AIRFRAME
STRESS ANALYSIS AND SIZING

About the Author

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Mr. Niu is the author of the texts, AIRFRAME STRUCTURAL DESIGN (1988) and COMPOSITE AIRFRAME STRUCTURES (1992). He has also written Lockheed's Composites Design Guide and Composites Drafting Handbook. He received the Lockheed Award of Achievement and Award of Product Excellence in 1973 and 1986, respectively. He is listed in Who's Who in Aviation, 1973.

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A MESSAGE FROM THE AUTHOR

In the universe, there is always a balance, typified by ying (negative) and yang (positive). This may help explain the Industrial Revolution which brought humankind civilization (positive) but also inflicted on us the problem of "pollution" (negative) which, if not effectively controlled, could be catastrophic. There are many such instances which require balance in this world and it all depends on how we handle them before it is too late. Diagnosing such problems in the early stages makes them much easier and less costly to handle.

Since the 1970's the calculation revolution instigated by the use of computer analysis has given the engineer quicker and more accurate answers. Computer analysis can even solve some problems of highly redundant structures that were practically impossible to calculate in the past. Computer analyses will replace all hand calculations in the near future. The merits of using computer hardware and software are not disputed; however, "Murphy's Law" is always operative everywhere and mistakes do happen in design. An engineer who only knows how to do inputs to computer analysis may not know whether or not the output is correct (the garbage-in and garbage-out process!). An engineer is not a robot or a machine; ingenuity comes from the engineer, not the machine. Unfortunately, industries ignore engineers' ambition to pursue the necessary experience due to cost considerations. But, engineers cannot learn valuable experience from computers; the computer is just a beautiful tool and is not everything!

A second issue is work experience; in particular, engineers now spend most of their time in front of computer screens and the importance of communication with colleagues from other disciplines, i.e. team work, is overlooked. Engineers are losing the opportunity to gain needed experience from the "old timers". The end result is that industries gradually lose the most valuable experience which passes away with the retiring engineers of the "old school". Industries should ask retiring engineers to write down their valuable experience in report form before they leave so that it will be passed on to those who follow. Big companies have their own handbooks, manuals, etc., for company use, but they are merely handbooks and do not provide enough experience. Industry management spends too much effort on figuring out how to save on costs, but, in the long run, they lose the bases of experience, and will end up as big losers. If this situation is not remedied soon, the aircraft manufacturing industries as well as other industries will walk into backlash.

Another issue concerns aging aircraft, an issue that has been debated since Aloha Airlines' old B737 aircraft disaster, but, as yet, nobody, including the aircraft manufacturers and users, wants to define the flyable life of the aircraft, i.e. limit flight hours or years of service, whichever is more appropriate. From the structural engineer's standpoint, we realize that any metallic structure has its own fatigue life, just like the human body, and no life can go on forever, even with vigilant maintenance work. When a vehicle becomes too old, even maintenance is of no use. If the aircraft has a problem in midair, it will fall and, unlike ground vehicles, cannot stop to wait for rescue. The ultimate goal of the aircraft manufacturers and the government certifying agency should be to determine a standard for a reasonable and affordable lifespan for aircraft to reduce peril to passengers. This should be done now, before more lives are lost.

AIRFRAME
STRESS ANALYSIS AND SIZING

Second Edition

Michael Chun-Yung Niu

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DISCLAIMER

It is the intent of the author of this book "AIRFRAME STRESS ANALYSIS AND SIZING" to include all the pertinent structural design data required for airframe stress analysis and sizing into one convenient book. The author does not guarantee the contents provided in this book, and it is the responsibility of the reader to determine if the data and information in this book are in agreement with the latest design allowables and the reader's authoritative company source.

Printed in Hong Kong

PREFACE

This book has been prepared as a source of data and procedures for use in the sizing of both airframe and space vehicle structures. The material presented herein has been compiled largely from the published data of government agencies, such as NACA reports and technical publications. The reader will not, of course, be able to read this book with complete comprehension unless he is familiar with the basic concepts of strength of materials and structural analysis; it is assumed that the reader is familiar with these subjects and such material generally is not repeated herein. To maintain the compact size of this book, only data and information relevant to airframe structures are included. Since today's airframe structures are primarily constructed from metallic materials, this book focuses on metallic structural sizing. A few material allowables are included for reference and for in performing the sizing examples.

