CHAPTER 9 STRUCTURAL RELIABILITY

9.1 INTRODUCTION

Reliability is commonly defined (References 9.1(a) and (b)) as "the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered". There are four elements to the definition that must be considered. First, *probability* refers to the *likelihood* that a device or structural component will work properly. These terms imply acceptance of some degree of uncertainty. The second element refers to adequate performance. In order to determine whether a component has performed adequately, a standard is needed to define what is meant by adequate performance. The third element is the intended period of time. This is the mission endurance or lifetime of the structure under consideration. The final element of the definition is the operating conditions. Environmental conditions play a large role in reliability of composite materials, particularly polymer matrix composites. Simply stated, structural reliability is a yardstick of the capability of a structure to operate without failure when put into service. In the broadest sense, structural reliability includes events that are safety and non-safety related.

Until recently, structural reliability was not routinely analyzed or quantified in the design process. Reliability was accounted for tacitly by the factor-of-safety approach to design. Also guidelines and lessons learned helped to improve reliability. The structural designer/analyst does not perform a formal risk analysis on newly designed structure. This task is performed by reliability specialists who employ methodologies that are empirically based. The reliability assessment is usually conducted after a drawing or concept is produced and bears little relationship to the structural margin-of-safety.

As implied in the definition, structural failure and, hence, reliability, is influenced by many factors. In its simplest form, the measure of reliability is made by comparing a component's stress to its strength. Failure occurs when the stress exceeds the strength. The larger this gap, the greater the reliability and the heavier the structure. Conversely, the smaller the gap, the lower the r, but the lighter the structure. The gap between stress and strength, enforced by the factor-of-safety, generally produces adequate although unmeasured reliability.

The complications that mask the ability to quantify reliability reside in the stochastic nature of design inputs. The calculations are relatively easy; statistical characterizations of the strength and stress distributions are compared mathematically and a probability of failure calculated. Definition of these distributions however, can be an imposing, if not impossible, task. Each is influenced by many considerations with relatively unknown effects.

The primary purpose for establishing a factor-of-safety for design is to ensure safety. Until recently, no objective analysis has gone into the choice for factor-of-safety. Consequently, no evaluations are performed on the factor-of-safety as new materials or technologies are developed. As suggested by methodologies developed in Reference 9.1(c), these evaluations can now be performed. This fact suggests that future design and design processes might benefit greatly by focusing on reliability targets rather than factors-of-safety. This may be particularly true for composite materials.

The following sections discuss some of the important factors that affect composite structure reliability.

9.2 FACTORS AFFECTING STRUCTURAL RELIABILITY

9.2.1 Static strength

An aircraft structure's capability to sustain operational flight loads is commonly assessed by comparing material performance parameters to limit or ultimate loads. Limit loads are generally defined as the maximum load expected during the life of the aircraft. Ultimate loads are obtained by multiplying limit loads by the factor-of-safety. Limit loads are derived by considering the extremes of flight envelopes, gross weight, load factors, environments, and pilot inputs. In some cases, the likelihood of encountering limit load is very remote. The 1.5 factor-of-safety used to obtain ultimate design loads from applied loads has been widely accepted by generations of engineers, mostly without questioning the origin of the factor. Reference 9.2.1 provides an excellent historical review of the evolution of the 1.5 factor-of-safety in the United States.

From the beginning of flight, occupant safety has been a primary concern in designing manned vehicles and the "factor-of-safety" has been a prominent design criteria. Like many design requirements, the implementation of the 1.5 factor-of-safety evolved over a period of time and was influenced by many concerns.

