523-24
51391
p.11

PROBABILISTIC DESIGN

OF

ADVANCED COMPOSITE STRUCTURE

P. M. GRAY

M. G. RISKALLA

LTV AEROSPACE AND DEFENSE

AIRCRAFT DIVISION

DALLAS, TEXAS

ABSTRACT

Advanced composite technology offers potentials for sizable improvements in many areas: weight savings, maintainability, durability, and reliability. However, there are a number of inhibitors to these improvements. One of the biggest inhibitors is the imposition of traditional metallic approaches to design of composite structure. This is especially detrimental in composites because new materials technology demands new design approaches. Of particular importance are the decisions made regarding structural criteria. Significant changes cannot be implemented without careful consideration and exploration. This new approach is to implement changes on a controlled, verifiable basis. Probabilistic design is the methodology and the process to accomplish this. Its foundation is to base design criteria and objectives on reliability targets instead of arbitrary factors carried over from metallic structural history.[1]

This paper discusses the background of probabilistic design and presents the results of a side-by-side comparison to generic aircraft structure designed the "old" way and the "new". Activities are also defined that need to be undertaken to evolve available approaches to probabilistic design followed by summary and recommendations.

INTRODUCTION

Current aerospace design procedure disregards the fact that component dimensions, environment (temperature and aging), manufacturing quality, and even the externally applied loads pertaining to aircraft structure are statistical in nature as opposed to deterministic, or single-valued variables. That is, these variables fall within a spectrum of possible values, and no specific value should be singled out as representing a reliable solution for a mechanical equation. Conventional solutions to design equations generally result in an uncertainty between prediction versus performance; this uncertainty is hidden under a blanket of safety factors. A more rational

PRECEDING PAGE BLANK NOT FILMED
PAGE 522 INTENTIONALLY BLANK

solution to this reality is to strive for a predetermined reliability goal. This will require more knowledge about the nature of design inputs. The ultimate goal is to change the design path from: "...if it can happen at all, design to it," to "...design to an acceptable probability of failure, accounting for the likelihood and consequences of occurrence."

Composite materials are known to be susceptible to two environmental factors: elevated temperature and moisture. They are also sensitive to flaws that can originate during the manufacturing process or in operational usage. The conventional design approach adopted by government and industry does not recognize the variable nature of design manufacturing and operational input data. Current procedures force the engineer to design aircraft structure for worst-case scenarios adhering to contractually defined margins of safety with no knowledge of reliability performance. This is the traditional deterministic approach. In effect, it forces a weight increase with an unknown reliability that must be tolerated for every part regardless of the probability of encountering adverse conditions.

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

- Worst case loading X safety factor (1.5)[2]
- Worst case temperature
- Worst case moisture
- Worst case damage, undetected

The effect of combining these conservative structural criteria is to continually drive down the allowable stresses. This has reduced weight savings to the extent that composites are not realizing the payoffs originally forecast. This current approach is illustrated in Figure 1. Significant changes must occur in the design approach to future military and space programs to take full advantage of composite material performance and to be able to more accurately manage risk.

DETERMINISTIC VS. PROBABILISTIC DESIGN

Figure 2 presents a comparison of the two (2) different approaches. The deterministic philosophy utilizes worst case design parameters to produce structural components which are overly conservative and heavy. The deterministic approaches possess positive margins to withstand given maximum load, but there also are inherent, unknown reliabilities at the given load levels.

An intermediate approach is to apply a portion of probabilistic design but still retain the limit to ultimate factor. This type of risk analysis augments the structural design engineer's current capabilities and allows him to quantify the structural reliability of the aircraft structure. Previous risk analyses have shown that by accounting for the stochastic nature of design parameters and identifying the risk drivers, one can produce reliability based structures which meet the operational requirements.

The probabilistic approach is to utilize the design data characterized by statistical distributions to identify/optimize the risk drivers to produce minimum weight structures for which the reliability has been specified.

