envelopes, both steady and transient, extremely difficult due to the aeroservoelastic complications of the problem. Structural design philosophies for rotorcraft have evolved at a much slower rate than for fixed wing aircraft, largely due to the inability to accurately predict the oscillatory loads and track crack growth in a high cycle environment. The utility of rotorcraft and their usage in a variety of environments also make tracking fleet usage and crack detection and growth extremely difficult. Therefore, no single structural design philosophy, such as damage tolerance, has been accepted. There are low level efforts in industry and government to move toward an integrated structural design philosophy/methodology, but no unified approach. One particular promising technology for rotorcraft structural integrity is Health Usage Monitoring Systems (HUMS) which will allow the individual tracking of usage, provided it proves to be cost effective. If successful, affordability can be achieved through a tradeoff between the minimum *Safe Life* and *Reliability* required and the minimum number of inspections required to achieve this *Reliability*. This can evolve into the optimum structural integrity approach for rotorcraft.

As stated at the beginning of this paper, much of aircraft structural integrity and damage assessment is based on metallic structures and databases. Research efforts are underway to include approaches to damage calculations for composites, such as that being conducted at the Georgia Tech Center of Excellence in Rotorcraft Technology (CERT) [Ref. 23]. Damage Modes for Composite Fracture Analysis are illustrated in Figure 14 and shows the complexity of the problem, although fail safety is inherent in most composite structures.

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Mode of Failure	Design Criteria	Allowables Data
Static strength of undamaged structure	Structure must support ultimate loads without failure for 3 seconds	Static properties
Deformation of undamaged structure	Deformation of the structure at limit loads may not interfere with safe operation	Static properties and creep properties for elevated temperature conditions
Fatigue crack initiation of undamaged structure	1. Fail-safe structure must meet customer service life requirements for operational loading conditions 2. Safe life components must remain crack free in service. Replacement times must be specified for limited life components	Fatigue properties
Residual static strength of damaged structure	1. Fail-safe structure must support 80-100% limit loads without catastrophic failure. 2. A single member failed in redundant structure or partial failure in monolithic structure	1. Static properties 2. Fracture toughness properties
Crack growth life of damaged structure	1. For fail-safe structure inspection techniques and frequency must be specified to minimize risk of catastrophic failures. 2. For safe-fail structure must define inspection techniques and frequencies and, replacement times so that probability of failure due to fatigue cracking is extremely remote	1. Crack growth properties 2. Fracture toughness properties

Figure 1 - Design Criteria for Sizing Aircraft Structures
(Aircraft Structural Design, Niu, Ref. 1, 1988)

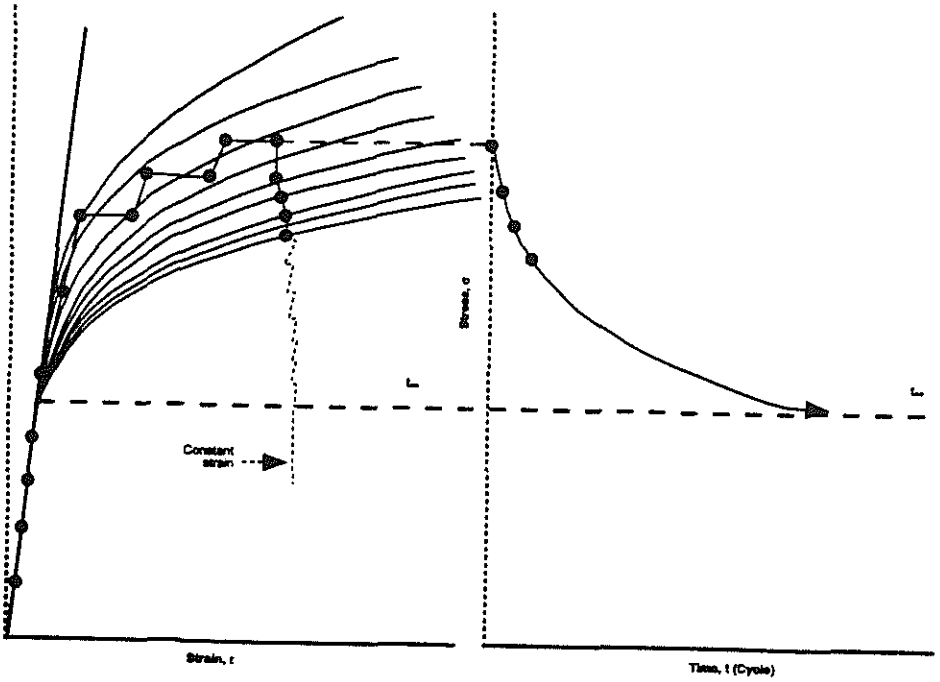

Fig. 2 - Relaxation stress-strain diagram
Relaxation stress-time curve (not to scale)
(Shanley, Ref. 2, 1960)

