Risk-Based Structural Design: 
Designing for Future Aircraft

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1. Introduction

As the aerospace industry, particularly, the military progresses into the development of hypersonic vehicles, there is an increasing need for a new design methodology that is able to verify the safety and reliability of a design, especially the airframe. The current deterministic methodology is not suited well for future aircraft development because of the limitations of using safety factors that were developed without using explicit reliability calculations\(^1\). The current methodology requires that full scale prototypes be built to be tested under flight conditions. However, hypersonic aircraft cannot be tested under full thermo-acoustic-mechanical conditions on a full scale as the current design methodology requires. In order to verify the reliability of such an aircraft, a new methodology that is based upon risk needs to be utilized\(^2\). Designing an aircraft using a risk or the probability of failure will allow uncertainties, such as geometric tolerances, to be captured and help to reduce “overdesigning” of the aircraft, which will increase the performance and decrease the cost of the aircraft\(^2\).

This paper will provide an overview of the basic concepts of a risked-base design methodology and the benefits of using it over the current deterministic design methodology as it applies to the development of future aircraft. It will also present the preliminary results of using this new methodology on a simplified spar example.

2. Overview of Risk-Based Design Methodology

A risk based design methodology allows the user to incorporate uncertainty into the design analysis by using probability distributions rather than safety factors. Uncertainty can be divided into two main types: aleatory and epistemic uncertainty. Aleatory uncertainty is irreducible and related to the inherent randomness of nature. An example of an aleatory uncertainty is the velocity of the air flow as an aircraft flies through a given point in space. No
matter how much information is known about the environment, mission of the aircraft, etc. it is impossible to predict, with certainty, what the velocity will be as the aircraft flies through it. However, usually the mean of an aleatory uncertainty is known and a probability distribution can be used to characterize the variation. Epistemic uncertainty contains all the uncertainty that is due to lack of knowledge about a physical process or modeling process. This type can be reduced as more information is gathered about the topic. An example of an epistemic uncertainty is uncertain initial boundary conditions\(^3\). These uncertainties are negligible individually, but can negatively impact performance of an aircraft as a system of uncertainties.

In order to assess the reliability of an aircraft, the parameters (ie. Velocity) and the modeling processes need to be analyzed for possible variations and then, characterized with probability distributions. Once the distributions are known, the uncertainty can be propagated through the model by parametric studies of the uncertain parameters. The resulting output probability distributions can be used with statistical measures of confidence to assess the reliability of the aircraft\(^4\). Since aircraft are unique and complex systems, this author does not know of a methodology that is able to analyze an entire aircraft at this time. Most methodologies are still in the development stages and are being applied to simplified academic problems.

3. **Benefits of Using Risk-Based Design Methodology**

3.1 **Captures More Variability in Designs**

One of the anticipated benefits of using a risk based design methodology is a more optimal structural design. The current design process entails sizing the structure so that the stress in the component does not reach a critical value\(^2\). There are two types of critical values: the limited loads that are determined by the engineer and the requirements dictated by the design specifications. Usually a safety factor of 1.5 is applied to the limited load, known as design
loads, and the component is sized to meet the larger of the two loads\(^2\). However, the adoption of the safety factor of 1.5 does not have a foundation based upon mathematical equations and reliability theory. Instead, it is a historical convention that has been accepted because ‘there have not been “too many failures” when it is used’\(^2\). Figure 1 compares the percent failure for prototypes of modern aircraft that were made with finite element models to aircraft that were designed between 1940 and 1976 as a percentage of the designed limit load. The modern aircraft fail at a higher rate during the initial testing phase. This has been linked to analysis errors, material processing issues, and production anomalies\(^5\). Clearly, the current process is neglecting these errors which cause costly design failures. A risked-based methodology includes these errors. These errors are caused by variations or uncertainties, which on individual components are negligible, but applied to the entire system can cause unforeseen failure modes.

![Figure 1. Structural failures for two eras on aircraft design\(^2\).](image-url)
3.1.1. Reducing Overdesigning of Aircraft.

Another anticipated result of a risked based design is that “overdesigning” of the aircraft is reduced. The current process encapsulates all the uncertainty into one safety factor. This has the potential to unnecessarily increase the safety and increase the weight and cost of the aircraft. This idea is illustrated by an example of design a wing spar in which it is designed using both methodologies. The bending of an ideal spar, shown in Figure 2, is considered to show that the design would be more efficient using a risked based design. The military requirements of an attack/fighter aircraft (B-basis) will be applied to the spar. These are 1) that detrimental deformations should not occur at or below 115% of limit load and 2) rupture or collapsing failure should not occur at or below ultimate loads.

\[
I_x = \frac{wh^3}{12} - \frac{(w - tw)(h - 2t)^3}{12}
\]

**Material:**
7175-T74 Die Forging (L-direction)
(25.4 to 50.8 mm thick)
Fx (B-basis) = 461.6 MPa
Fy (B-basis) = 530.5 MPa

Limit Moment, \(M_L = 5209 \text{ N-m}\)

Since bending is only considered, the problem becomes determining the minimum allowable section modulus, Equation 1, to meet the design requirements, where \(I_x\) is the area moment of inertia and \(c\) is the distance from the horizontal axis of symmetry.

