PRACTICAL CONSIDERATIONS IN AEROELASTIC DESIGN

Bruce A. Rommel and Alan J. Dodd
Douglas Aircraft Company
McDonnell Douglas Corporation

ABSTRACT

This paper examines the structural design process for large transport aircraft. Practical considerations include design criteria to satisfy certification requirements of FAR Part 25 and selected JAR requirements. Critical loads must be determined from a large number of load cases within the flight maneuver envelope. The structural design is also constrained by considerations of producibility, reliability, maintainability, durability, and damage tolerance, as well as impact dynamics and multiple constraints due to flutter and aeroelasticity. Aircraft aeroelastic design considerations in three distinct areas of product development (preliminary design, advanced design, and detailed design) are presented and contrasted. The present state of the art is challenged to solve the practical difficulties associated with design, analysis, and redesign within cost and schedule constraints. The current practice consists of largely independent engineering disciplines operating with unorganized data interfaces. The need is then demonstrated for a well-planned computerized aeroelastic structural design optimization system operating with a common interdisciplinary data base. This system must incorporate automated interfaces between modular programs. In each phase of the design process, a common finite-element model for static and dynamic optimization is required to reduce errors due to modeling discrepancies. As the design proceeds from the simple models in preliminary design to the more complex models in advanced and detailed design, a means of retrieving design data from the previous models must be established.

The past 20 years have seen spectacular advances in the methodology for computer-aided design of aerospace structures. However, the gap between theoretical and pilot program development and the practical application to hardware development has remained significant. This paper examines the practical aspects of the aircraft structural design process and attempts to define areas of research needed to close the gap between theory and application. This discussion will illustrate why the gap exists and why the traditional organization of the design process has not led to the new technologies needed to close the gap.

The process of aircraft structural design has traditionally been one of sizing and drawing by the designer. This is followed by analytical and test verification of the design throughout the design development process. The aircraft structural design must, of course, sustain the aeroelastic loads throughout the flight envelope, including dynamic landing and taxi loads, impact dynamics, and acoustics. The aircraft structural design must also be able to prevent the aeroelastic instabilities of flutter and divergence. As shown in Figure 1, the first step in the design process is to establish the design criteria necessary to satisfy the certification requirements for the Federal Aviation Administration, the Joint Airworthiness Requirements, or Military Procurement Specifications. Included in these design requirements are considerations of flutter and aeroelasticity, durability and damage tolerance, and the less tangible requirements stemming from company experience, philosophy, and economics. The purpose of these requirements is to ensure product safety and reliability.

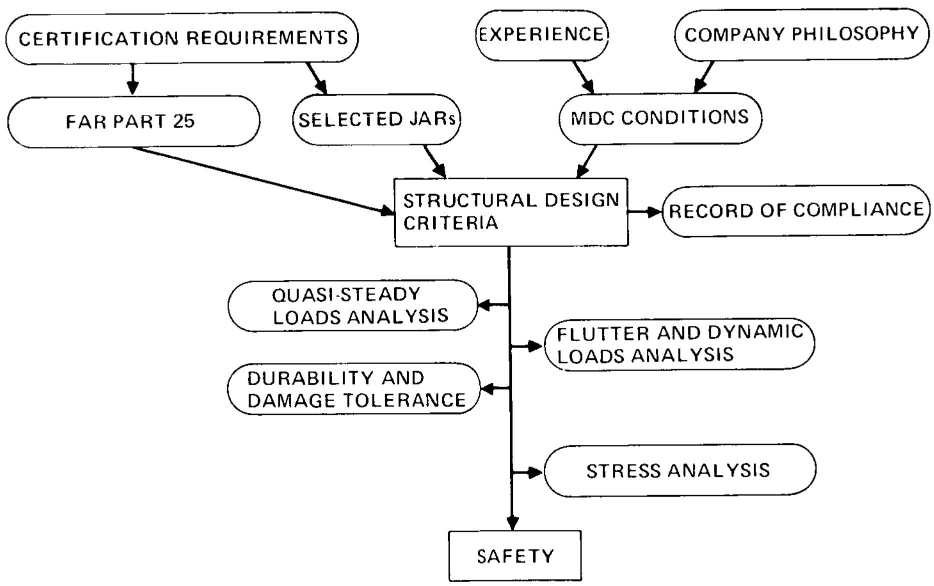

FIGURE 1. DESIGN CRITERIA – THE FIRST STEP

Figure 2 shows a basic breakdown of loads analyses required to satisfy the design requirements of a typical commercial transport aircraft. These analyses include flexibility effects for both steady and dynamic flight loading conditions. Loads induced by balanced maneuvers in flight, as well as dynamic landing and taxi loads and PSD gust loads, must be investigated to ensure that worst-case design loads for a specific aircraft have been found. In addition to the loads induced by normal operation, the off-limits performance induced by possible malfunctions of automated control systems must also be accounted for. Life-cycle loads spectra must provide design criteria for durability and damage tolerance to ensure an adequate service life. The purpose of all of these loads predictions is to provide structural design integrity for strength, fatigue, damage-tolerant, and fail-safe design of the aircraft structure. The "Catch-22" is that most of these loads evaluations require a structural model to predict the load redistribution that takes place due to aeroelastic effects. That is, some design cycle iteration is required between the loads prediction and the structural design before the design loads can be established.