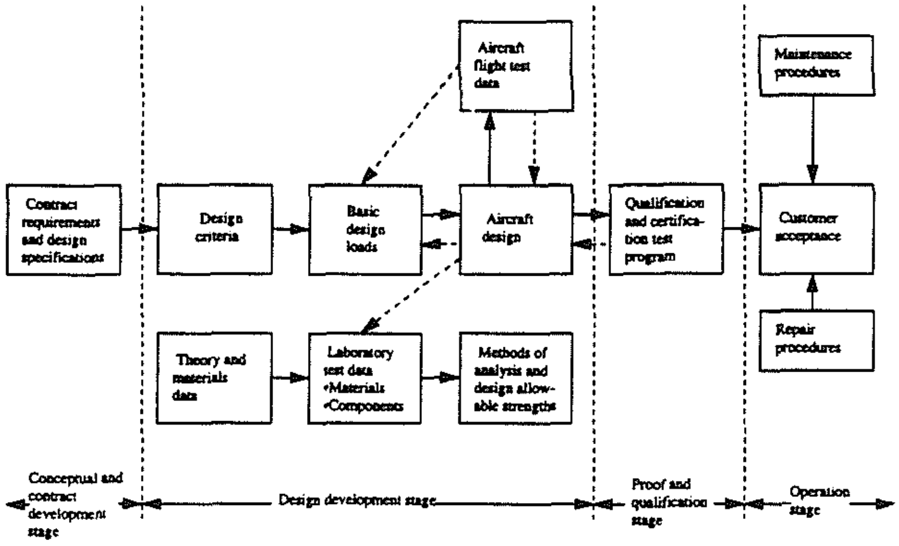

Figure 3 - Aircraft Design, Development and Certification
(Aircraft Structural Design, Niu, 1988)

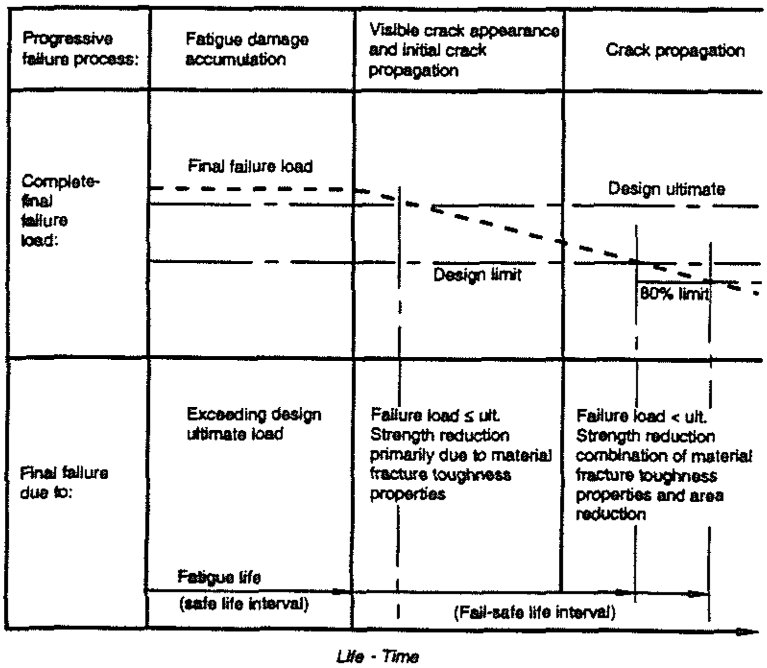

Figure 4 - Progressive Failure of a Structural Element
(Aircraft Structural Design, Niu, 1988)