\[
Z = \frac{I_x}{c}
\]  

(1)
First, the section moduli are calculated using normal safety factors. The section modulus for the first requirement, where an outer fiber must not plastically deform is given by Equation 2 and the section modulus for the second requirement, where the component must not fail, is given by Equation 3. In these equations, the number multiplying the limit moment is the safety factors and $F_{ty}$ and $F_{tu}$ are the yield strength and ultimate strength for 7175-T74, respectively.

$$Z \geq \frac{1.15M_L}{F_{ty}} = 12,977.4 \text{ mm}^3$$  

(2)

$$Z \geq \frac{1.5M_L}{F_{tu}} = 14,728.6 \text{ mm}^3$$  

(3)

From this analysis, the engineer would require that the section modulus resulting from requirement 2 be designed. This will be the base for the comparisons of the section moduli resulting from the Risk-based methodology.

To apply the risk-based methodology, the limit moment, $M_L$, is the random variable. It is random because the load is the result of uncertainties in the aerodynamic parameters (air density, free stream velocity, skin roughness, etc.) and uncertainties in how the load is transmitted to the spar (strength of composite bonds, geometric tolerances etc.). However, no data on how the limit moment varies is available so the risk base design will be conducted when 1) the limit moment is 5209 N-m with no variation and 2) when it is normally distributed with a mean, $\mu_M$, of 5209 N-m with $\pm 10\%$ variability. For these two cases the section moduli are tabulated in Table 1. The values in bold are the values that the spar would ultimately be designed for to meet the two requirements. For a more detailed explanation of how the values are obtained see reference 2.

**Table 1. The sectional moduli calculated for each case.**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>$M_L$ with 0% variation</th>
<th>$M_L$ with $\pm 10%$ variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastically Deforming</td>
<td>12,520.4 mm³</td>
<td>13,583.5 mm³</td>
</tr>
<tr>
<td>Failure</td>
<td>13,277.8 mm³</td>
<td>14,197.1 mm³</td>
</tr>
</tbody>
</table>
The highlighted values in Table 1 are then compared with the base section modulus that was calculated earlier using the deterministic design approach and tabulated in Table 2.

Table 2. The risk-based calculations compared to the base design\(^2\).

<table>
<thead>
<tr>
<th></th>
<th>Deterministic Design</th>
<th>Reliability-based Design ML with 0% variation</th>
<th>Reliability-based Design ML with ±10% variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z (\text{mm}^3) )</td>
<td>14,728.6</td>
<td>13,277.8</td>
<td>14,197.1</td>
</tr>
<tr>
<td>% difference</td>
<td>0</td>
<td>-10%</td>
<td>-4%</td>
</tr>
</tbody>
</table>

The risk-based design process resulted in smaller sectional moduli. This would cause a decrease in weight and cost of the aircraft. From this analysis, the risk-based design methodology has the potential to reduce overdesigning and increase performance without sacrificing reliability.

3.2 More Cost Effective Approach

The current design method of “design, build, and test,” mandates that prototypes be built for full-scale testing to verify the safety and reliability of the aircraft. This has created a trial and error approach to design and testing of aircraft. This approach has been accepted in the past because large quantities of planes have been purchased. The larger the quantity of planes being purchased, the lower the price per plane, so it is justified to spend extra money on building a prototype for testing. However, for a hypersonic vehicle and assuming that the military will have smaller fleet sizes in the future, the price or opportunity cost of building a multi-million dollar prototype just to have it destroyed while testing is too great to justify spending the money\(^5\). Also, for hypersonic vehicles the extreme thermo-acoustic-mechanical flight conditions can only be tested in a reduced setting. It is very hard and expense to test all aspects of the mission environment. These tests would greatly increase the price of development and not
guarantee the reliability of the aircraft. Clearly, a new design methodology is needed that can incorporate computer simulations\textsuperscript{4}.

3.3 More Proactive Design Methodology

Also, the “design, build, test” method is a reactive design methodology\textsuperscript{2}. It cannot predict failure modes, it only is designed for the failure modes that the engineers determined were relevant. For example, the Aloha Airline Flight 243 fuselage failed due to fatigue caused cracks. However due to the uncertainties, namely corrosion and small damage sites on the airplane, the fuselage failed. This lead to investigations into fatigue and crack progression that result from small damage sites. In this case and many other (de Havilland Comet), action was only taken in response to the accident. A design methodology based upon risk would analyze the uncertainties on the system as a whole and could predict unforeseen failure modes and could reduce costly failures\textsuperscript{3}.

Conclusion

The current deterministic design approach uses a design, build, and test method to verify the reliability of the aircraft. However future aircraft, especially hypersonic aircraft, will need to be designed in a new way in which the reliability of the aircraft is determined through explicit reliability calculations rather than safety factors\textsuperscript{1}. This new risk based design methodology has the potential to optimize the structural design of the aircraft by reducing or eliminating the “overdesigning” of the aircraft while being a cost effective. The new risked based design methodology can be utilized to make the design process more proactive and reduce costly unforeseen failures.
References