Design criteria require structures to withstand ultimate loads without failure and limit loads with no permanent deformation. This has led to the impression that the 1.5 factor-of-safety was due to the performance of metals, 2024 in particular. At the time the 1.5 factor-of-safety was established, 2024 aluminum had a ratio of ultimate to yield stress of approximately 1.5. However, in the early 1930's when the 1.5 factor-of-safety was formally established by the Air Corps, material properties were not considered. Mr. A. Epstein, who worked for the United States Army Air Corps Material Center from 1929 to 1940, prepared the original Air Corps Structures Specification X-1803 in 1936. Mr. Epstein noted (Reference 9.2.1) that "the factor-of-safety of 1.5 has withstood many moves to alter it, but there was a period in 1939 when the Chief of the Structures Branch of Engineering Division at Wright Field thought seriously of reducing the value of the factor. Newer aluminum alloys were becoming available with higher ratios of yield to ultimate strength and he interpreted the factor as the ratio of ultimate to yield. However, no action was taken when the following explanation was offered: 'The factor-of-safety is not a ratio of ultimate to yield strength, but is tied in with the many uncertainties in airplane design, such as fatigue, inaccuracies in stress analysis, and variations of material gages from nominal values. It might also be considered to provide an additional margin of safety for an airplane subjected to shellfire.'" Thus, while the factor-of-safety does much to promote reliability, it was defined independently of any specific reliability goal.

Generally speaking, composite structures are sized by comparing ultimate internal stresses to statistically reduced material parameters (e.g., B-basis strengths). The internal stresses are a result of applied design ultimate loads (1.5 x DLL). In general the deterministic approach produces adequate reliability, but not necessarily the same as metallic structure. This is because composite materials exhibit different statistical distribution and variation from metals (see Figure 9.2.1). The result is that even though materials may have equivalent B-basis strengths, their reliabilities may be quite different. Reliability-based design procedures may be necessary to account for this difference (see Reference 9.1(c)).

9.2.2 Environmental effects

Composite material components are subjected to a wide range of environments. The operating conditions in which the aircraft must perform are not well characterized. Environmental factors of major importance include a combination of humidity and temperature. Many studies have been conducted to investigate moisture absorption as well as the reduction of mechanical properties due to temperature and moisture exposure. The current approach used to account for environmental factors is to define exposures that are extremes and selectively evaluate by test the effects on material properties. These extremes are then considered to be invariant during the lifetime of the structure. Strength values are reduced to coincide with the environmental extremes.

9.2.3 Fatigue

Composite materials exhibit higher fatigue threshold stresses than metals. Once this threshold is exceeded, composites show more scatter in fatigue than metals and might tend toward lower reliability performance if the composite structures were stressed that highly. Because of this high threshold stress, fatigue is not the limiting factor in the design of composite structures. Design criteria such as damage tolerance limit the stress levels in composite structures to such low values that fatigue does not generally represent a design constraint. However, this is not necessarily true for high-cycle fatigue (e.g., $n > 10^7$)

dynamic system components in rotorcraft. (For more information on fatigue or durability of composite structures, see Volume 3, Sections 4.10 and 4.11.2).