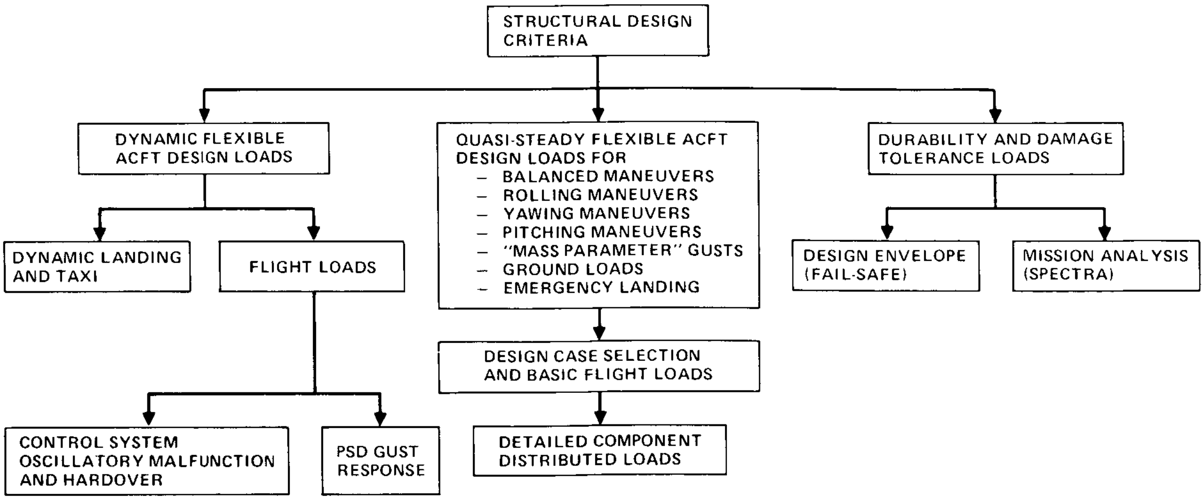

FIGURE 2. LOADS ANALYSIS SUMMARY

Figure 3 shows the primary critical load conditions established for the design of a typical commercial aircraft. Each of these load conditions must be examined for a number of variations of flight parameters. Figure 4 shows that, even for a relatively small number of flight parameter variations, a very large number of flight load conditions will result. These loads must then be evaluated to select the critical design loads for structural analysis and design. To accomplish this, most airframe manufacturers use box beam models of the aircraft for loads and dynamics analysis.

Figure 5 shows the critical design considerations for the fuselage of a commercial aircraft. These considerations include impact dynamics for a number of scenarios of survivable crashes. These impact dynamics studies are nonlinear dynamic analyses of a portion of the aircraft. The purpose of these studies is to provide design criteria, such as frame spacing, to limit the damage in these events. An entirely different type of analysis is required to determine fuselage design criteria to limit cabin interior noise due to acoustic effects. These design considerations, coupled with producibility, repairability, durability, damage tolerance, and other factors, make it impossible to achieve minimum weight for fuselage flight design loads.

