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History of Key Technologies

Evolution of Structures Design Philosophy and Criteria

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I. Introduction

THE challenge in airframe structure design has always been to provide an optimum solution satisfying the competing requirements for safety, performance, and cost. To achieve this goal effectively, the designer today works within a clearly established philosophy and well-defined criteria, which have evolved over more than 50 years, through often painful service experience, emerging technology, and recognition of new evolving critical design parameters.

This paper reviews the critical elements of the current philosophy and discusses the authors' perspective of some of the most significant events since the 1950s that have shaped today's approach to structural design. It concludes with some thoughts on future challenges we must face to enhance safety, utilize technology improvements intelligently, and provide airline operators with the most user-friendly airplanes possible, while at the same time learning to use our design resources more efficiently.

Future programs will see increased emphasis on design/build global partnerships to draw upon the best available engineering and manufacturing talents worldwide. The potential benefits to cost, quality, and cycle time are considerable. Realization will depend on unprecedented levels of seamless cooperation. As we meet these challenges successfully, we can expect the next generations of commercial airplanes to offer the airline passenger even safer and more comfortable travel at lower cost while having minimum impact on the environment.

II. Structural Design Challenge

The perennial and ongoing challenge in airframe structural design is to simultaneously satisfy three major competing and disparate requirements in one optimum solution. They are 1) to provide maximum inherent safety, 2) to achieve superior structural performance in terms of weight and durability, and 3) deliver an airframe with minimum costs of production and long-term ownership by the operator. These requirements must always be mutually and efficiently satisfied to bring real value to the flying public, which is ultimately an airplane manufacturer's only reason for existence.

The essential requirement for structural performance (weight control) has challenged design safety factors more than in any other branch of engineering. In turn, this demands the use of high strength materials and relatively high design and operating stresses. Also, as commercial airplane usage and life spans have increased so has the need for more robust, durable, damage tolerant, and corrosion resistant structures. Consequently, airframe designers are always operating within exacting constraints, which leave essentially no margin for error. Success requires an intimate knowledge and understanding of the operating environment, the structural and material behavior, and the proper tools for accurate prediction. A clearly established philosophy and well-defined criteria are essential to this success.

Today this philosophy and associated criteria exist and are essentially universally accepted to govern current design practices. This framework has enabled designers to develop near-optimum solutions for safety, weight efficiency, reliability, and a reasonable cost of ownership throughout service lives of 20, 30, or more years. The frame work has slowly evolved over more than 50 years, shaped by often painful experience, emerging technology, and the recognition of new critical design parameters as airplanes have flown faster, farther, higher, and in ever greater numbers. Figure 1 shows the continuous feedback process that is used to update the regulatory and The Boeing Company design requirements. This process has been enhanced by increasing cooperation between manufacturers, regulators, and operators worldwide as shown in Fig. 2.

The principal structural design requirements consist of 10 core elements shown in Fig. 3. Figure 3 also acts as a roadmap to the next level of detail in the structures design requirements and criteria. It can be used as a check list by the designer to make sure that all requirements for a given design have been met.

This paper reviews the present philosophy governing design for safety, performance, and cost, their interrelationships, and some of

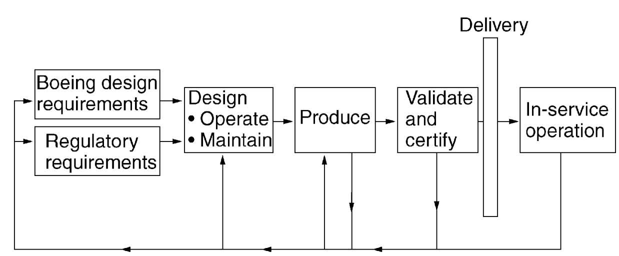

Fig. 1 Continuous feedback process.

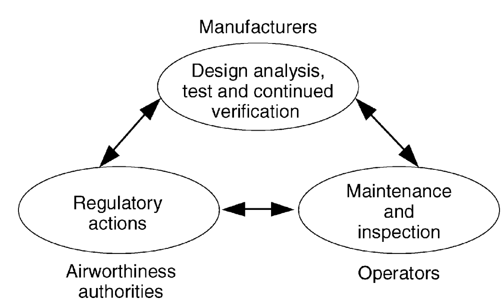

Fig. 2 Cooperation between manufacturers, regulators, and operators.