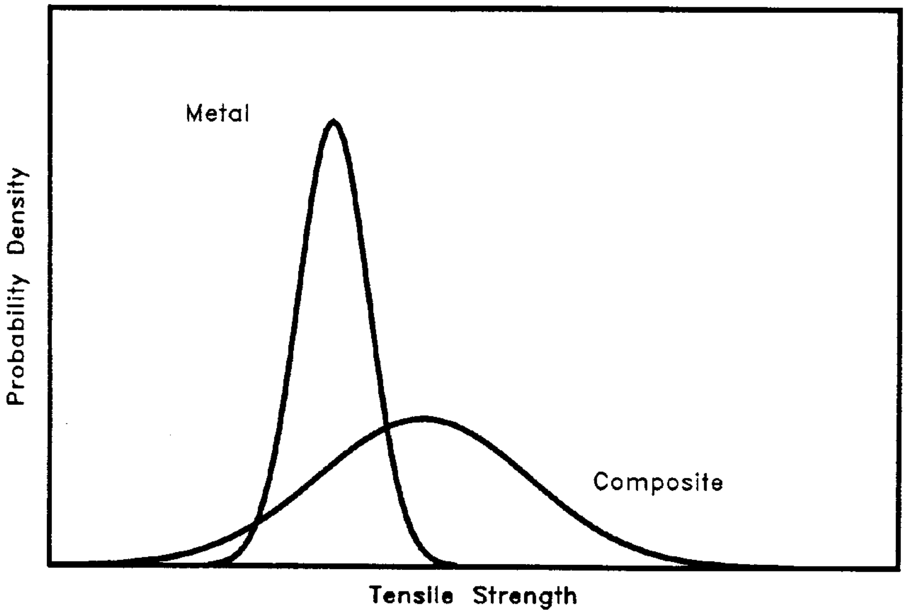

FIGURE 9.2.1 *Composites generally exhibit variation in material performance different from their metallic counterparts.*

9.2.4 Damage tolerance

As stated in Volume 3, Section 5.12.1, "damage tolerance is defined as a measure of a structure's ability to sustain a level of damage or presence if a defect and yet be able to safely perform its operating functions." Damage to composite structures can occur during manufacturing or operational usage. In order to design the structure to operate safely after sustaining such damage, a common practice is to limit the stress allowed in the composite structure. Typically, composite structures are designed to withstand the most severe of either of the following tow conditions: a 0.25-inch open hole in any location at ultimate load or damage sustained when objects of specified size strike the surface (representative of barely visible impact damage threats). Both criteria assume the defect exists for the life of the part. These criteria reduce the allowable strength.

9.3 RELIABILITY ENGINEERING

Reliability is of such concern to the military that specific requirements are defined in contractual documents. Industry satisfies these requirements by employing engineers who specialize in reliability to guide the design. Currently, structural reliability is being increasingly emphasized. The reasons are two-fold. First, advances in materials technology have resulted in higher performance materials that often possess detrimental side effects (e.g., high strength steels that exhibit low fracture toughness). Second, the need for higher vehicle performance has pushed operating stresses to higher levels in order to reduce structural weight.

Structural designs are documented via engineering drawings. Drawings are not "released" until they undergo scrutiny by several technical disciplines. Reliability is one of the concerns that is dealt with by the technical disciplines. Reliability specialists ensure that these concerns are incorporated into the design.

Customer reliability criteria typically specify three goals. These are: Mean Time Between Failure (MTBF), mission reliability, and Failure Modes Effects Criticality Analysis (FMECA). MTBF is measured in unscheduled maintenance events per million flight hours. Mission reliability is an indication of the probability of having to abort a flight. FMECA determines the impact of specific failures on mission performance, safety, and utilization.

In addition to supplying input to design, reliability engineering output is supplied to maintainability groups for maintenance man-hour predictions. Their results are used by logistics persons to establish provisioning requirements for spare parts.

9.4 RELIABILITY DESIGN CONSIDERATIONS

The following is a list of general composite structures considerations which provide insight on improved reliability and causes of poor reliability:

- Eliminate/minimize potential galvanic corrosion and/or thermal expansion problems by selecting compatible materials.

- Allow for the difference in thermal expansion when mating composites to metals. The coefficient of thermal expansion for composites is low.

- Assess carefully the use of honeycomb sandwich panels which utilize thin facesheets in areas where Foreign Object Damage (FOD) and bird strikes are likely to occur. Thin facesheets are susceptible to impact damage.

- Protect the structure for possible lightning strikes. Good electrical contact between all metallic and carbon/epoxy structural components must provide for the dissipation of static and lightning-induced electrical currents.

- Fasteners: Use titanium alloy or other materials that are compatible with carbon/epoxy to prevent galvanic corrosion.

- The current ability to detect flaws in composite structures, especially honeycomb, is evolving. Designs that enhance access for inspection tend to promote reliability.

- Improved reliability can be obtained by avoiding anomalies such as wrinkling and porosity in integral stiffeners. The ability to detect such flaws is limited.

- Extreme care should be taken during the repair of composite structures. Avoid damaging additional plies during patch or repair operations as it may result in a decline in reliability.