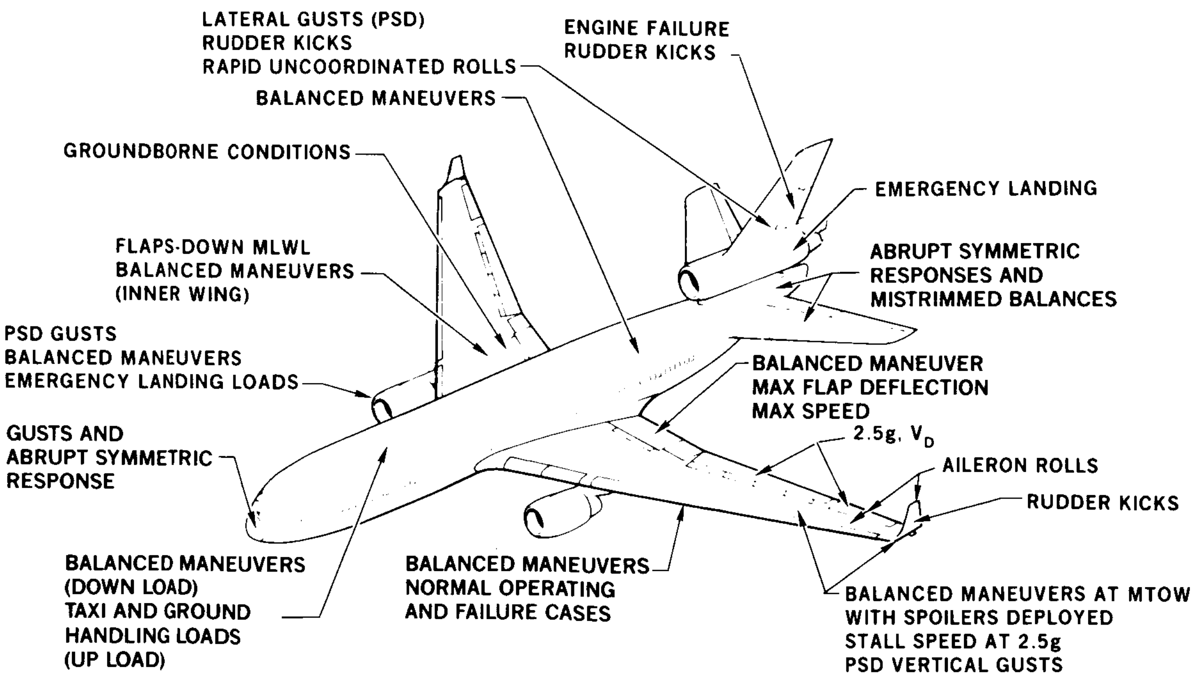

FIGURE 3. PRIMARY CRITICAL LOADING CONDITIONS

ORIGINAL PAGE IS
OF POOR QUALITY

BALANCED MANEUVER DESIGN ENVELOPE

PARAMETER	TYPICAL NUMBER OF VALUES USED
SPEED	5
MACH NO. (ALTITUDE)	x 10
WEIGHT	x 4
CENTER OF GRAVITY	x 2
WING FUEL QUANTITY	x 2
SPEED-BRAKE SPOILER	x 2
THRUST MAX/MIN	x 2 = 3,200 CONDITIONS

FLAPS DOWN BALANCED MANEUVER SURVEY = 1,600 CONDITIONS

TOTAL 4,800 CONDITIONS

LARGE NUMBER OF ANALYSIS CONDITIONS MADE POSSIBLE BY USE OF
COMPUTER-BASED METHODS

FIGURE 4. COMPREHENSIVE SURVEY FOR CRITICAL CASE SELECTION

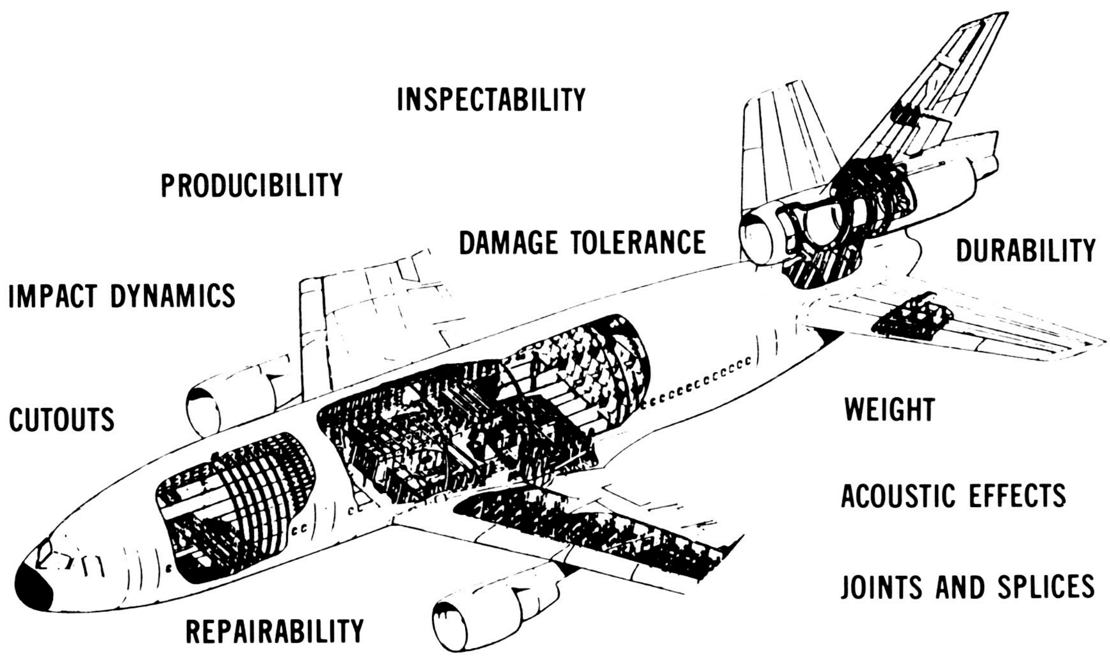

FIGURE 5. CRITICAL FUSELAGE DESIGN CONSIDERATIONS

Figure 6 shows typical service and fatigue life design criteria for a commercial aircraft. Typically, these aircraft are designed for a service life of 20 years or 60,000 flight hours. The fatigue life goal is typically twice the normal service life.

A commercial aircraft, like a combat aircraft, must tolerate a certain amount of damage without being unsafe to fly. Figure 7 shows some of the fail-safe and damage tolerance considerations in use at Douglas Aircraft Company. The fuselage must be able to sustain full design limit loads with a skin crack passing through two bays, including a break in the central longeron or crack stopper. Damage tolerance analysis of composite materials is still immature. There is no universal agreement on failure criteria or even what constitutes a failure in composite materials. Other fail-safe and damage tolerance considerations include maintaining adequate flutter margin after failures in the engine mounts or pylons.

