AIRCRAFT STRUCTURAL SAFETY: EFFECTS OF EXPLICIT AND IMPLICIT SAFETY MEASURES AND UNCERTAINTY REDUCTION MECHANISMS

By

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This dissertation is dedicated to my family: my father Zuhuri Acar, my mother Şerife Acar, and my sister Asiye Acar.

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NOMENCLATURE

ARS	= Analysis response surface
A'_{req}	= Minimum required cross sectional area for the component to carry the service loading without failure
A_0	= Load carrying area if there is no variability and no safety measures
α_1, α_2	= Coefficient of thermal expansion along and transverse to fiber direction
b_e	= Bound of error
β	= Reliability index
C	= Capacity of structure, for example, failure stress
CFD	= Cumulative distribution function
CFR	= Certification failure rate
CLT	= Classical lamination theory
c.o.v.	= Coefficient of variation
DRS	= Design response surface
Δ^*	= Relative change in the characteristic stress σ^* corresponding to a relative change of Δ in stress σ
e	= Error factor
e_{fc}	= Error in failure prediction at the coupon level
e_C	= Error in capacity calculation
e_{fe}	= Error in failure prediction at the element level
e_{fs}	= Error in failure prediction at the structural level

e_{fT} = Total error in failure prediction

e_m = Error in material property prediction

e_P = Error in load calculation

e_R = Error in response calculation

e_σ = Error in stress calculation

e_t = Error in thickness calculation

e_{total} = Total error factor

e_w = Error in width calculation

e^A = Error in facture toughness assessment if traditional (averaging) method is used

e^{MM} = Error in facture toughness assessment if traditional (averaging) method is used

ER = Error reduction

E_1, E_2 = Young's modulus along and transverse to fiber direction

ε_1, ε_2 = Strains in the fiber direction and transverse to the fiber direction

f( ) = Probability density function of the failure stress

F( ) = Cumulative distribution function of the failure stress

FAA = Federal Aviation Administration

G = Strain energy release rate

G_C = Fracture toughness

G_{12} = Shear modulus

γ_{12} = Shear strain

k = Error multiplier

k_A, k_B = Tolerance coefficients for A-basis and B-basis value calculation

k_{dc}	= Knock-down factor used to calculate allowable stress
K_I, K_{II}	= Model I and II stress intensity factors, respectively
M	= Number of simulations in the first stage of MCS
MCS	= Monte Carlo simulation
MEF model	= Multiple error factor model
N	= Number of simulations in the second stage of MCS
N_x, N_y	= Mechanical loading in x and y directions, respectively
n_c	= Number of coupon tests
n_e	= Number of structural element tests
p_{allow}	= Allowable flight load
P	= Load
PDF	= Probability density function
PSF	= Probability sufficiency factor
P_d	= Design load according to the FAA specifications
P_f	= Probability of failure of a component
P_f*	= Approximate probability of failure of probabilistic design
P_{fd}	= Probability of failure of deterministic design
P_F	= Probability of failure of a system
$\overline{P}_c$	= Average probability of failure after certification test
$\overline{P}_{nc}$	= Average probability of failure before certification test
QC	= Quality control for manufacturing
r_{et}	= Ratio of failure stresses measured in test and its predicted value
R	= Response of a structure, for example, stress

RMSE	= Root mean square error
RSA	= Response surface approximation
R^2_{adj}	= Adjusted coefficient of multiple determination
ρ	= Coefficient of correlation
s( )	= Probability density function of the stress
SEF model	= Single error factor model
S_c	= Additional company safety factor
S_{cl}	= Additional company safety factor if the failure stress measured in element tests are lower than the predicted failure stress
S_{ch}	= Additional company safety factor if the failure stress measured in element tests are higher than the predicted failure stress
S_{fe}	= Total safety factor added during structural element tests
S_{FL}	= Load safety factor of 1.5 (FAA specification)
S_F	= Total safety factor
σ	= Stress
σ^*	= Characteristic stress
σ_a	= Allowable stress
σ_f	= Failure stress
t	= Thickness
v_t	= Variability in built thickness
v_w	= Variability in built width
V_R	= Coefficient of variation
w	= Width
W	= Weight