- Variations in manufacturing processes such as curing and machining can be responsible for a range of part strengths thus influencing reliability.

- The supplier's prepreg material should be closely monitored (i.e., acceptance testing) to assure incoming material consistency and conformance to design values.

9.5 RELIABILITY ASSESSMENT AND DESIGN

9.5.1 Background

Advanced composite materials offer sizable improvements in weight savings, maintainability, durability, and reliability. There are a number of performance factors that have limited their success. Thus far, composite design and treatment of unique performance factors have been handled in a traditional metals approach in the aircraft industry. This approach is characteristically deterministic in nature. Probabilistic methods offer a different technology that can be used as a design tool, or, in a more conservative manner, as a risk analysis. The application of probabilistic methods opens up technical information not available in traditional approaches.

Probabilistic methods represent a technology that cannot be implemented without careful development. It is, however, a technology that is easily controllable. It may be used as an assessment of deterministic designs; it may be used to establish realistic criteria for deterministic designs; or it may be implemented as a preferred design approach. If used as the preferred design approach, probabilistic methods utilize a reliability target in lieu of factors-of-safety. Disclosure of risk characteristics alone should interest the designer in applying the technology.

Probabilistic design is an integrated process as shown schematically in Figure 9.5.1(a). The approach is to define/develop the functional relationships of the operations within the boxes, then build the relationships between them. This interconnects the entire process. In this way, when a factor in one operation changes, its effect can be determined on the others. The end result is the effect on failure probability.

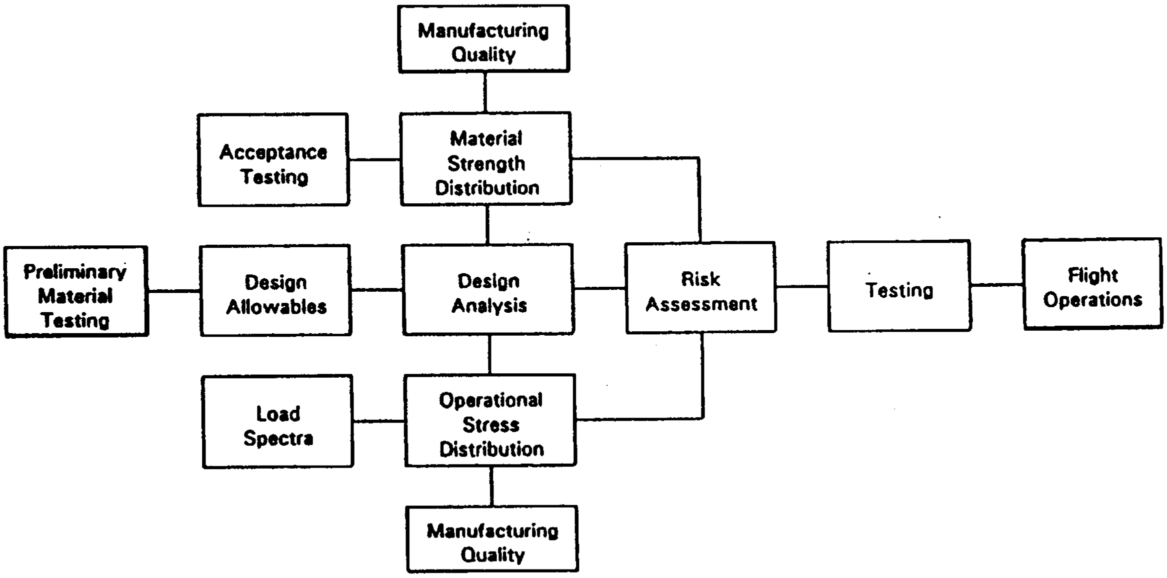

FIGURE 9.5.1(a) *Full probabilistic process.*

A flowchart of a Probabilistic Design model is shown in Figure 9.5.1(b). This model consists of four major activities; namely, the design process, material production, manufacturing, and operations. Output from the design process is the expected operating stress distribution resulting from the flight spectra. The remaining three activities provide the material strength distribution, determined through Monte Carlo simulation of random variables representing random variation of incoming material strength, manufacturing defects, and operational factors. Probability of failure occurs when the stress exceeds the strength. This is calculated by a double integral of the stress and the strength probability density functions to determine the probability that "stress exceeds strength".