	FLIGHT STRUCTURE	LANDING GEAR	
	FAIL-SAFE STRUCTURE	SAFE-LIFE STRUCTURE	
	MEDIUM AND LONG RANGE	MEDIUM RANGE	LONG RANGE
DESIGN SERVICE LIFE (20 YEARS)	60,000 FLIGHT HOURS 30,000 FLIGHTS/LANDINGS	50,000 LANDINGS	33,300 LANDINGS
FATIGUE LIFE GOAL (DESIGN MEAN LIFE)	120,000 FLIGHT HOURS 60,000 FLIGHTS/LANDINGS	150,000 LANDINGS	100,000 LANDINGS

FIGURE 6. SERVICE LIFE AND STRUCTURAL FATIGUE DESIGN CRITERIA

PRIMARY FLIGHT STRUCTURE IS DESIGNED TO BE FAIL-SAFE SO AIRCRAFT MAY BE SAFELY OPERATED AFTER FAILURE OF ANY PRINCIPAL STRUCTURAL MEMBER

DOUGLAS CRITERIA EQUAL OR EXCEED FAR REQUIREMENTS

FUSELAGE SHELL WILL SUSTAIN DESIGN LIMIT LOADS AFTER A FULL TWO-SKIN-BAY CRACK LENGTH IN ANY DIRECTION (WITH CENTRAL CRACK STOPPER OR CENTRAL LONGERON BROKEN)

WING WILL SUSTAIN DESIGN LIMIT LOADS AFTER A FULL TWO-BAY CRACK IN THE SKIN WITH CENTRAL STRINGER BROKEN

ALL PRIMARY CONTROL SURFACES WILL SUSTAIN DESIGN LIMIT LOADS AFTER FAILURE OF ANY HINGE FITTING OR SUPPORT MEMBER

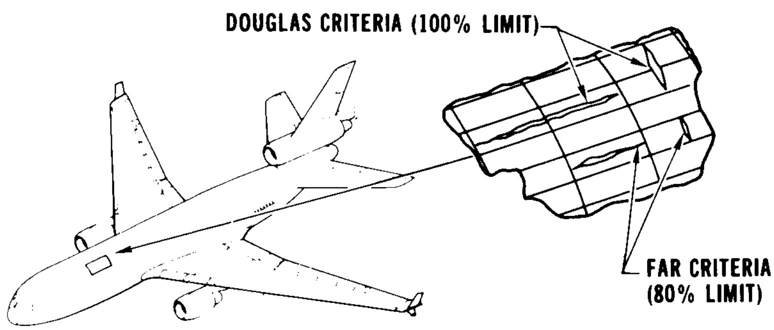

FIGURE 7. DAMAGE TOLERANCE

Figure 8 shows some of the parameter variations that must be studied to certify that a commercial airliner will meet FAA requirements. The basic flutter design requirements permit no flutter, buzz, or divergence below 1.2 V_D and no flutter below V_D after any single mechanical failure or any combination of extremely improbable failures, including dual hydraulic system failures. Most of these events can be certified by adequate analysis, but some must be substantiated by testing. Flutter speeds are highly dependent on aircraft geometry as well as the distribution of weight and stiffness. If the flutter margin is negative for any fuel weight, payload configuration, or other parameter variation, a structural redesign is required to raise the flutter speed. About 60 percent of the weight of a commercial aircraft is due to nonstructural components, and not all of the remaining 40 percent is represented in any finite-element model of the aircraft. To account for the difference, the total weight must be estimated from semiempirical data. The weight of material in the finite-element model may be subtracted from the total weight, and the remainder may be distributed to the nodes and elements in the finite-element model.