PROBABILISTIC DESIGN

Probabilistic design is a finely integrated process as shown schematically in Figure 3. The approach is to define/develop the functional relationships of the operations within the boxes, then build the relationships between them, thus integrating the entire process. In this way, when a factor in one operation changes, its effect can be determined on the others. The most important evaluation is the effect on failure probability.

A flowchart of the LTV-AD Probabilistic Design model is shown in Figure 4. 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."

The basic probabilistic design concept, as shown below, looks into the probability distributions of both material strength and operating stress. Because failure is a local phenomenon, division of a component into nodes can be 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 7 assumes that material strengths at the nodes are independent from each other. As in step 8, if the calculated probabiity of failure does not agree with the pre-defined and acceptable level, sensitivity analysis resulting from changes in distribution(s) will provide invaluable information on needed changes in the design.

Step No.

1. Establish allowable failure rate.

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

3. Determine probability distribution for loads.

   $$P(X_S < x_S) = F(x_S)$$

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. Determine the material strength probability density function $f_M(y)$.

7. Calculate failure probability P.

$$P_f = \int_x f_S(x)\,[1-[\int_{y>x} f_M(y)\,dy]^N]\,dx$$

8. If P_f is not in agreement with the established failure rate, then modify 2 or 3.

Probabilistic analysis requires that the random variables be statistically characterized. Statistical design databases, in general, do not exist.

In order to conduct a probabilistic design exercise one must characterize many parameters, including the following:

(1) Incoming 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 locations, severity, probability of occurrence and effect on strength.

Quality of incoming composite material is crucial to final product quality. To assure incoming material meets specifications, testing procedures and measured value limits must be established to sufficiently discriminate between inferior and specified 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.

PROBABILISTIC DESIGN APPLICATION AND EVALUATION

In order to calculate potential weight savings from a probabilistic design, a simplified two-cell box beam was selected to represent aircraft wing and tail structure. Most of the usual design concerns and requirements inherent in military aircraft programs can be simulated in multicell, pressure-loaded box beams. Two independent design approaches were implemented: the traditional deterministic method and probabilistic design.

The generic composite, two-cell, three-spar wingbox used in this exercise is presented in Figure 5. The wingbox is fixed (i.e., cantilevered) at the root (Y=0.0). Design ultimate pressures of 10.0 and 5.0 psi are applied to the forward and aft cell lower skins, respectively, in the upward (+z) direction. The ultimate pressures were used only for the deterministic analysis. Geometric details of the wingbox are presented in Figure 6, and the wingbox section thicknesses are presented in Figure 7. Two categories of aircraft were evaluated in this program, a Class A (attack) aircraft and a Class B_{II} (bomber) aircraft. Both spectra were derived from Mil-A-08866B[3] and are shown in Figure 8.

The composite wingbox was optimized for minimum weight using both the deterministic and probabilistic design approaches. Buckling and damage tolerance criteria were major factors in the sizing. The wing weight reduction as a function of probability of failure is presented in Figure 9. The reliability target determines the amount of weight savings. Two criteria were applied:

(1) The probability of failure for an aircraft's single flight should be 1×10^{-7} or less.

(2) The expected number of aircraft lost by structural failure in the lifetime of the fleet should be less than one.

Probabilistic design showed a possible weight savings of 13% when using a fighter load spectrum, and a weight savings of 20% when using a bomber load spectrum.

Deterministic/Probabilistic Equivalence

Incorporated in the methodology is the ability to relate probabilistic design to the factor-of-safety used in deterministic design. The issue is to determine the benefits to the aircraft if probabilistic advantages were converted to increased performance rather than weight savings. Figure 10 shows how much gain is available in maneuver load factor using probabilistic design assuming the weight of the two design approaches is the same. The fighter aircraft can sustain a 62 percent increase in "g" level (i.e., 16.2 vs. 10.0 g's) indicating the significant increase in maneuverability.