Step-by-step procedures are included whenever possible and, in many chapters, examples of numerical calculation are included to clarify either the method of analysis or the use of design data and/or design curves to give engineers a real-world feeling of how to achieve the most efficient structures. The intent of this book is to provide a fundamental understanding of the stress analysis required for airframe sizing. The emphasis is on practical application with input from both material strength and hands-on experience. A balance between theory and practical application in airframe structures depends extensively on test data which must be correlated with theory to provide an analytical procedure.

The structural problems of aircraft usually involve the buckling and crippling of thin-sheets (or shells) and stiffened panels. Thin sheet buckling design is one of the most important subjects of airframe analysis. The NACA reports from the 1940's have contributed tremendous amount of information and design data in this field and today's airframe engineers still use them and consider them to be the backbone of airframe stress analysis.

The careful selection of structural configurations and materials, which are combined to produce an optimized design while also considering the effects of static loads, fatigue, fail-safe requirements, damage tolerance and cost, is the most important issue in this book. A considerable amount of material on the sizing of metallic airframes is presented in tables, charts and curves that are based on past experience and/or test results. Another purpose of this book is to give airframe engineers a broad overview of data and information based on the experience and the lessons learned in the aircraft industry (including service of components) that can be used to design a weight-efficient structure which has structural integrity.

Structural sizing approaches and methods will be introduced for those who need to do rough estimations to support aircraft structural design during the preliminary aircraft design stage and also for those who are involved in airframe repair work.

There is a big gap between theoretical and practical design and this book attempts to bridge the two with real-life examples. The list of references at the end of each chapter complements the material presented in this book and provides the interested reader with additional sources of relevant information.

In order to reinforce the reader's knowledge of airframe sizing, it is strongly recommended that the reader use the author's book AIRFRAME STRUCTURAL DESIGN as an important complementary reference source because it contains a tremendous amount of design information and data that are generally not repeated in this book.

This book was put together in the style of an engineering report with clear sketches of good quality instead of expensive commercial illustrations like those in old-fashioned textbooks. Sincere appreciation and thanks to those who have contributed to correct many errors in the first edition. Special thanks to Mr. Lawrence W. Maxwell for his review in checking for errors throughout the entire book (first edtiion). It is inevitable that minor errors will occur in this book and the author welcomes any comments for future revisions.

Michael Chun-yung Niu
(牛春匀)

Los Angeles, California, U.S.A.
October, 1998 (second edition)