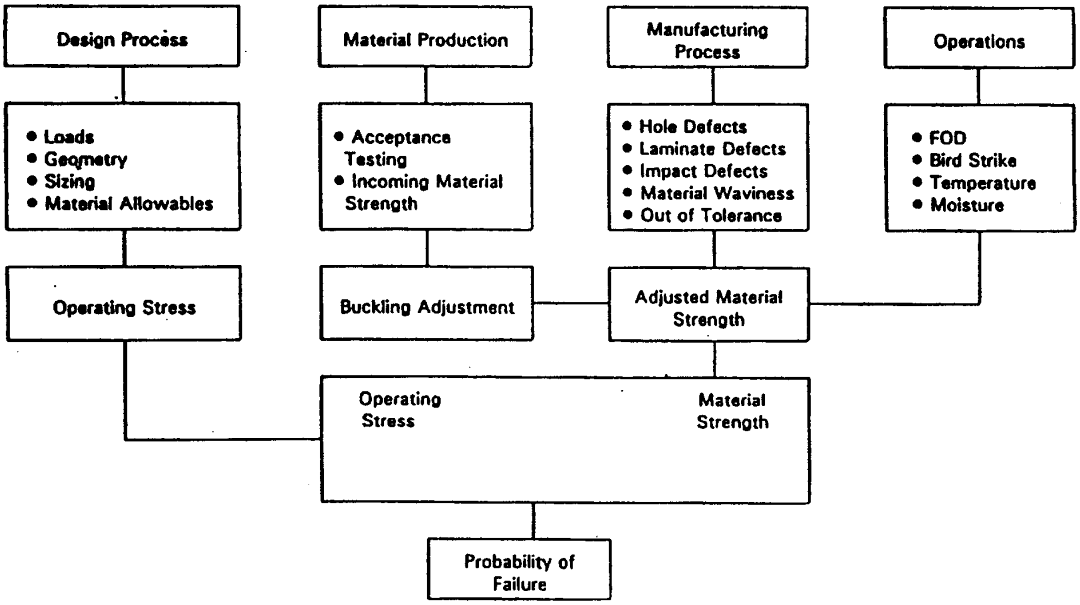

FIGURE 9.5.1(b) *Probabilistic design.*

9.5.2 Deterministic vs. Probabilistic Design Approach

Component dimensions, environmental factors, material properties, and external loads are design variables. They may be characterized with statistical modes. The deterministic approach seeks out and defines a worst case or an extreme value to meet in the design. The probabilistic approach utilizes the statistical characterization and attempts to provide a desired reliability in the design. The deterministic approach introduces conservatism by specifying a factor of safety to cover unknowns. The factor of safety is traditionally 1.5. The probabilistic approach depends on the statistical characterization of a variable to determine its magnitude and frequency. The amount of data (how well the variable is defined) influences its extreme values.

Application of a factor-of-safety to cover unknowns has a history of success. The danger in this approach is that the factor of safety may be too large, or in some cases, too small. Because it has worked in the past is no guarantee that it will suffice in the future. The whole approach of worst case extremes can lead to compounding and inefficiency. To select a factor-of-safety solely on the basis of "it worked in the past" should be examined.

Advanced composite materials were introduced in the early 1960's and since that time have undergone significant development. Some obstacles appeared insurmountable, including susceptibility of material strength degradation to elevated temperature, absorbed moisture, impact damage, and hidden flaws or damage. The approach to accommodate these material strength reduction factors has been to develop worst case manufacturing and operational scenarios and assume their existence for the life of the part. These factors, which are in reality variables, are thereby treated as constants.