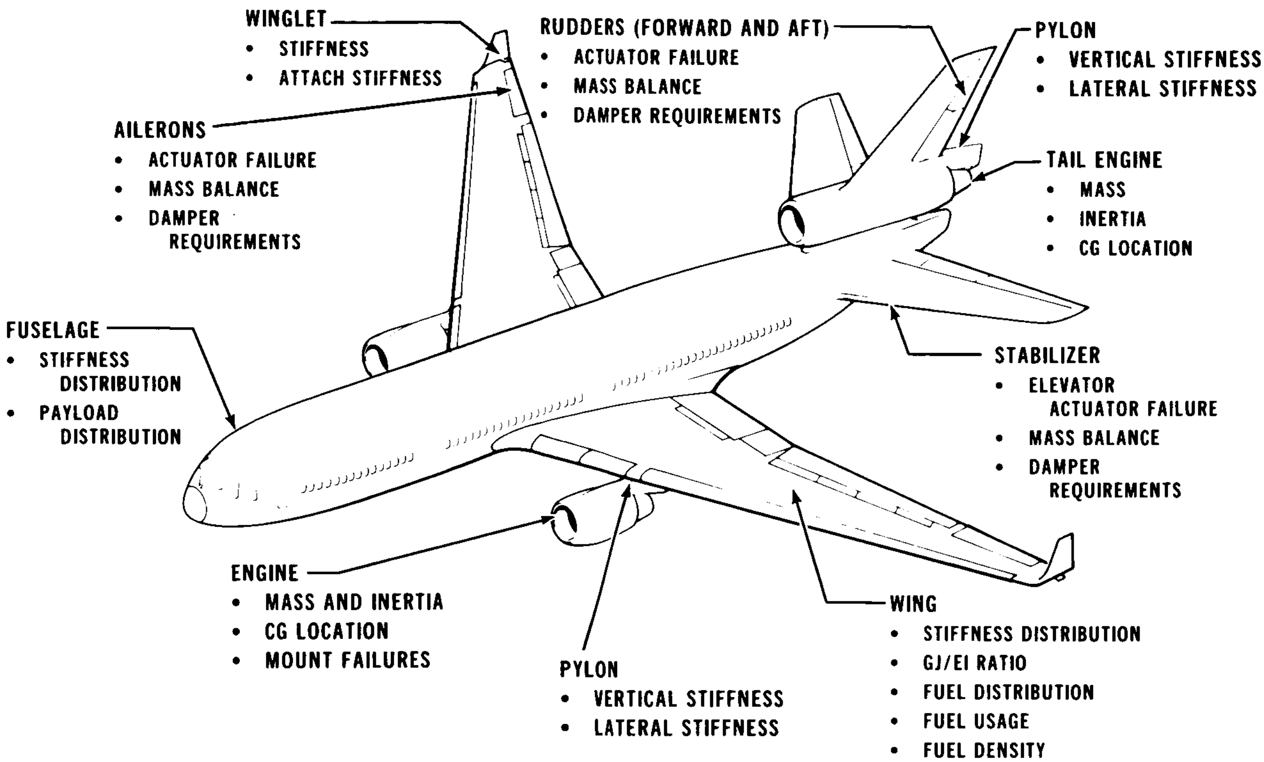

FIGURE 8. PARAMETERS INVESTIGATED FOR FLUTTER

As shown in Figure 9, aeroelastic structural design is constrained by the basic "abilities" – producibility, reliability (fail-safe and safe-life), maintainability, durability and damage tolerance, and inspectability. It may be argued that since the design is not optimum anyway, there is no need to optimize the aircraft structure. The answer is that while the "abilities" constrain the design, satisfying these constraints alone does not ensure that an optimum design has been found. The "abilities" are an important consideration in the design process, but are not the only binding constraints. These constraints may be considered as a set of side constraints that determine upper and lower bounds on the geometric and behavior variables.

As has been shown, the aeroelastic design process is necessarily an iterative process. For example, if analysis shows any part of the structure to be under-strength or vastly over-strength, then design changes are required. Following the design change, new loads are required based on the revised flexibility of the structure. Perhaps a new structural model will be created at this time. In a large aerospace organization, these changes often involve many groups of specialists, each of which has a detailed knowledge of a specific task but little or no knowledge of related tasks. This traditional organization of the design process is slow and unresponsive to the rapid design changes required in preliminary and advanced aircraft design. Furthermore, different structural models are used by different groups for the special needs of each group.

PRODUCIBILITY

RELIABILITY (FAIL-SAFE AND SAFE-LIFE)

MAINTAINABILITY

DURABILITY (AND DAMAGE TOLERANCE)

INSPECTABILITY

FIGURE 9. AEROELASTIC STRUCTURAL DESIGN IS CONSTRAINED BY THE BASIC "ABILITIES"

Figure 10 shows some of the organizational constraints imposed on the aeroelastic design process by the traditional approach. These constraints include (1) the multiplicity of structural models, (2) inconsistency in data requirements, (3) lack of interdisciplinary awareness, (4) vesting of traditional values, and (5) loss of communication in the data flow. The use of different structural models by different groups leads to a basic difficulty that must be dealt with in the design optimization process. The problem is in relating the results from one structural representation to the results from another structural representation. For example, the Loads group wants a beam model so that it can find the worst load cases in a set of 4,800 load conditions. Using the beam model, the stress resultants of shear, moment, and torque provide a quick and easy discriminant. On the other hand, the Stress or Strength group needs a finite-element model to perform an adequate stress analysis. The Stress group needs the loads, but frequently it will get the shear, moments, and torques instead. Worse yet, these stress resultants may not be self-consistent, since they may only represent an envelope of the flight load conditions. Adding to the difficulty is the vesting of traditional values by each group and the loss of communication in the data flow. Frequently, data requirements are passed between groups by a trail of interoffice memos rather than the orderly flow of structured data files.

MULTIPLICITY OF STRUCTURAL MODELS

INCONSISTENCY IN DATA REQUIREMENTS

LACK OF INTERDISCIPLINARY AWARENESS

VESTING OF TRADITIONAL VALUES

LOSS OF COMMUNICATION IN THE DATA FLOW

FIGURE 10. ORGANIZATIONAL CONSTRAINTS ON AEROELASTIC DESIGN

As shown in Figure 11, the aircraft design development process may proceed in several phases. The first is the initial design phase, in which the aircraft configuration is selected. The second phase is advanced design, where trade studies are performed on a few candidate configurations, and the primary structure is designed and analyzed. Proposal activities are supported by trade studies in the advanced design phase. Source selection and procurement of long-lead-time items may have to be based solely on the results from the advanced design studies. In the third phase, we have the detail design activity. In this stage, a single aircraft configuration has been selected, and detailed design and analysis leading to drawing release and tooling for manufacture are completed. In the fourth phase, we have the growth design stage of the aircraft design cycle. In this last phase, modifications to an existing design (fuselage stretch, re-engine, wing extensions, etc.) lead back to Phase III activities.