SUMMARY/RECOMMENDATIONS

Probabilistic Design is a powerful alternative to today's approach for composite design. It will require the development of sophisticated techniques in probability and statistics and characterization of statistical data for engineering variables just now becoming available. However, it is gaining momentum as more people become aware of its presence and benefits.

"One Time Only" designs that cannot be tested to failure (such as missiles and flight vehicle systems) are best designed by probabilistic methods where the additional analysis complexity is justified from a safety or economic standpoint. Likewise, in situations where a design is put into production before it can be tested, probabilistic design would be the best way to predict service life. In addition, probabilistic design is the best way to minimize the weight of a component, and so should be used to design critical parts for lightweight applications such as aerospace vehicles.[4]

As the demand grows for more accurate, sophisticated designs, the requirement for probabilistic design methodology will become more and more a necessity. The incorporation of Probabilistic Design, while quite challenging technically, will net significant payoffs in the form of improvement in vehicle performance accompanied by a reduction in operating costs. To be in a position to approach a new design/program from a probabilistic standpoint, additional studies need to be performed including:

- Probabilistic Design Philosophy/Methodology
- Risk analysis of current aircraft structure
- Fighter/bomber probabilistic design study
- Development of statistical data bases required for probabilistic design
- Total quality management relating to material performance (i.e., Reliability-based material acceptance criteria)
- Probabilistic Design of Advanced Primary/Secondary Aircraft Structure
- Qualification/certification methodology.

The application of Probabilistic Design to new and emerging aerospace systems will result in minimum weight structures which have reliability as the heart of the design and not just a "fall-out" from a designed-in capability to withstand a given load.

REFERENCES

1. AFP 800-7, "USAF R&M 2000 Process", 1 January 1989.

2. Muller, G. E. and Schmid, C. J., "Factor of Safety - USAF Design Practice", Technical Report AFFDL-TR-78-8, April 1978.

3. MIL-A-008866B, "Military Specification: Airplane Strength and Rigidity Reliability Requirements, Repeated Loads, and Fatigue", 22 August 1975.