Composite part design is governed by compounded conservatism illustrated by the following criteria:

- Worst case loading x safety factor (1.5)
- Worst case temperature
- Worst case moisture
- Worst case damage, undetected
- Material allowables derived from conservative statistical criteria

The effect of combining these conservative structural criteria is to produce inefficient products. Probabilistic methods offer an alternative to compound conservation. They quantify the degree of safety and permit the designer to discover the risk drivers.

9.5.3 Probabilistic Design Methodology

The basic probabilistic design mathematical theory, shown below, accounts for the probability distributions of both material strength and operating stress. Because failure is a local phenomenon, division of a component into N numbers of nodes is done to represent all the locations at which failure is possible to occur. In general, the distributions are assumed to be identical at all the nodes. Step 6 assumes that material strengths at the nodes are independent from each other.

Step No.

1. Establish allowable failure rate.

2. Establish the number of nodes where failure is possible.

3. Determine probability distribution for loads.

$$P(X_x < x_s) = f(x_s)$$

4. Determine the operating stress probability density function $f_s(x)$.

5. Determine probability distribution for strength.

$$P(Y_M < y_m) = F(y_m)$$

6. Calculate failure probability P.

$$P_f = \int_x f_s(z)\left[1 - F_M(x)^N\right]dx$$

An alternative probabilistic design approach has been discussed in References 9.5.3(a) and 9.5.3(b). The fundamental elements of this approach are:

1. Identify all possible uncertain variables at all scales of composite structures. This includes variables at constituents scale, at all stages of fabrication process and assembly, and applied loads.

2. Assign a probabilistic distribution function for each variable.

3. Process all the random variables through an analyzer which consists of micro- and macro-composite mechanics and laminate theories, structural mechanics and probability theories.

4. Extract useful information from the output of the analyzer and check against defined probabilistic design criteria.

The IPACS (Integrated Probabilistic Assessment of Composite Structures) computer code developed at NASA Lewis integrated the above elements for probabilistic design of composite structures. A schematic of the computer code is shown in Figure 9.5.3.

9.5.4 Data Requirements

In order to conduct a probabilistic design exercise, the following parameters must be characterized as random variables:

1. Material mechanical properties
2. External loads anticipated during the life of the article
3. Manufacturing processes and their effect on material strength
4. Environmental effect on strength
5. Environmental history during operational usage
6. Flaw and/or damage locations, severity, probability of occurrence and effect on strength
7. Predictive Accuracy

Quality of incoming composite material is crucial to final product quality. To assure incoming material meets specifications, testing procedures and measurement value limits must be established to sufficiently discriminate between inferior and desired material. These criteria must be agreed upon by producer and consumer. Each wants to minimize their risk. The producer's risk is the probability of rejecting "good material" and the consumer's risk is the probability of accepting "inferior material".

9.5.5 Summary

Adopting specific structural criteria should not be done without a reason. The current criteria has its origins in metals technology. The goal of probabilistic design is to make reliability the foundation of composite structural criteria. It *will not* replace most structural mechanics functions.

Probabilistic Design is a powerful supplement/alternative to today's approach for composite design. It requires the development of sophisticated techniques in probability and characterization of statistical data for engineering variables. It is gaining momentum as more people become aware of its presence and benefits.

As the demand grows for more accurate, sophisticated designs, the requirement for probabilistic design methodology will become more and more accepted. The incorporation of Probabilistic Design, while quite challenging, offers significant payoffs not available with conventional technology.