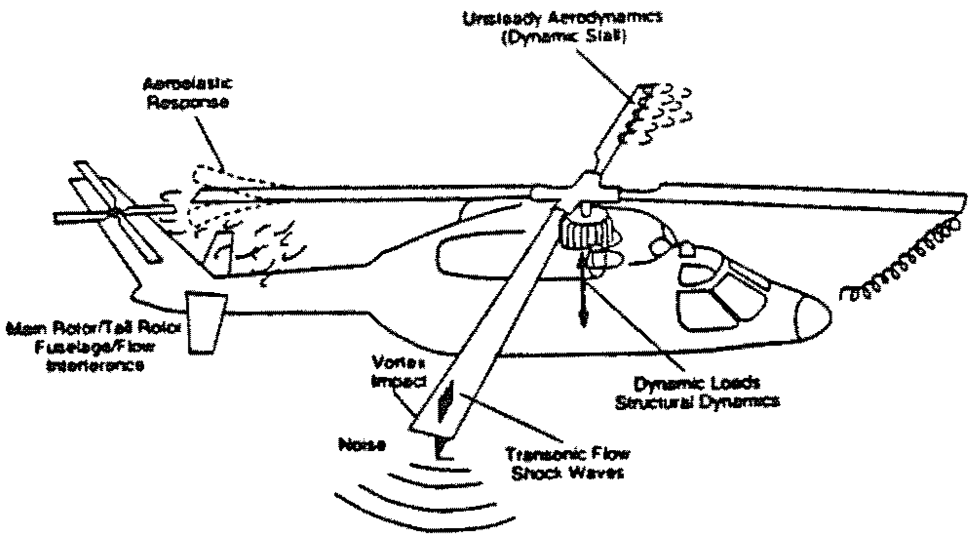

Figure 5 - Rotorcraft Multidisciplinary Complexity

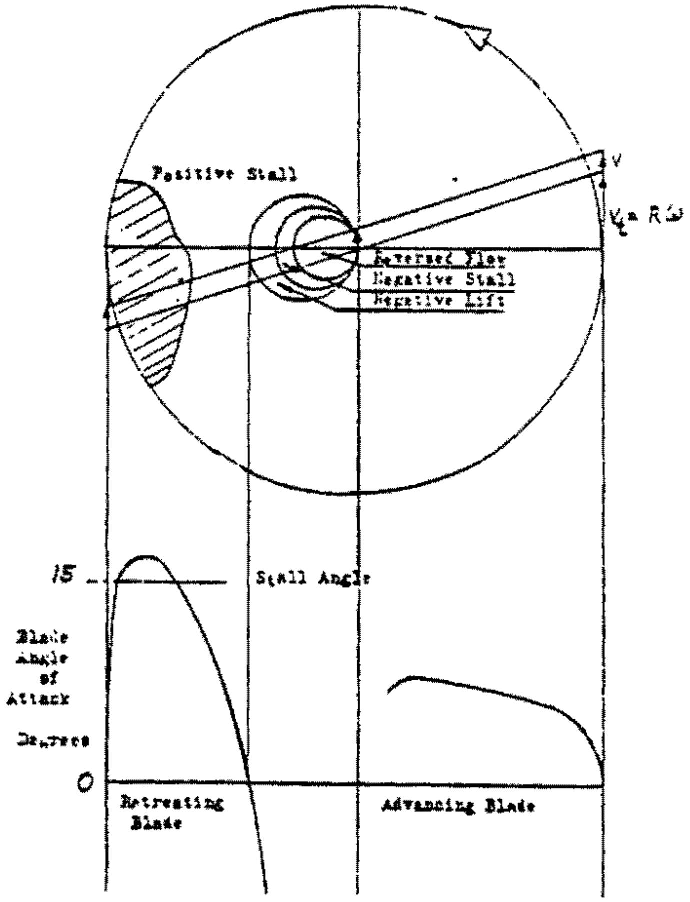

Figure 6 - Adverse Forward Flight Environment for Helicopters