PHASE I	CONFIGURATION DESIGN INITIAL PRELIMINARY DESIGN EFFORT. CONFIGURATION ANALYSES. BASIC WEIGHTS BREAKDOWN. THREE-VIEW DRAWING.
PHASE II	ADVANCED DESIGN ADDITIONAL POINT DESIGNS. TRADEOFF STUDIES. PRIMARY STRUCTURE LAYOUT AND ANALYSIS. PROPOSAL EFFORTS.
PHASE III	DETAIL DESIGN DETAILED DESIGN AND ANALYSIS LEADING TO DRAWING RELEASE.
PHASE IV	GROWTH DESIGN MODIFICATIONS OF EXISTING DESIGNS (FUSELAGE STRETCH, RE-ENGINE, WING EXTENSION, ETC). PROPOSALS. TRADEOFFS. FOLLOWED BY PHASE III ACTIVITY.

FIGURE 11. BASIC AREAS OF DESIGN ACTIVITY

In the initial or configuration design stage of the aircraft design process, weights are determined by semi-empirical data, and the preliminary aerodynamic design is optimized. A preliminary structural model like the box beam model of Figure 12 may be constructed for aeroelastic loads and flutter analysis. These models usually will involve no more than 300 to 500 degrees of freedom (DOF). Flexibility effects that result from changes in direction in the elastic axis and wing-fuselage or tail-fuselage intersections may be estimated or ignored. At a later stage in the design process, these "stick" models may be corrected using the results from finite-element models of local portions of the aircraft structure as shown in Figure 13.

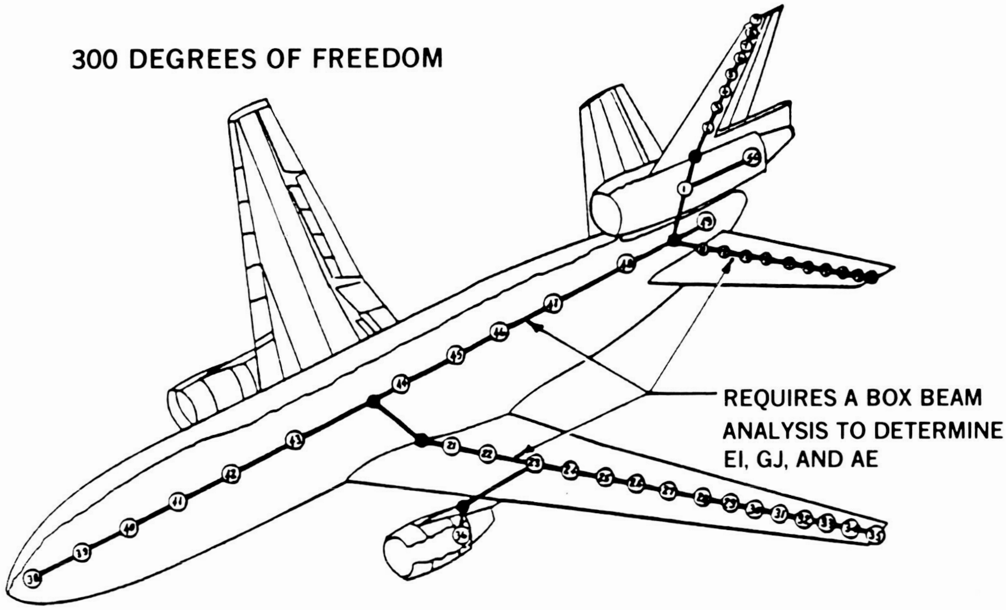

FIGURE 12. BEAM-STICK MODELS MAY BE USED IN PRELIMINARY DESIGN

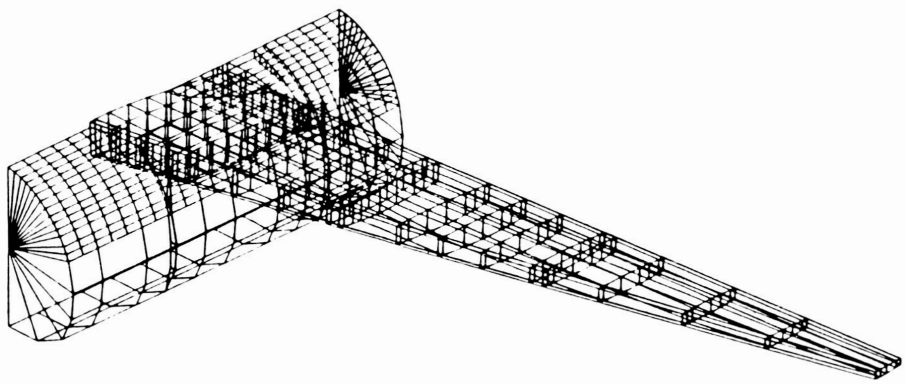

FIGURE 13. WING/FUSELAGE INTERSECTION FINITE-ELEMENT MODEL

In the advanced design phase, these stick models and local structures models may be replaced by coarse-grid finite-element models like that shown in Figure 14. Typically, these coarse-grid models may employ 3,000 to 5,000 DOF. The beam stick models may still be used for loads and dynamic modal analysis of high-aspect-ratio-wing aircraft. For these configurations, beam models are adequate, providing allowances are made for flexibility effects that result from stress redistributions. These stress redistributions, which are a secondary effect in the loads and modal analyses, are of primary importance to the static strength analyses. For this reason, the structural model for static strength analyses includes structural details often omitted or only grossly represented in the dynamics and loads model.

To automate the design process, one must use common structural models at each stage of the design process and provide a uniform if not consistent means of relating the results from one structural model to those of another. This is true for both the sequential design and the simultaneous design process.