4. Lincoln, J. W. and Snead, J. M., " the X-30 Structural Integrity Program: The Challenge Ahead".

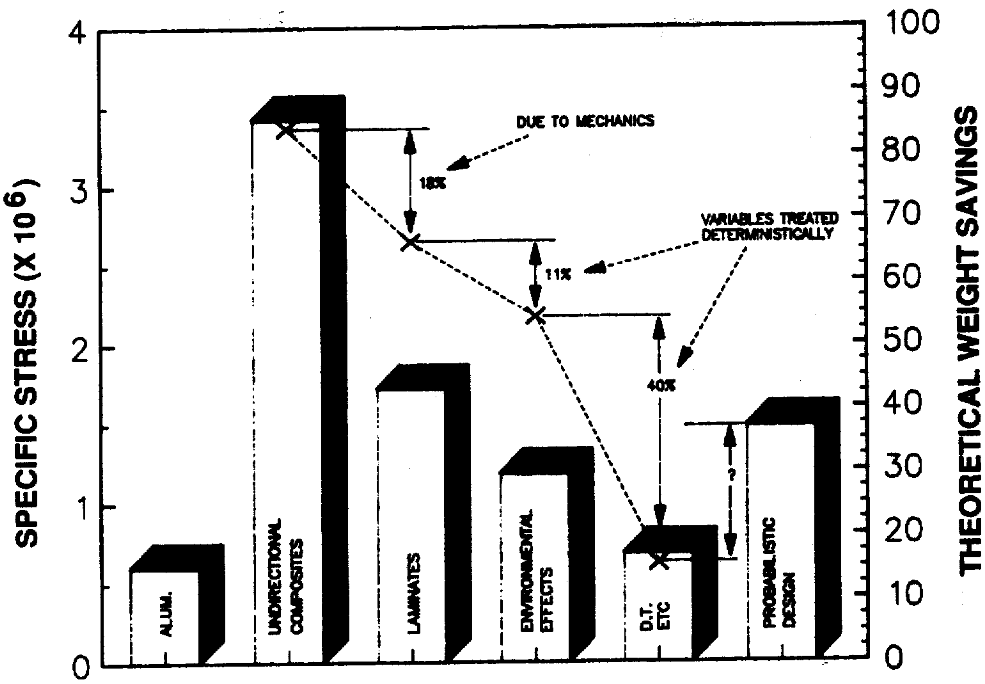


FIGURE 1. DETERMINISTIC REDUCTION FACTORS VS. PROBABILISTIC WEIGHT SAVINGS

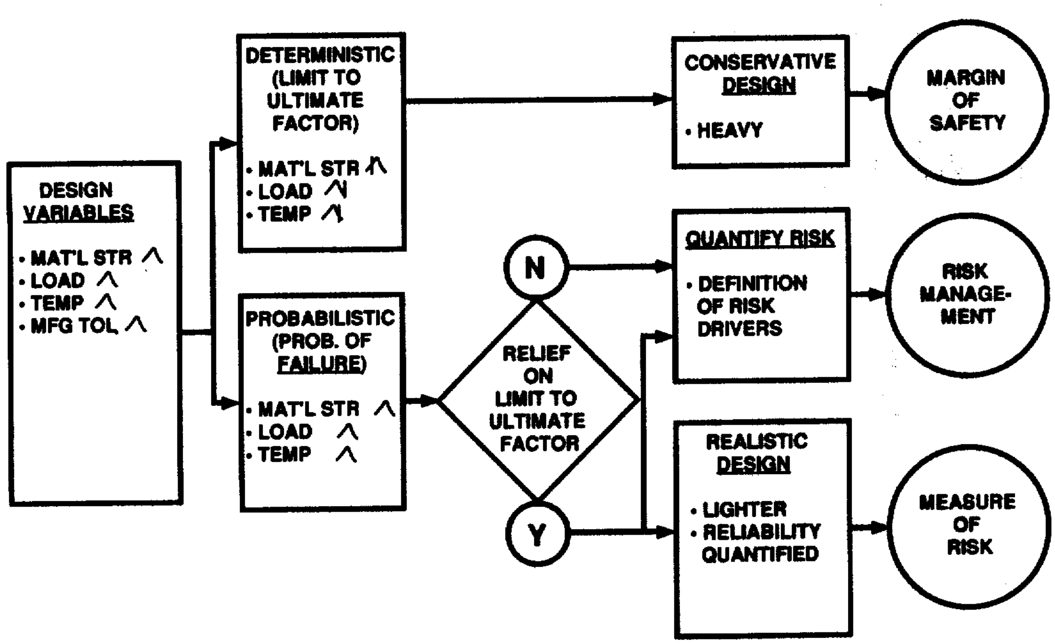


FIGURE 2. PROBABILISTIC VS. DETERMINISTIC DESIGN