W_d = Weight of the deterministic design

Φ = Cumulative distribution function of the standard normal distribution

ψ = Mode-mixity angle

Subscripts

act = The value of the relevant quantity in actual flight conditions

built = Built value of the relevant quantity, which is different than the design value due to errors in construction

calc = Calculated value of the relevant quantity, which is different from the true value due to errors

cert = The value of the relevant quantity after certification test

d = Deterministic design

design = The design value of the relevant quantity

spec = Specified value of the relevant qunatity

target = Target value of the relevant quantity

true = The true value of the relevant quantity

worst = The worst value of the relevant quantity

W = Wing

T = Tail

Subscripts

ave = Average value of the relevant quantity

ini = Initial value of the relevant quantity

upd = Updated value of the relevant quantity

U = Upper limit of the relevant quantity

L = Lower limit of the relevant quantity

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AIRCRAFT STRUCTURAL SAFETY: EFFECTS OF EXPLICIT AND IMPLICIT SAFETY MEASURES AND UNCERTAINTY REDUCTION MECHANISMS

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Aircraft structural safety is achieved by using different safety measures such as safety and knockdown factors, tests and redundancy. Safety factors or knockdown factors can be either explicit (e.g., load safety factor of 1.5) or implicit (e.g., conservative design decisions). Safety measures protect against uncertainties in loading, material and geometry properties along with uncertainties in structural modeling and analysis. The two main objectives of this dissertation are: (i) Analyzing and comparing the effectiveness of structural safety measures and their interaction. (ii) Allocating the resources for reducing uncertainties, instead of living with the uncertainties and allocating the resources for heavier structures for the given uncertainties.

Certification tests are found to be most effective when error is large and variability is small. Certification testing is more effective for improving safety than increased safety factors, but it cannot compete with even a small reduction in errors. Variability reduction is even more effective than error reduction for our examples.

The effects of structural element tests on reducing uncertainty and the optimal choice of additional knockdown factors are explored. We find that instead of using implicit knockdown factors based on worst-case scenarios (current practice), using test-dependent explicit knockdown factors may lead weight savings. Surprisingly, we find that a more conservative knockdown factor should be used if the failure stresses measured in tests exceeds predicted failure stresses in order to reduce the variability in knockdown factors generated by variability in material properties.

Finally, we perform probabilistic optimization of a wing and tail system under limited statistical data for the stress distribution and show that the ratio of the probabilities of failure of the probabilistic design and deterministic design is not sensitive to errors in statistical data. We find that the deviation of the probabilistic design and deterministic design is a small perturbation, which can be achieved by a small redistribution of knockdown factors.

CHAPTER 1
INTRODUCTION

Motivation

Traditionally, the design of aerospace structures relies on a deterministic design (code-based design) philosophy, in which safety factors (both explicit and implicit), conservative material properties, redundancy and certification testing are used to design against uncertainties. An example of explicit safety factor is the load safety factor of 1.5 (FAR 25-303), while the conservative decisions employed while updating the failure stress allowables based on structural element tests are examples for implicit safety factors. In the past few years, however, there has been growing interest in applying probabilistic methods to design of aerospace structures (e.g., Lincoln 1980, Wirsching 1992, Aerospace Information Report of SAE 1997, Long and Narciso 1999) to design against uncertainties by effectively modeling them.

Even though probabilistic design is a more efficient way of improving structural safety than deterministic design, many engineers are skeptical of probability of failure calculations of structural designs for the following reasons. First, data on statistical variability in material properties, geometry and loading distributions are not always available in full (e.g., joint distributions), and it has been shown that insufficient information may lead to large errors in probability calculations (e.g., Ben-Haim and Elishakoff 1990, Neal *et al*. 1992). Second, the magnitude of errors in calculating loads and predicting structural response is not known precisely, and there is no consensus on how to model these errors in a probabilistic setting. As a result of these concerns, it is possible that transition to probability based design will be gradual. An important step in this transition is to understand the way safety is built into aircraft structures now, via deterministic design practices.