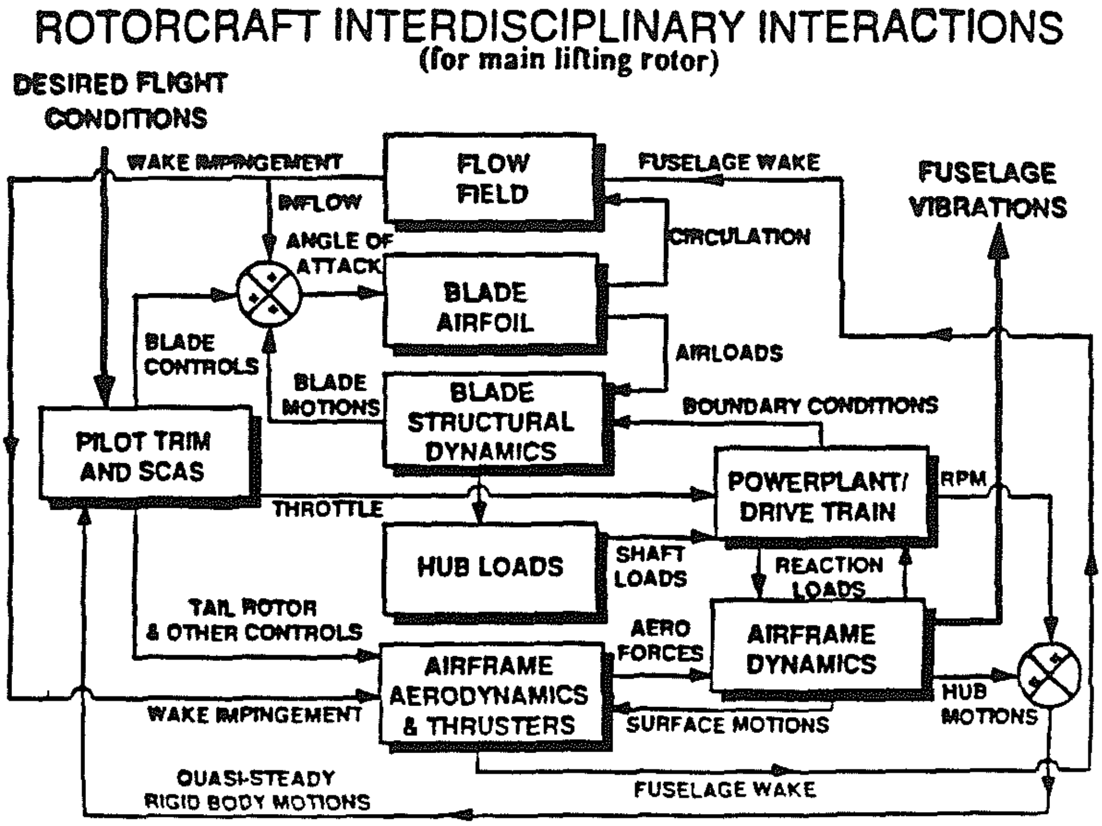

Figure 7 - Rotorcraft Interdisciplinary Interaction

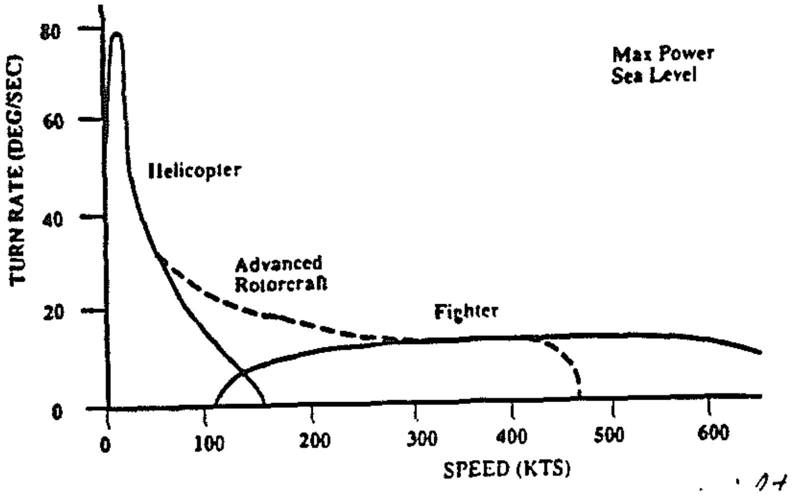

Figure 8 - Rotorcraft Agility

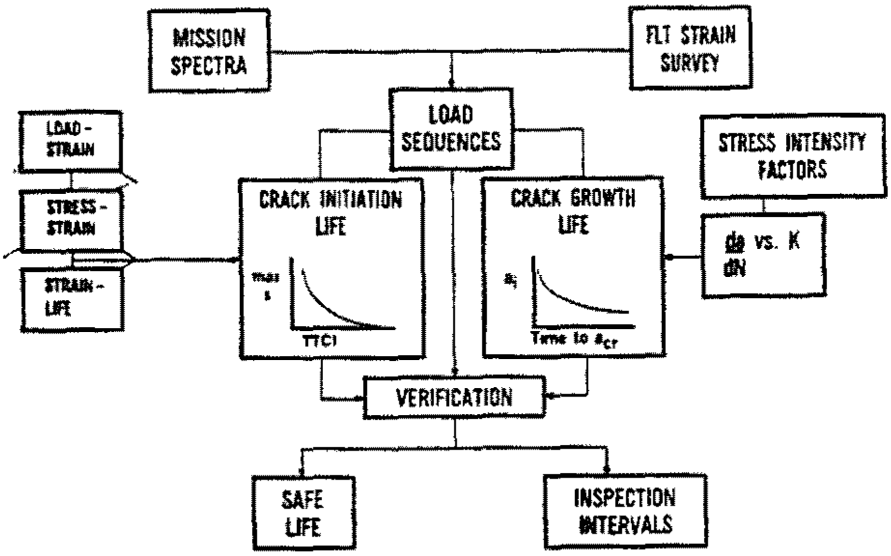