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ABBREVIATIONS, ACRONYMS AND NOMENCLATURE

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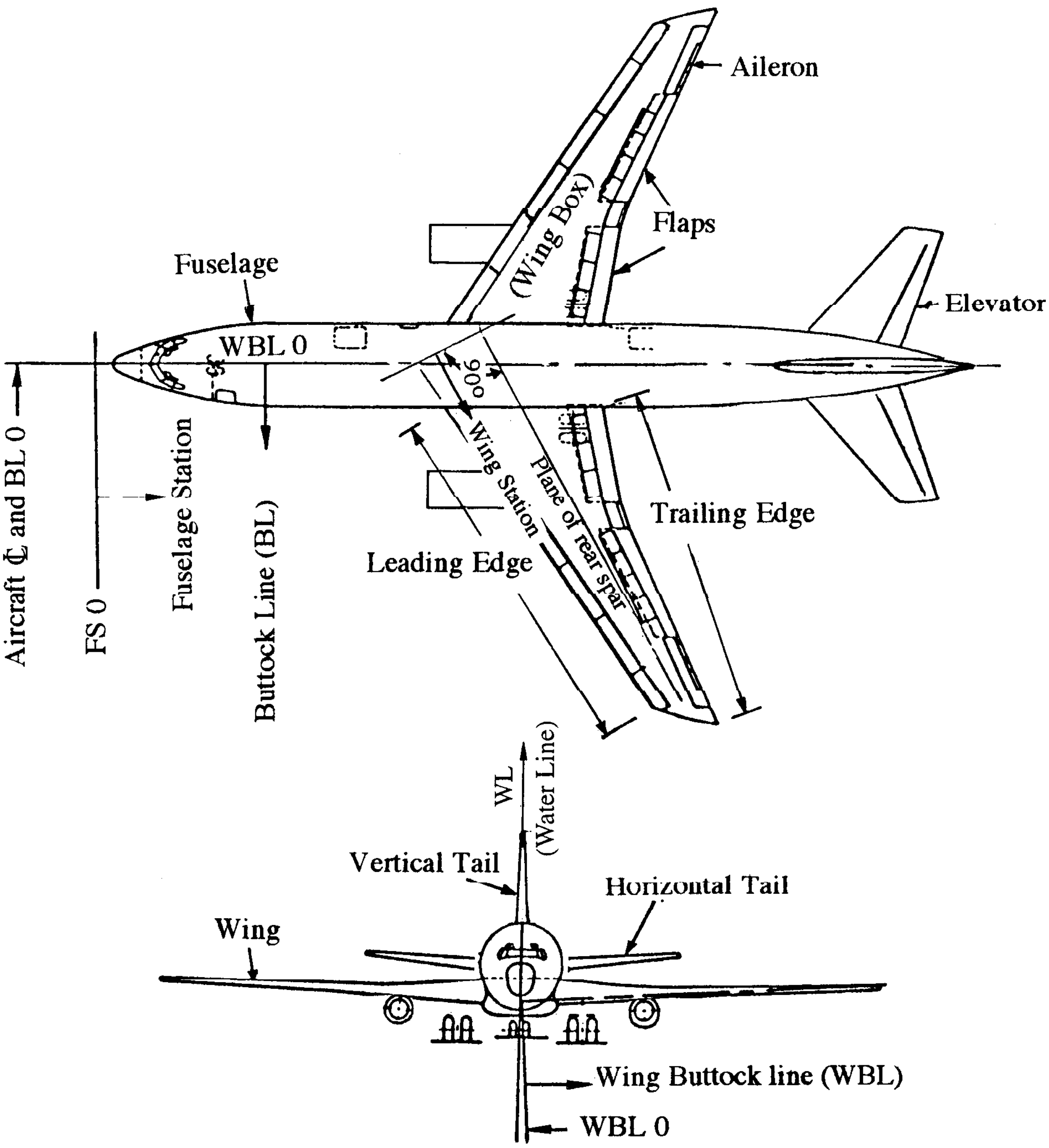
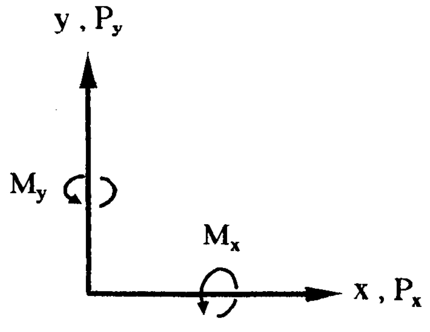
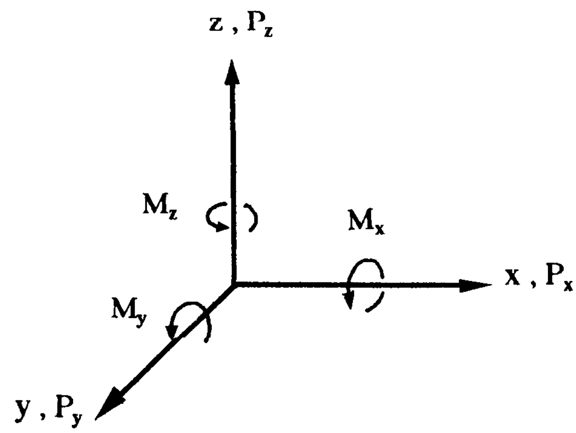