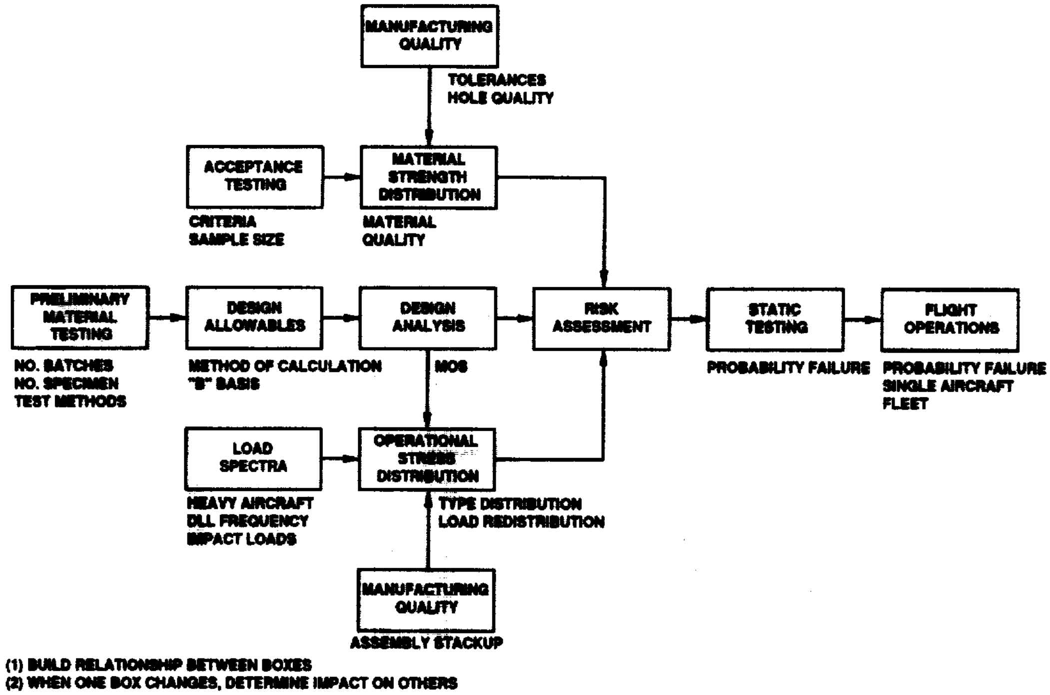


FIGURE 3. FULL PROBABILISTIC ANALYSIS

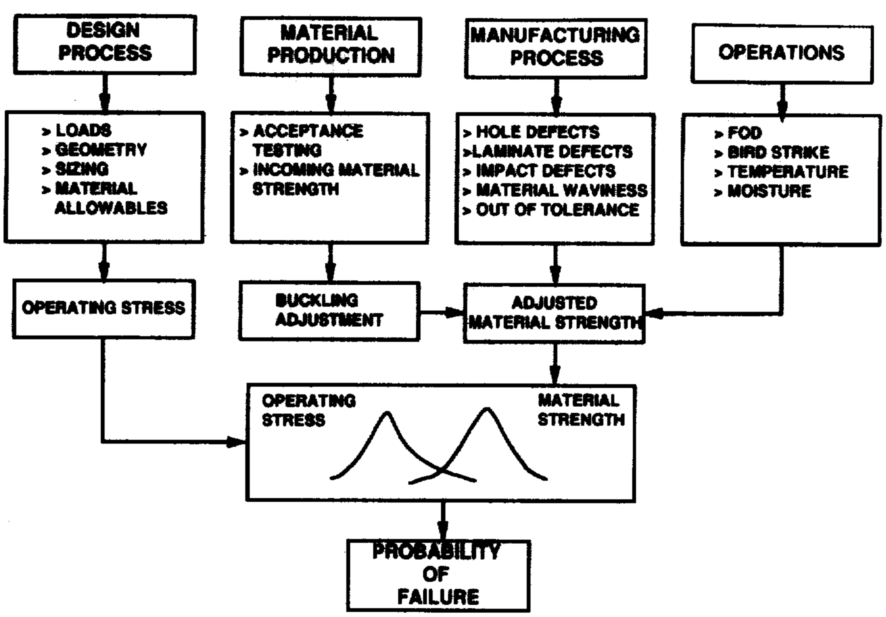


FIGURE 4. PROBABILISTIC DESIGN

STRUCTURAL FEATURES

- TENSION SKIN
- COMPRESSION SKIN
- SPARS
- RIBS
- FASTENERS (JOINTS)
- TAPERED THICKNESSES
- BUCKLING
- DAMAGE CRITERIA
- COMBINED LOADS
- VARIABLE PLY ORIENTATION