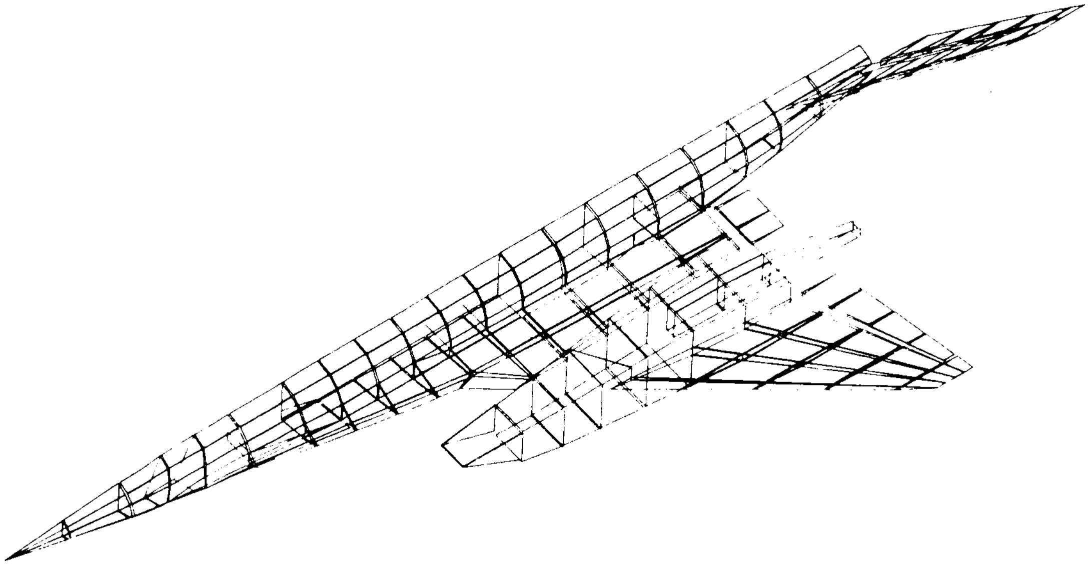

FIGURE 14. FINITE-ELEMENT AIRCRAFT MODEL USED IN ADVANCED DESIGN

In the sequential design process, a suboptimization is performed to satisfy a subset of the constraints. For example, one may perform a static strength optimization to resize the structure for a number of the most critical load conditions. This process may be followed by a flutter optimization to increase the flutter speed for a number of different payloads and fuel weight conditions. To avoid violating the static strength constraints during the flutter resizing, one may use the structural sizes found by the static strength optimization as minimum gauge constraints in the flutter optimization. However, if one is using a detailed finite-element model for static strength optimization and a beam stick model for flutter optimization, then one is faced with the very difficult task of converting the finite-element model into an equivalent beam representation and defining the minimum gauge constraints. Also, the joint flexibility that results from stress redistribution at discontinuities in the elastic axis will be altered by the flutter resizing process. These problems can be eliminated if one uses the same structural model for both static strength and flutter optimization.

In the simultaneous design process, both strength and flutter constraints must be satisfied at the same time. It seems apparent that simultaneous design requires common models for both strength and dynamics work. This, too, is not without difficulty.

Figure 15 shows one of the models used in a recent Phase III design study. In the detailed design phase, structural models may use 20,000 to 60,000 DOF, which will pose great challenges for the dynamic and loads analysis. Figure 16 shows some of the approaches to modal analysis of very large models. These approaches include direct methods, such as subspace iteration and the Lanczos algorithm, as well as indirect methods, such as component mode synthesis and successive mesh refinement (modal assembler solver).

Most of these techniques have been used on models as large as that shown in Figure 15. However, the cost of these analyses continues to be a significant factor. Until these techniques are in routine use on super computers or low-cost "super-mini's," there will be strong opposition to using these models in automated aeroelastic design.

Figure 17 summarizes some of the challenges that must be met in developing a practical aeroelastic design optimization system. These challenges are as follows:

Fatigue and Damage Tolerance Design Criteria – To begin with, one must determine fatigue and damage tolerance design criteria for use in the preliminary and advanced design phases of the aircraft design process.

Finite-Element Modeler (FEM) Extensions – FEM programs developed for conventional analysis do not provide details such as design vector definition and design variable linkage data, nor do they provide for broken member element groups.

Damage Tolerance in Design – Special analysis procedures must be developed to handle damage tolerance considerations within the design cycle. In principle, some aspects of damage tolerance analysis can be handled as a sensitivity analysis. This simple strategy is complicated by a large combination of member groups and load sets.

Aeroelastic Tailoring with Composite Materials – The strength and stiffness of composite materials may be tailored to achieve desired aeroelastic characteristics. However, this advantage of composite materials will not be fully realized until experimentally verified failure criteria can be agreed upon.