Right-hand rule for positive moments

(2-dimensional Coordinates) **(3-dimensional Coordinates)**

Coordinate Systems

a	–	Panel skin length (long side); crack length
A	–	Cross-sectional area
A/C	–	Aircraft
b	–	Width; panel skin width (short side)
BL	–	Buttock Line - distance in a horizontal plane measured from fuselage centerline
c	–	Column end-fixity; distance from N.A. to extreme fiber
C	–	Coefficient; fastener constant
c.g.	–	Center of gravity
C_N MAX	–	Maximum lifting coefficient
CSK	–	Countersunk
d	–	Diameter
D	–	Drag; diameter; plate stiffness
DM	–	drag force on main gear
DN	–	drag force on nose gear
Dia.	–	Diameter
e	–	Elongation; edge distance; shear center; eccentricity; effective
E	–	Modulus of elasticity (Young's modulus in elasticity range)
Eq.	–	Equation
E_t	–	Tangent modulus
f	–	Applied stress
F	–	Allowable stress; Farrar's efficiency factor
FAA	–	Federal Aviation Administration
FAR	–	Federal Aviation Requlations
fps	–	Feet per second
FS	–	Fuselage station – distance measured parallel to fuselage from a vertical plane forward of fuselage
ft.	–	Foot
Fwd	–	Forward
g	–	Load factor; gross
G	–	Modulus of rigidity (or shear modulus)
GAG	–	Ground-air-ground cyclic load spectrum
h	–	Height
HD	–	Head

H.T.	–	Heat treat
I	–	Moment of inertia; Angular inertia force necessary for equilibrium
in.	–	Inch
Inb'd	–	Inboard
in.-kips	–	Inch-(1,000) pounds
in.-lbs	–	Inch-pound
j	–	$\sqrt{\frac{EI}{P}}$
J	–	Torsional constant
JAR	–	(European) Joint Airworthiness Regulations
k	–	Buckling coefficient; section factor; kips; fastener spring constant; diagonal tension factor;
K		Modified buckling coefficient; shear lag parameter; stress intensity factor; stress concentration factor; fatigue quality index; efficiency factor
kip(s)	–	1,000 lbs.
ksi	–	(1,000 pounds) per square inch
L	–	Wing lift; length; longitudinal grain direction
LT	–	Long transverse grain direction
L'	–	Effective column length ($\frac{L}{\sqrt{c}}$)
lbs.	–	Pounds
lbs./in. or #/in.	–	Pounds per inch
m	–	Bending moment; meter; empirical material constant; mean value
M	–	Bending moment; Mach Number;
MAC	–	Mean Aerodynamic Chord
max.	–	Maximum
MFD	–	Manufactured
Min. or min.	–	Minimum
MS or M.S.	–	Margin of Safety
n	–	Material shape parameter; load factor; drag factor; number of cycles
N	–	Load intensity; number of cycles
NA or N.A.	–	Neutral axis
NACA	–	National Advisory Committee for Aeronautics
NASA	–	National Aeronautics and Space Administration
Outb'd	–	Outboard
P	–	Concentrated load; column load
psi	–	Pounds per square inch
pt.	–	Point
q	–	Shear flow
Q	–	First moment of area; concentrated load; shear load
R	–	Support reaction load; radius; load ratio; stress ratio
r	–	Radius
rad.	–	Radian
s	–	Fastener spacing
S	–	Stress
SF	–	Severtiy factor
S-N	–	Cyclic stress; stress vs. number of cycles
ST	–	Short transverse grain direction
T	–	Torsion load; total thickness
t	–	Thickness
Typ	–	Typical
V	–	Velocity; vertical load; shear load

W	–	Weight; width; concentrated load
w	–	Uniform loading; width
WBL	–	Wing Buttock Line – a plane normal to wing chord plane and parallel to fuselage and distance measured from intersection of wing chord plane and BL 0.0
WL	–	Water line – distance measured perpendicular from a horizontal plane located below bottom of fuselage
WS	–	Wing station – a plane perpendicular to wing chord plane and plane of rear spar, distance measured from intersection of leading edge and BL 0.0
x	–	x-axis
X	–	c.g. location in x-axis direction
y	–	y-axis
Y	–	c.g. location in y-axis direction
z	–	z-axis
Z	–	c.g. location in z-axis direction
"	–	Inch
α	–	Angle of oblique load; coefficient; angle of diagonal tension web; hole condition factor; correction factor
β	–	Coefficient; hole filling factor; reinforcement factor
γ	–	Shear strain; coefficient
θ	–	Twist angle; tangential angle; bearing distribution factor; petch angle
ϕ	–	Principal stress inclined angle; meridian angle; roll angle
ψ	–	Yaw angle
ρ	–	Radius of gyration ($\sqrt{\frac{I}{A}}$); density
μ	–	Poisson's ratio; torsional spring constant; coefficient
η	–	Plasticity reduction factor; fastener hole-out efficiency; plasticity correction factor
δ	–	Deflection
Δ	–	Deflection; increment
ε	–	Strain; rotational restraint
Σ	–	Summation
#	–	Pound
τ	–	Shear stress
κ	–	Coefficient
λ	–	Fitting factor; cladding reduction factor; buckling wave length
ν	–	Coefficient
£	–	Plasticity correction ratio for skin-stringer panel