Figure 9 - Flow Diagram of the Total Life Methodology (Spigel, Ref. 9, 1988)

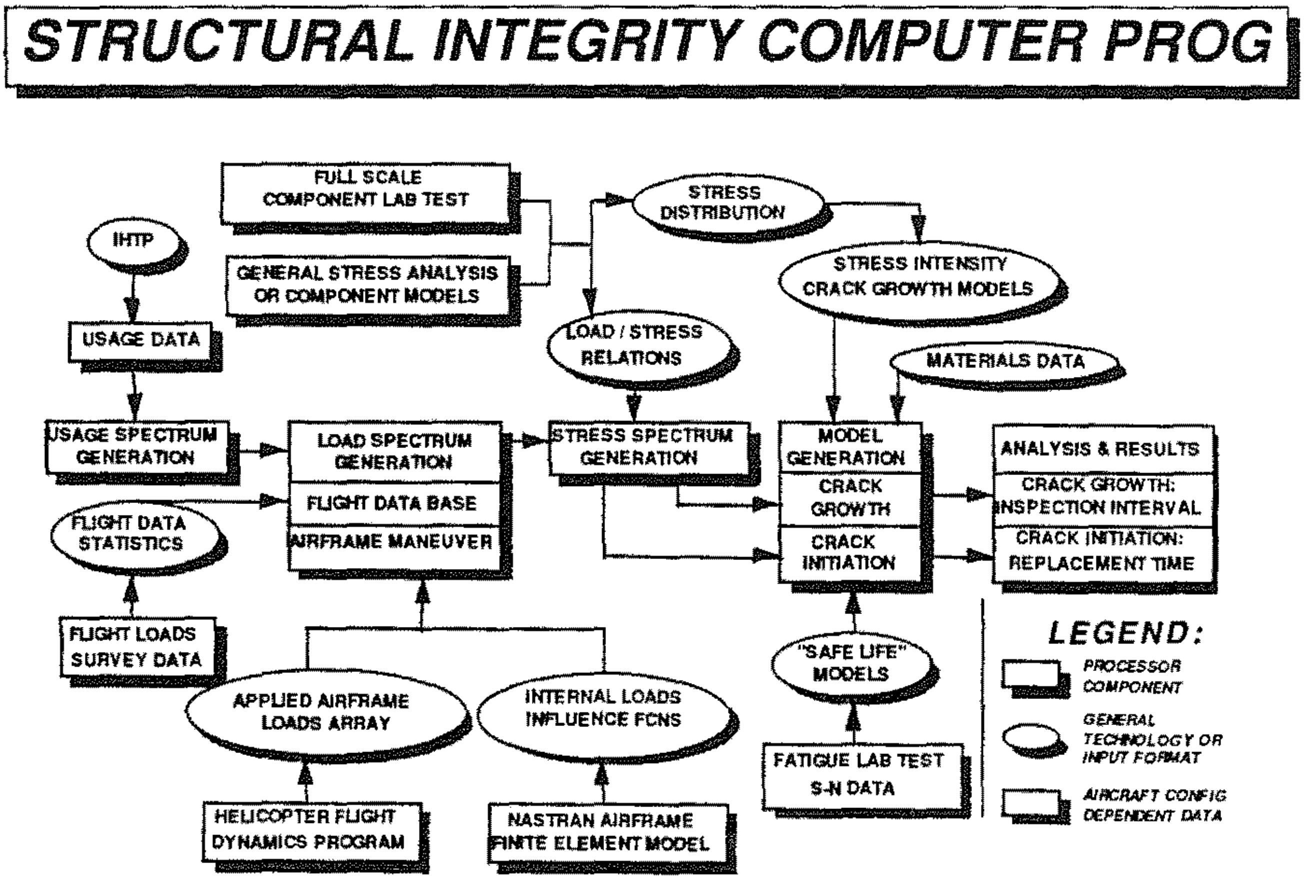

Figure 10 - USAF WR-ALC Structural Integrity Computer Program (SICP) (Ref. 12, 1996)