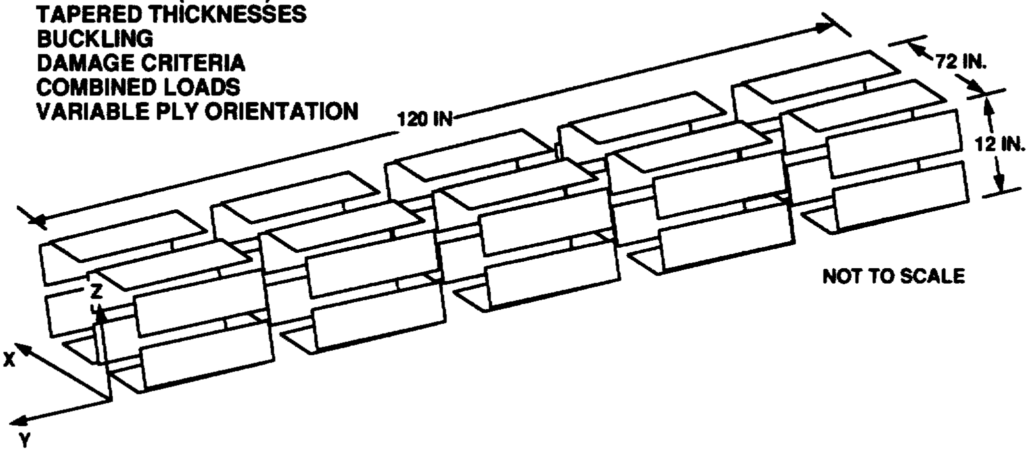


FIGURE 5. GENERIC COMPOSITE WINGBOX

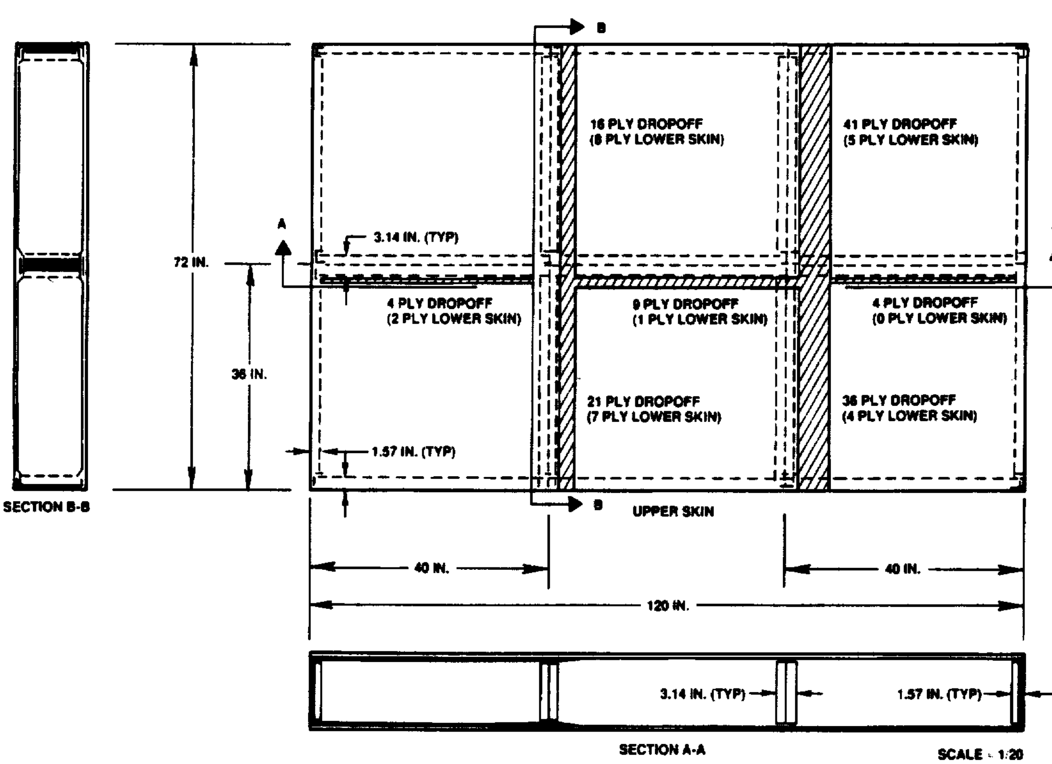


FIGURE 6. WING BOX CONSTRUCTION