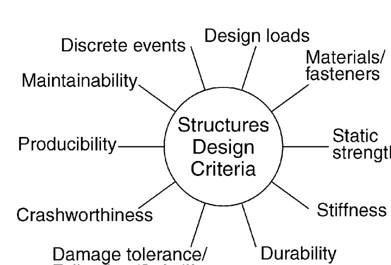

Fig. 3 Structures design criteria.

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the significant events over the past 50 years that have shaped today's approach to structural design. It concludes with a discussion of some of the new challenges we can expect and must embrace in the future. These include the impact of new technology advances, increased maintenance efficiency for the operator, better management of our design and manufacturing resources, and a growing use of global design/build partnerships.

Although this paper focuses mainly on Boeing commercial experience, it is thankfully acknowledged that the industry in general, both commercial and military, has contributed vastly to today's understanding and practices of structural design.

III. Safety

Commercial airplane design philosophy has always been to deliver a safe airframe based on state-of-the-art understanding of the operating environment and structural behavior. Initially this was achieved primarily by designing for strength and stiffness.

A. Flutter

The airplane must be free from flutter, divergence, control reversal, and any undue loss of stability and control as a result of structural deformation because of inadequate stiffness. Flutter is a self-excited, often destructive, in-flight structural oscillation of the airplane that derives its energy from the airstream. The structural modes of vibration of the airplane, combined with the aerodynamic forces and the flight control system control laws, are the important parameters involved in the prediction of flutter (aeroservoelastic) characteristics. Structural, aerodynamic, and system analytical models are developed for the dynamic aeroelastic stability solution. Figure 4 shows an example of flutter failure that did not result in the catastrophic failure of the airplane.

B. Static Strength

Static strength of structure is predicted by analysis methods validated by cumulative and collective experience. Validation testing is conducted where sufficient confidence does not exist for the analysis or if specific validation testing is required for certification [Federal Aviation Regulation (FAR) 25.307]. Figure 5 shows the deflected shape of the 777 airplane wing just before static ultimate failure. Static failure of metallic airplane structures has been predicted with an increasing high level of accuracy.

However, with increased service experience and more sophisticated performance demands, many other influencing factors have become increasingly important to a successful design. These factors have been steadily incorporated into industry and regulatory requirements to arrive at today's philosophy and practices. Some of the key events and milestones are discussed here.

C. Evolution of Design Requirements

Since 1927, in the U.S. federal government has taken the responsibility for establishing structural design criteria, among many other standards. The original Bureau of Air Commerce became the Civil Aeronautics Administration in 1938, and later became today's Federal Aviation Authority (FAA). Similar organizations in Europe and other countries perform the same safety related functions as the FAA, with a high degree of mutual cooperation.

The early requirements focused on flight and ground load conditions to be considered and the requirement to demonstrate adequate limit and ultimate strength and sufficient stiffness to prevent flutter and divergence. However, some dramatic events in service led to additional and more sophisticated requirements. These events include the Comet accidents in the 1950s, which led to the universal recognition of the need to design for fatigue performance and fail safety (Fig. 6). Later, the failure of a Boeing 707 stabilizer showed that fail-safe design, although necessary, may not always be sufficient (Fig. 7). In turn, this led to the damage tolerance requirements incorporated in 1978.

Fig. 4 Example of structural failure caused by flutter.

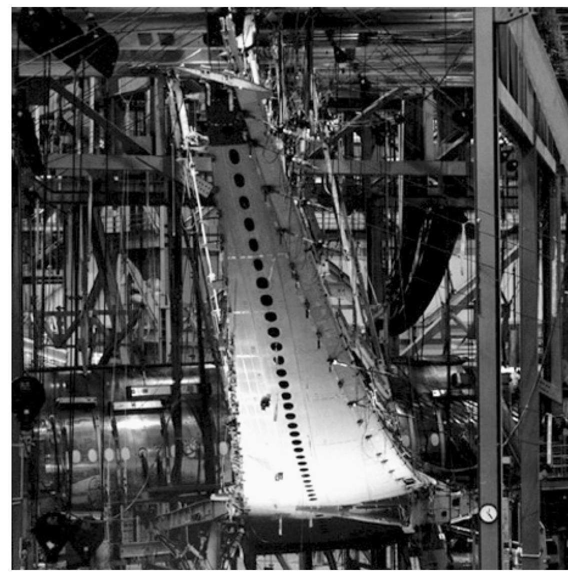


Fig. 5 Wing static strength test.