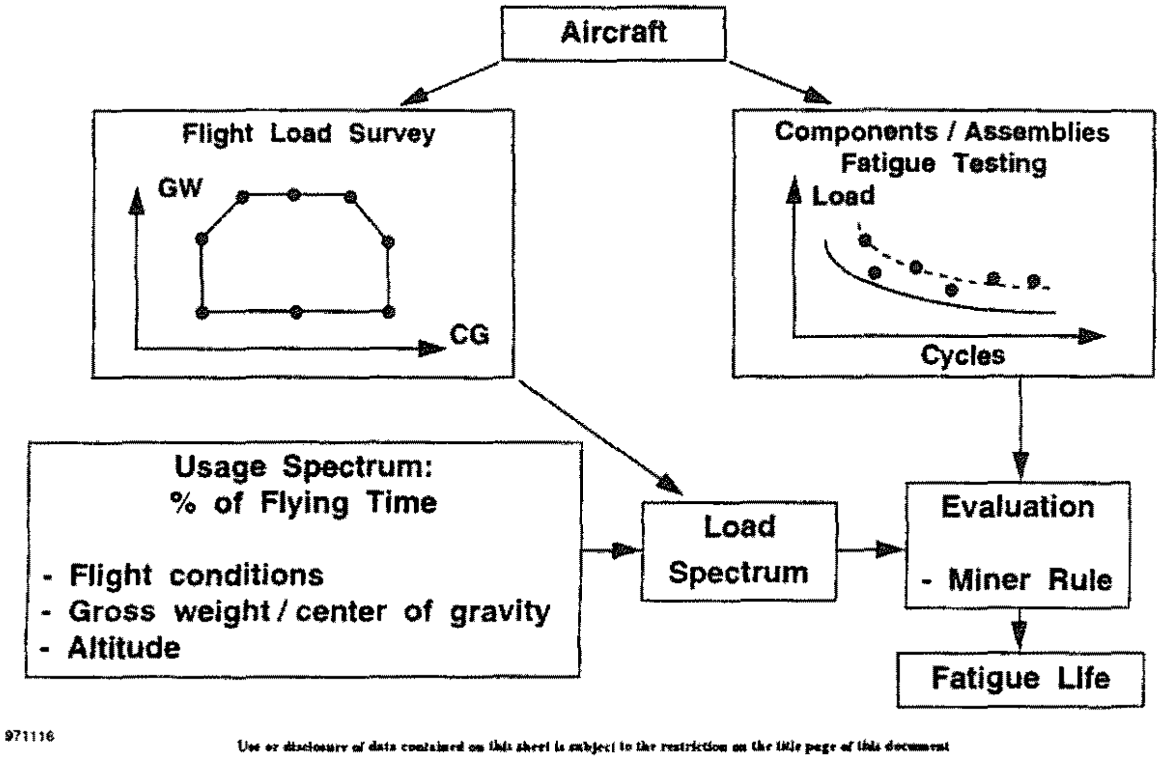

Figure 11 - Limited Life: Current Practice
(Krasnowski, BHT, Ref. 17, 1997)