One step taken in the transition to probabilistic design is in the definition of conservative material properties (A-basis or B-basis material property values depending on the failure path in the structure) by the Federal Aviation Administration (FAA) regulation (FAR 25.613). A-basis material property is one in which 99 percent of the material property distribution is better than the design value with a 95 percent level of confidence, and B-basis material property is one in which 90 percent of the material property distribution is better than the design value with a 95 percent level of confidence. The use of conservative material properties is intended to protect against variability in material properties.

In deterministic design the safety of a structure is achieved through safety factors. Even though some safety factors are explicitly specified, others are implicit. Examples of explicit safety factors are the load safety factor and material property knock-down values. The FAA regulations require a load safety factor equal to 1.5 for aircraft structures (FAR 25-303). The load safety factor compensates for uncertainties such as uncertainty in loading and errors in load calculations, structural stress analysis, accumulated damage, variations in material properties due to manufacturing defects and imperfections, and variations in fabrication and inspection standards. Safety factors are generally developed from empirically based design guidelines established from years of structural testing of aluminum structures. Muller and Schmid (1978) review the historical evolution of the load safety factor of 1.5 in the United States. Similarly, the use of A-basis or B-basis material properties leads to a knock-down factor from the average values of the material properties measured in the tests. Note that these knock-down factors depend on the number of tests, because they compensate for both variability in material properties and uncertainty due to a finite number of tests.

As noted earlier, an important step in transition to probabilistic design is to analyze the probabilistic impact of the safety measures used in deterministic design. This probabilistic analysis requires quantification of uncertainties encountered in design, manufacturing and actual service conditions of the aircraft structures.

A good analysis of different sources of uncertainty in engineering modeling and simulations is provided by Oberkampf *et al*. (2000, 2002). These papers also supply good literature reviews on uncertainty quantification and divide the uncertainty into three types: variability, uncertainty, and error. In this distinction, variability refers to aleatory uncertainty (inherent randomness), uncertainty refers to epistemic uncertainty (due to lack of knowledge), and error is defined as a recognizable deficiency in any phase or activity of modeling and simulation that is not due to lack of knowledge.

To simplify the treatment of uncertainty control, in this dissertation we combine the unrecognized (epistemic) and recognized error in the classification of Oberkampf *et al*. and name it error. That is, we use a simple classification that divides the uncertainty in the failure of a structural member into two types: errors and variability. Errors reflect inaccurate modeling of physical phenomena, errors in structural analysis, errors in load calculations, or deliberate use of materials and tooling in construction that are different from those specified by the designer. Errors affect all the copies of the structural components made and are therefore fleet-level uncertainties. Variability, on the other hand, reflects the departure of material properties, geometry parameters or loading of an individual component from the fleet-average values and hence are individual uncertainties.

Modeling and quantification of variability are much easier compared to that of error. Improvements in tooling and construction or application of tight quality control techniques can reduce variability. Quantification of variability control can be easily done by statistical analysis of records taken throughout process of quality control. However, quantification of errors is not as easy, because errors are largely not known before a structure is built. So, errors can only be quantified after the structure has been built. Errors can be controlled by improving accuracy of load and stress calculations, by using more sophisticated analysis and failure prediction techniques or by testing of structural components.

Testing of aircraft structural components is performed in a building block type of approach starting with material characterization tests, followed by testing of structural elements and including a final certification test. Testing of structures is discussed in detail in the next chapter.

The comparison of deterministic design and probabilistic design can be performed in many views. First of all, input and output variables of deterministic design are all deterministic values, while input and output variables of probabilistic design are random (along with some deterministic variables, of course). Here, on the other hand, we compare probabilistic design and deterministic design in terms of use of safety factors. In deterministic design uniform safety factors are used; that is, the same safety factor is used for all components of a system. However, probabilistic design allows using variable