Chapter 1.0

GENERAL OVERVIEW

1.1 OVERVIEW

A knowledge of structural design methods and an understanding of the load paths are essential to advancement in nearly all phases of airframe engineering. Approximately ten percent of the engineering hours spent on a new airframe design project are chargeable directly to:

- The obtaining of design loads in members
- The strength checking of drawings of the finished parts and assemblies

No aircraft engineer can expect to go far in advanced drafting, layout work, and design without a working knowledge of stress analysis. Thus, whether an engineer expects to go into the actual analysis work or to engage in some other type of aircraft engineering he will find a good working knowledge of stress analysis to be of great value in doing a better job.

The types of analysis used in airframe work are very different in many respects from those used in other types of engineering. The reason lies in the fact that the challenge of structural weight savings must be paramount if an efficient performance aircraft, i.e., one which carries a high percentage of pay load, is to be obtained.

(A) SIZING SCENARIO

In airframe structures, there are mostly redundant structures such as the typical wing box beam, which require the use of computer analysis. A three-stringer box beam, for instance, is a statically determinate structure but each additional stringer adds one more redundancy for each cross section. For airframe structures, the number of redundancies is of the order of thousands and the solution of such problems by conventional methods for solving highly indeterminate structures is extremely tedious and is, indeed, not feasible; computer analysis, such as the Finite Element Modeling (FEM) method and the method of successive approximation are the only reasonable methods to use in these cases.

If a simple structure with stringers of equal size and spacing is considered, analytical methods can greatly simplify the solutions to the problem for preliminary sizing work. If either the method or the structure analyzed is simplified when doing preliminary sizing, cost-effectiveness is increased, as shown below:

(a) Type of structures – For example, it may be possible to convert the wing box beam into a rectangular section with parallel shear webs and be symmetrical about a vertical plane.

(b) Lumping stringers – Reduce the complexity of large numbers of stringers by combining adjacent stringers into so-called 'lumped stringers'.

(c) Type of loading – Choose one of the critical or primary loads from the axial (from bending), shear flow (from vertical shear load or torsion) or lateral (from external aerodynamic or concentrated loads) loads to do the sizing.

(d) Limitation of stress distribution – Obtain the main or key stress distributions but not the detailed stresses.

Before going into detail sizing (also called production stress analysis), a rapid and reasonably accurate (i.e., approximate 0 – 10%) sizing of the structural dimensions is required for the preliminary aircraft design stage.

Another extremely important issue in every engineer's mind is that computer analysis will soon replace most, if not all, hand calculations in the aircraft industry. Computer analysis is a black-box operation in contrast to preliminary sizing which gives the engineer a feeling for the real world. With black-box operations, the engineer has no way of justifying the output results. When computer input is performed by the engineer, how can he verify that no mistakes were made in the input of numbers or decimals? Since Murphy's Law is always in operation, some mistakes are unavoidable in either design or analysis. All results or output should be reviewed by an experienced and/or knowledgeable engineer. If computer analysis is not performed by a knowledgeable engineer, it will turn out to be a "garbage in/garbage out" process which could result in very dangerous and questionable results. Preliminary sizing can be used in parallel to double check computer output to assure that the result is in the ballpark. All aerospace and aircraft engineers should learn preliminary sizing techniques to diagnose computer black-box problems. The difference between preliminary sizing and detail sizing (or detail stress analysis) can be summarized as follows:

(a) Preliminary sizing:

- Is a challenge and diagnosis job
- Most airframe structures are highly redundant structures, i.e., skin-stringer panels, cut-outs, tapered wing box structures, tapered fuselage cylindrical structures, etc.
- First simplify the structure into an equivalent, if it is a highly redundant one
- For simple members (and most airframe structures are not simple) there may be no difference between preliminary and detail sizing
- Sometimes requires the engineer to make assumptions and judgments based on previous experience
- Basically it is hand calculations plus help from a simple desk-top calculator
- Approximation methods may be used
- Apply simple methods of stress analysis approaches rather than detail analysis
- Prior to running airframe Finite Element Modeling (FEM), preliminary structural sizing input data are required for the first analytical cycles as shown in Fig. 1.1.1. and even the second or third cycles

(b) Detail sizing:

- A time-consuming and costly process
- Using the correct method and designing to the proper margin of safety (MS) is adequate as far as it goes.
- Gives more accurate results but usually requires help from a computer
- Involves more computer work including different software
- Most detail sizing is impossible by hand calculation within a reasonable time frame and cost because it involves too many equations (from a dozen to a few hundred):
  - load distribution in redundant structures.
  - cutout analysis
  - damage tolerance and fatigue analysis

Once the general features of an aircraft design have been decided, proceed as follows:

(a) First, lay out a structure which will accommodate those features and form a skeleton on which to hang the necessary installations.

(b) Next, determine the loading conditions which will cause the highest loads in the structures and make a preliminary sizing or analysis to find the effect of these loads. This preliminary sizing is necessary in order to determine approximate dimensions, since aircraft installations are as compact as possible and clearance allowances are low.

(c) After the final design features are decided upon and all installations, such as those for power plant, electrical system, control systems and furnishings, are placed it is possible to estimate the final dead weight and its distribution and to proceed with the final analysis (see Fig. 1.1.1).

The engineer should be not only thoroughly familiar with the requirements for routine strength checking but also have the knowledge necessary for:

- Detail design for fatigue considerations
- All structures must withstand hail and lightning strikes
- Must operate in and be protected against corrosive environments indigenous to all climates

The structure must have a serviceable life of 20 years or more with minimum maintenance and still be lighter than any vehicle built to date. Under stringent competition, the design must incorporate new materials such as advanced composite materials and processes that advance the state-of-the-art to improve aircraft performance.