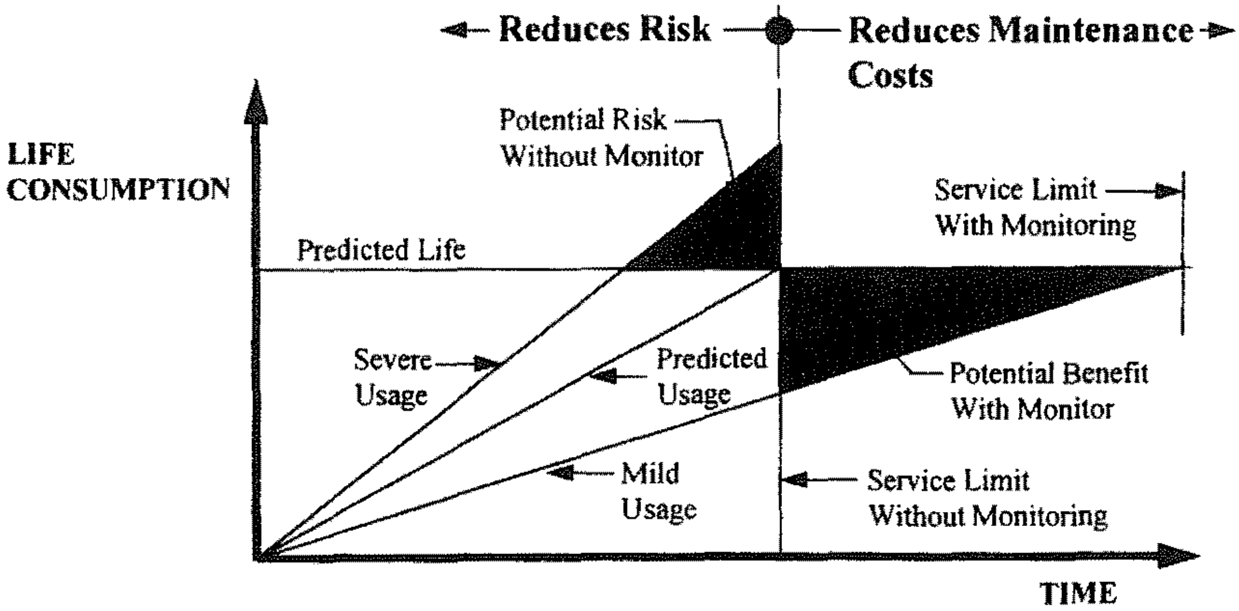

Figure 12 - Potential Benefit of Usage Monitoring
(Augustin, BHT, Ref. 19, 1997)

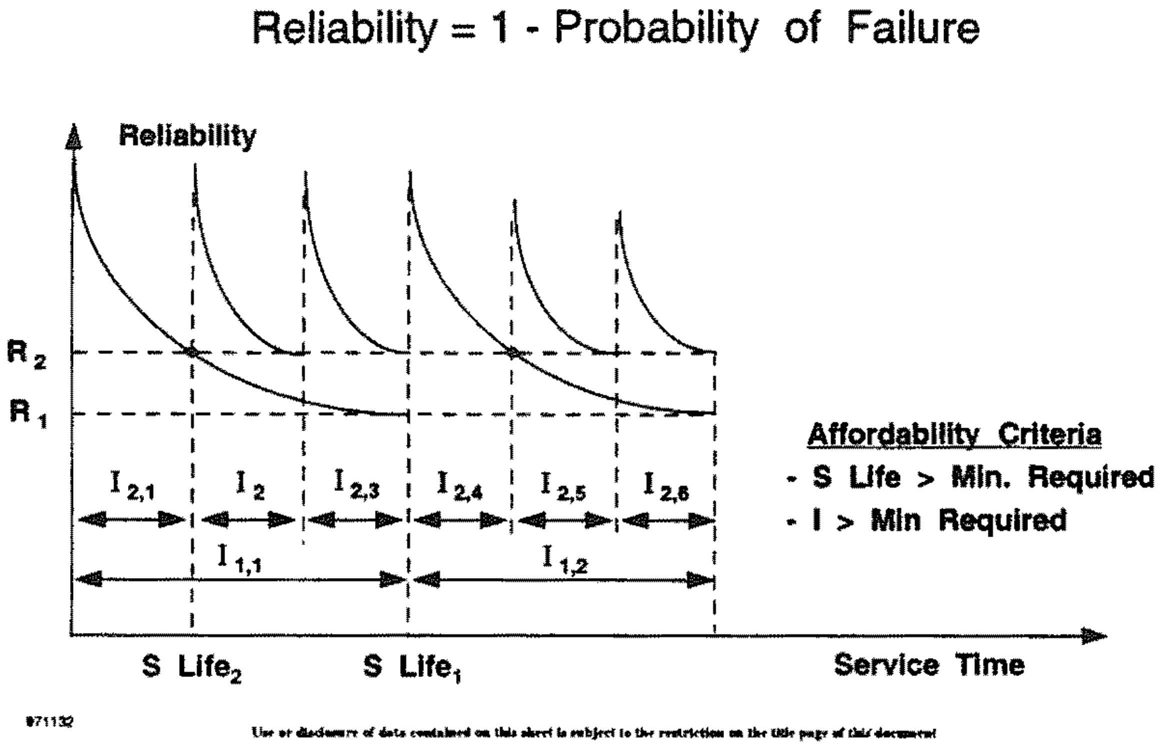

Figure 13 - Safety Level & Affordability
(Krasnowski, BHT, Ref. 17, 1997)