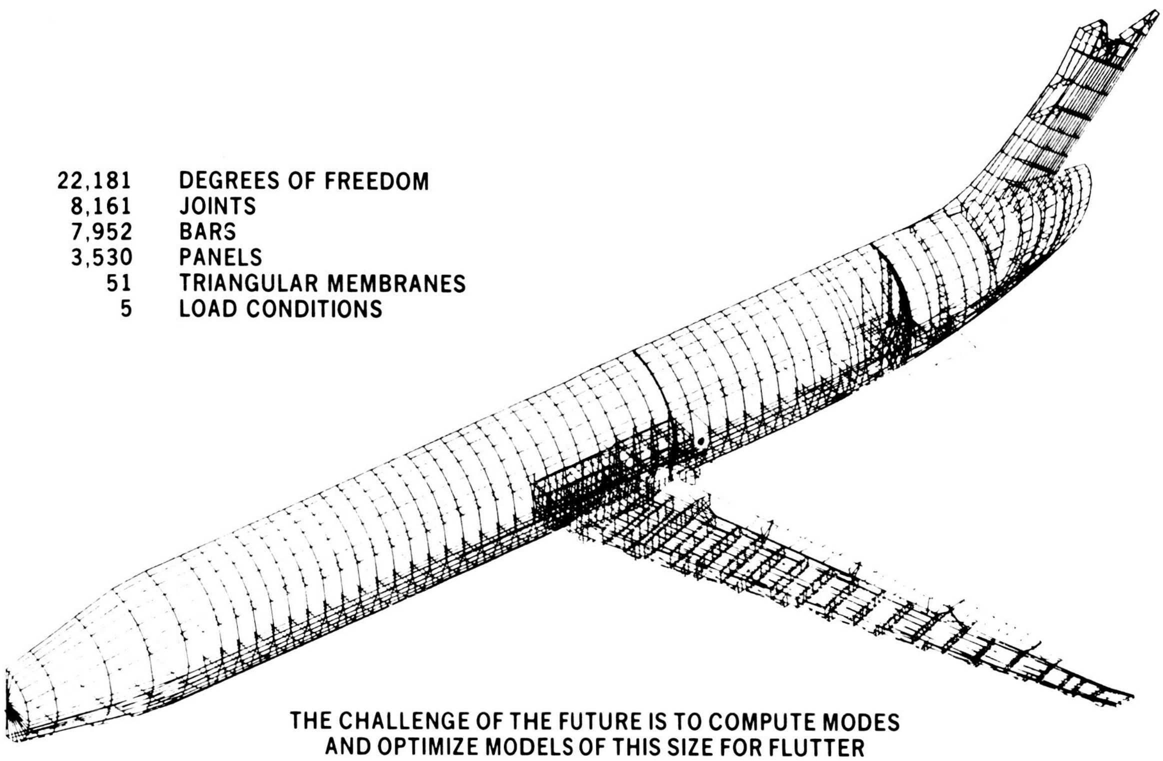

FIGURE 15. FINITE-ELEMENT AIRCRAFT MODEL USED IN DETAILED DESIGN STUDIES

DIRECT METHODS

- SUBSPACE ITERATION
- LANCZOS ALGORITHM

INDIRECT METHODS

- COMPONENT MODE SYNTHESIS
- SUCCESSIVE MESH REFINEMENT (MODAL ASSEMBLER SOLVER)

FIGURE 16. APPROACHES TO MODAL ANALYSIS OF VERY LARGE MODELS

DETERMINATION OF FATIGUE ALLOWABLES AND DAMAGE TOLERANCE CRITERIA FOR PRELIMINARY AND ADVANCED DESIGN STRUCTURAL OPTIMIZATION

FINITE-ELEMENT MODELER EXTENSIONS

DAMAGE TOLERANCE IN DESIGN

AEROELASTIC TAILORING WITH COMPOSITE MATERIALS

DETERMINATION OF BUCKLING AND CRIPPLING ALLOWABLES

MODAL ANALYSIS OF VERY LARGE STRUCTURAL MODELS

SPECIAL FINITE ELEMENTS

DEFINITION OF CRITICAL AEROELASTIC LOAD CASES FOR STATIC STRENGTH

SIMULTANEOUS DESIGN FOR STRENGTH AND FLUTTER

FIGURE 17. AEROELASTIC STRUCTURAL OPTIMIZATION CHALLENGES

Determination of Buckling and Crippling Allowables – Compression allowables may be determined by buckling stress, which is dependent on the design variables. When buckled skin models are used for static strength analysis, a model dependency results that is inappropriate in modal analysis for dynamics and loads work.

Modal Analysis of Very Large Structural Models – If common models are to be used for static strength and dynamics, then highly efficient means of modal analysis of very large structural models will have to be devised.

Special Finite Elements – Special finite elements are required for preliminary and advanced design as well as for structures that use composite materials.

Critical Aeroelastic Load Cases for Static Strength – The determination of critical aeroelastic loads for static strength involves a large number of load conditions and load cycling.

Simultaneous Design for Strength and Flutter – Sequential and simultaneous design both require common structural models or complex means of relating modeling parameters from different models.

Added to the above technical challenges are the organizational constraints discussed earlier and the reluctance to accept change.

The practical stituations described in this paper are changing. Comprehensive computer data bases are being developed to formalize and speed the transfer of data between engineering disciplines. To do this requires a dialogue between disciplines and a definition and awareness of common goals. AFFDL and NASA, among others, are funding development of program systems for automated aeroelastic design. On the horizon loom the super computers, holding out the prospect of eliminating most practical constraints on problem size and computing cost.

The challenge today is not how to solve the engineering problems as much as how to organize the solving of the engineering problems to take full advantage of the tools that are available.