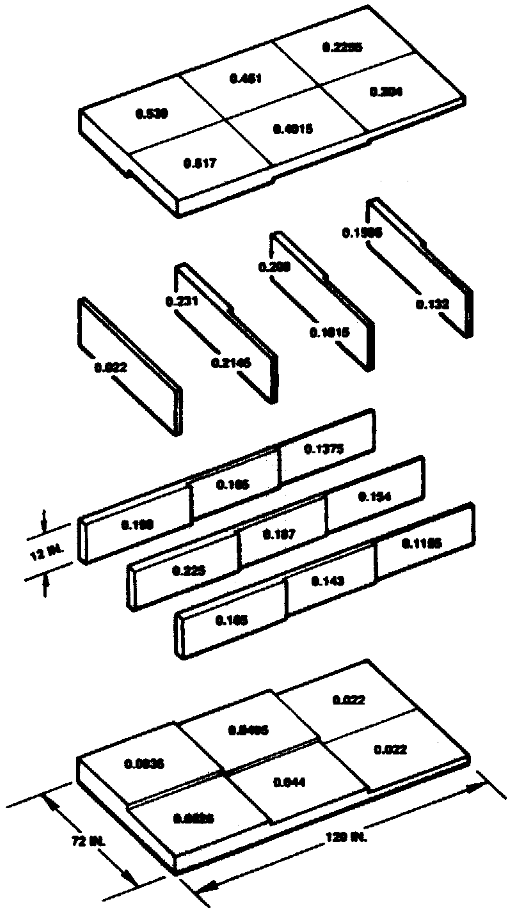


FIGURE 7. WINGBOX SECTION THICKNESSES

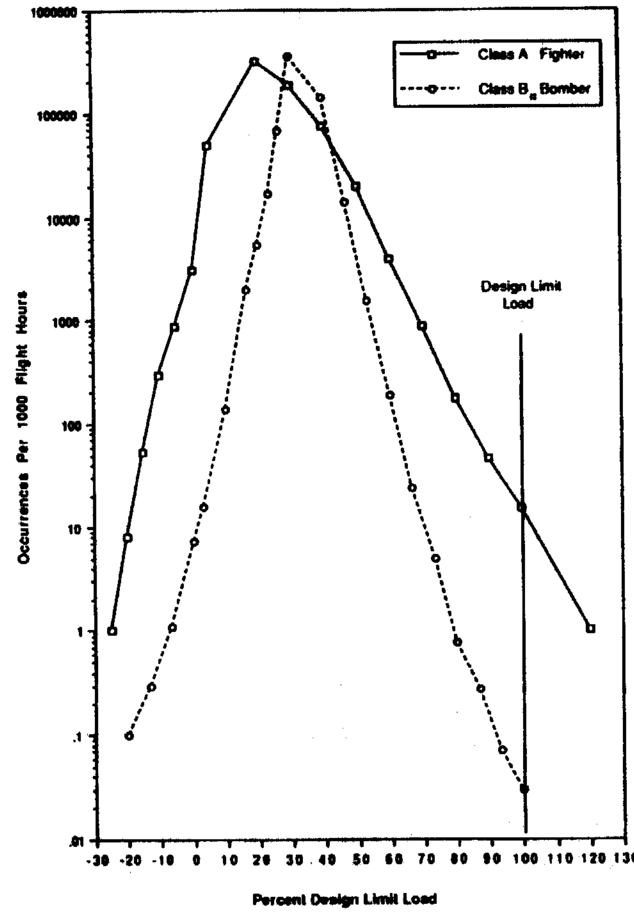
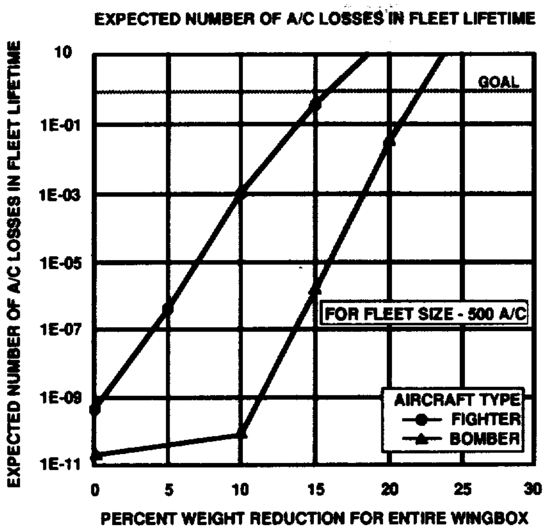