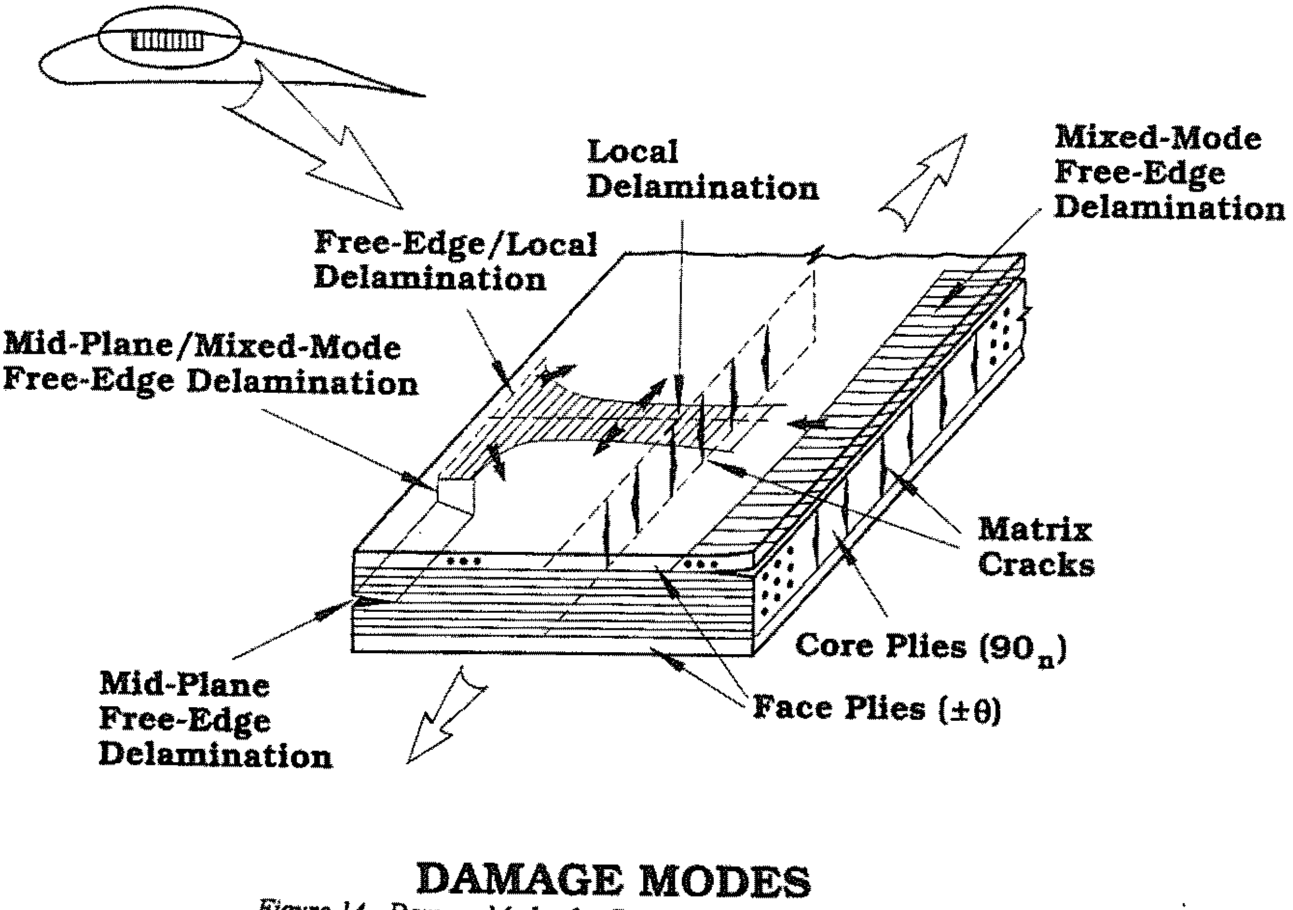

Figure 14 - Damage Modes for Composites Fracture Analysis
(Armanios, Ref. 22, 1993)