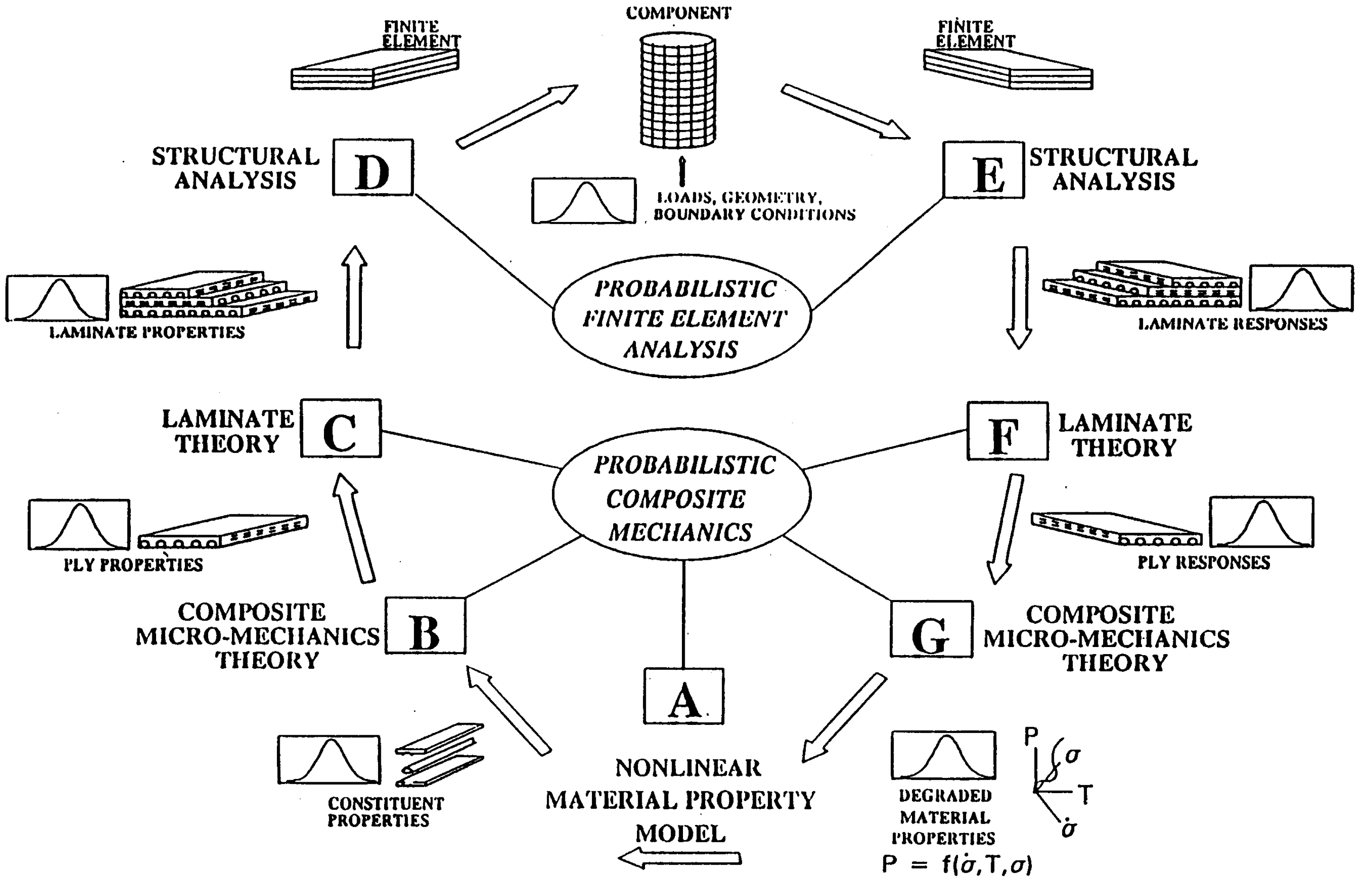

FIGURE 9.5.3 *Schematic of the computer code IPACS.*

9.6 RELIABILITY BASED STRUCTURAL QUALIFICATION

This section is reserved for future use.

9.6.1 Analysis

This section is reserved for future use.

9.6.2 Testing

This section is reserved for future use.

9.7 LIFE CYCLE REALIZATION

This section is reserved for future use.

9.7.1 Manufacturing

This section is reserved for future use.

9.7.2 Operational

This section is reserved for future use.

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