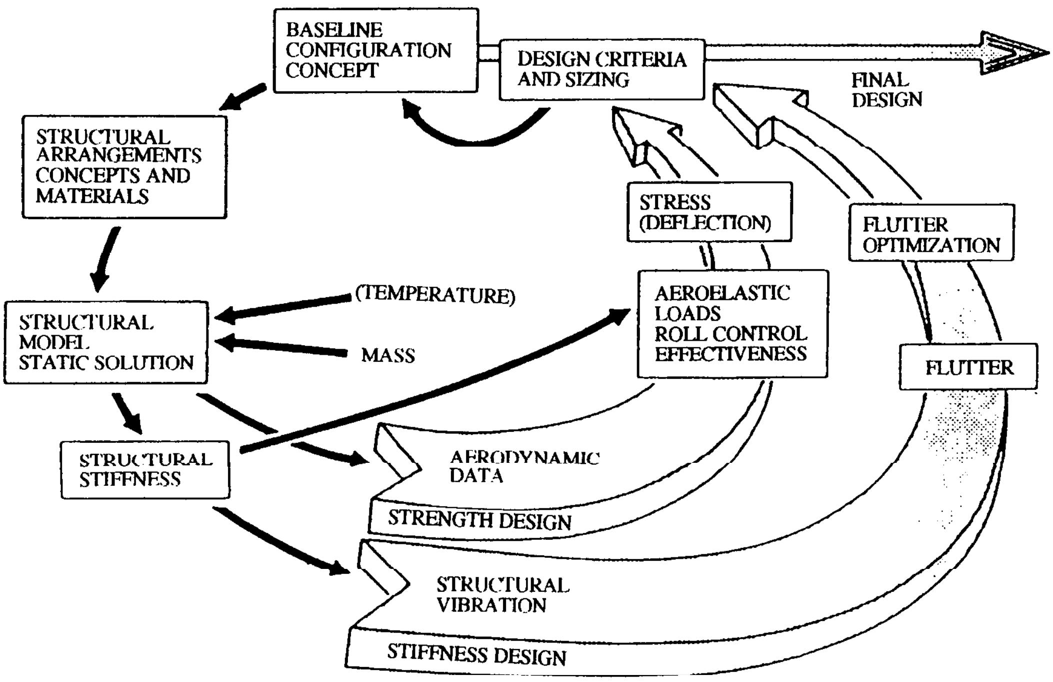


Fig. 1.1.1 Structural Analytical Design Cycles

(B) SPECIFICATIONS AND REQUIREMENTS

A good overall structural concept incorporating all these factors is initiated during preliminary design and sizing. At the very beginning of a preliminary design effort, a designer writes a set of specifications consistent with the needs. It should be clearly understood that during preliminary design it is not always possible for the designer to meet all the requirements of a given set of specifications such as shown in Fig. 1.1.2 and the U.S. FAA certification flowchart as shown in Fig. 1.1.3.

COMMERCIAL AIRCRAFT :

- FEDERAL AVIATION REGULATIONS (FAR), VOL. III, PART 23 - AIRWORTHINESS STANDARDS: NORMAL, UTILITY, AND AEROBATIC CATEGORY AIRPLANES
- FEDERAL AVIATION REGULATIONS (FAR), VOL. III, PART 25 - AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY
- JAR (Joint Airworthiness Requirements) - EUROPEAN COUNTRIES

MILITARY AIRCRAFT :

- MIL-A-8860(ASG) - GENERAL SPECIFICATION FOR AIRPLANE STRENGTH AND RIGIDITY (U.S.A.)

Fig. 1.1.2 Regulations and Specifications

In fact, it is not at all uncommon to find certain minimum requirements unattainable. It is necessary to compromise as shown in Fig. 1.1.4 which indicates what might happen if each design or production group where allowed to take itself too seriously.

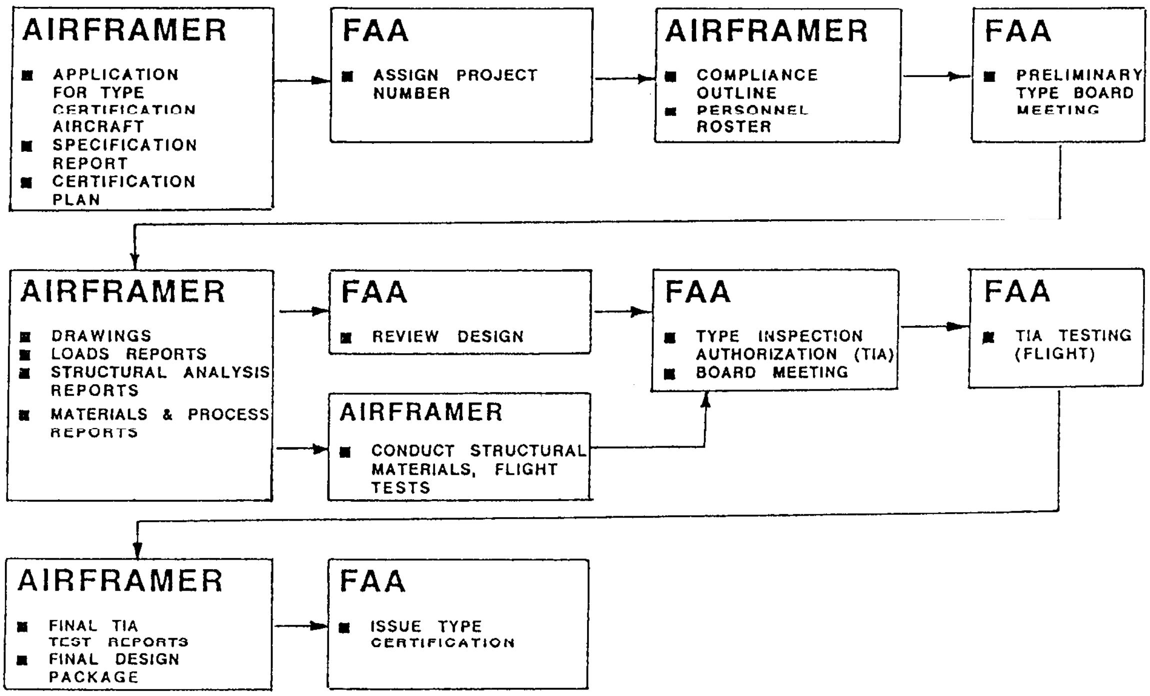
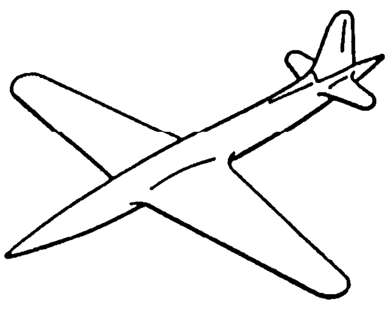
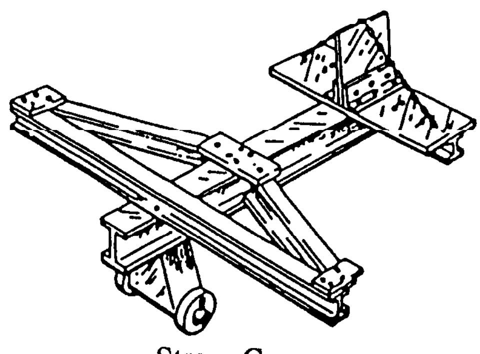