FIGURE 8. AIRCRAFT LOAD SPECTRA



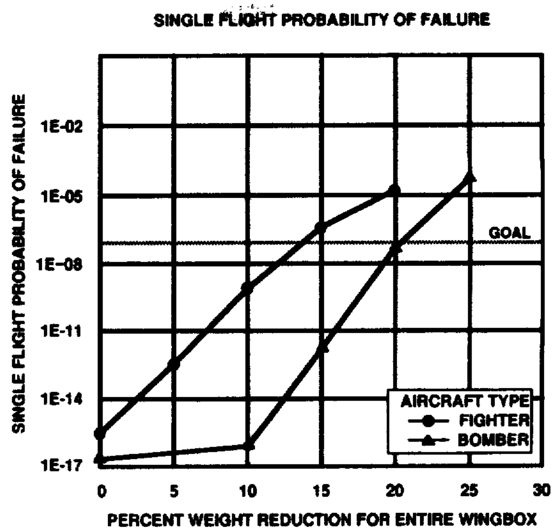


FIGURE 9. COMPOSITE WINGBOX WEIGHT REDUCTION BENEFITS

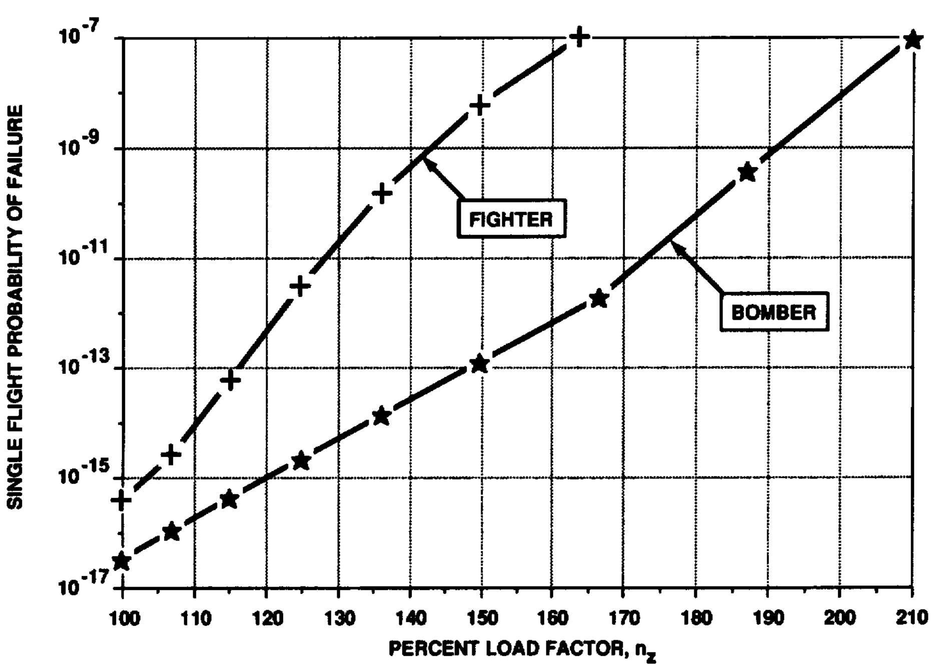


FIGURE 10. DETERMINISTIC/PROBABILISTIC EQUIVALENCE

THIS PAGE INTENTIONALLY BLANK