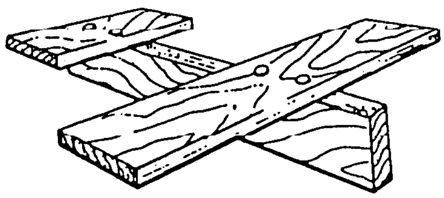
Fig. 1.1.3 U. S. FAA Certification Flowchart



Aerodynamics Group



Stress Group



Production Group

Fig. 1.1.4 Results of Group Dominance in Aircraft Design

(C) DESIGNER'S FUNCTIONS

The extent to which compromises can be made must be left to the judgment of the designer based on the designer's interactions with other disciplines. The structural designer is merely a focal point for the collect of all necessary data and information from all disciplines prior to making the engineering drawing.

Designer's functions (as shown in Fig. 1.1.5):

- Provide focal point
- May need to depend heavily on the support of others for scientific and technical analysis
- Must really understand and apply basics of engineering in the thought process of design
- Should understand specialized engineering disciplines sufficiently to evaluate influence on design
- Think design and engineering basics and their interplay

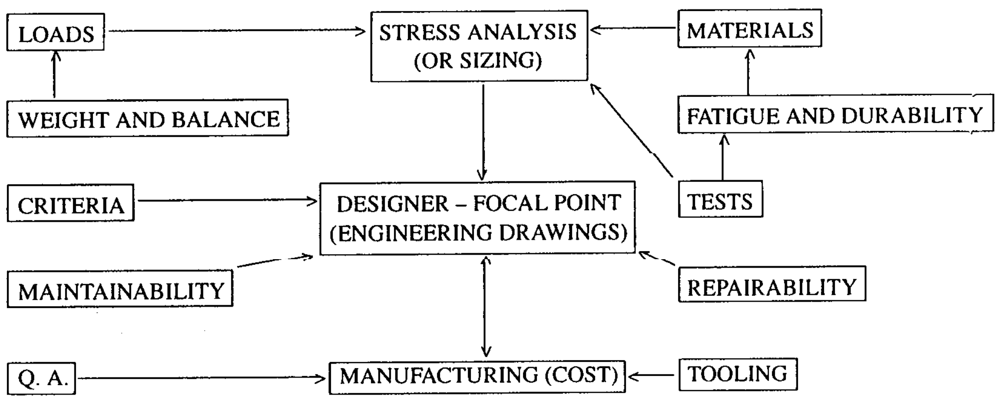


Fig. 1.1.5 Structural Designer's Function (make compromise with other groups)

(D) ENGINEER'S FUNCTIONS

- Many engineering functions do not require doing design, for example:
  - Analysis
  - Testing
  - Research
  - Metallurgy
  - Materials and Processes
  - Flight dynamics
  - Thermodynamics
  - Structural mechanics
  - Electromagnetic fields
- All engineers should have sufficient formal training in design and shop training subjects to understand the design process
- Some will not have an affinity or talent for design but the exposure will better equip them for productive work