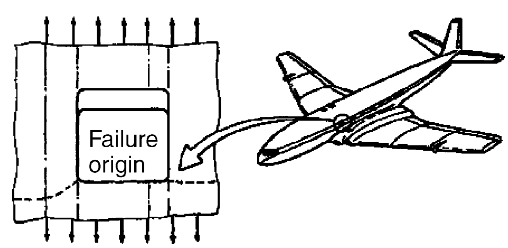


Fig. 6 Comet accident.

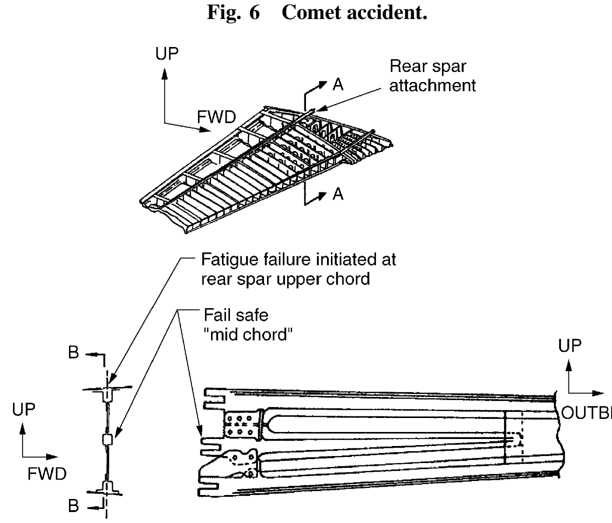


Fig. 7 Rear spar failure of Boeing 707 horizontal stabilizer.

At about the same time, as large fleets of commercial airplanes were approaching and exceeding 20 years of service use, the concern for an understanding of potential undetected widespread fatigue damage (WFD) was emerging. The Aloha 737 fuselage incident (see Fig. 8) concentrated this concern worldwide, with the result that regulatory actions were established to mandate adequate full-scale fatigue testing of new airframe designs to preclude widespread fatigue damage (WFD) in service. At the same time, more emphasis was placed on maintenance and inspection actions to enhance operational safety. Whereas these requirements have been promulgated by the regulatory agencies, they have generally been crafted by cooperative action with industry.

The evolution of FAR 25.571 shown in Table 1 shows how design requirements for fail/safety and damage tolerance emerged as a result of the service experience described above. These additional requirements profoundly influence airframe design today, and each warrants a brief review here to understand its particular influence.

D. Fail Safety

Fail safety is the ability to fly and land safely with significant structural damage. Fail-safe designs provide inherent robustness in the event of damage from many possible sources including fatigue cracking, corrosion, accidental damage, maintenance errors, and discrete events such as engine bursts.

Fail safety has been a fundamental design requirement since the Boeing 707. All primary flight-loaded structures must be designed to be fail safe. The general requirement is to be able to sustain limit load with any major element failed or an obvious partial failure of a multi-element panel. This has led to the familiar discretely stiffened wing and fuselage panel concepts and the multiply redundant two- and three-piece primary bulkheads, major fittings, and cutout reinforcements. Traditionally for panelized construction, Boeing has elected to design for limit load capability with a two-bay crack and a failed central stiffener or frame (Fig. 9). Also the need for damage arrest capability has often influenced material choices.

The main intent is the safe damage arrest and containment for a single high load event when significant damage may exist. The premise is that the damage will be obvious in flight or readily detected by normal visual inspections on the ground following the event. Confidence is obviously enhanced when the potentially critical areas are easily inspectable.

1. *In-service Incidents Involving Structural Failure*

A fail-safe structure has always been a fundamental design feature on Boeing commercial jet transports. This design philosophy has resulted in a robust structure that can withstand a great deal of damage in service and still allow an airplane to land safely. Continued attention to fail-safe structural features is critical to continuously improving the level of safety on Boeing airplanes.

There have been over 40 incidents of failed structure on heritage Boeing and non-Boeing airplanes. They include incidents where fail-safe features allowed the airplane to survive with significant damage. Incidents are also included where catastrophic failure occurred in the absence of sufficient fail-safe features.

This compilation is by no means all inclusive, but does provide a broad range of examples. Damage sources include fatigue, corrosion, improper maintenance, manufacturing defects, and discrete events such as engine burst, bombs, bird strike, tire burst, and tail strike. Fail-safe features were summarized into the following categories: alternate/intermediate/adjacent members that pick up load from failed members, for example, typical frames; crack arrest features, for example, tear straps; boundaries of components and subcomponents, for example, major joints; substantial boundary

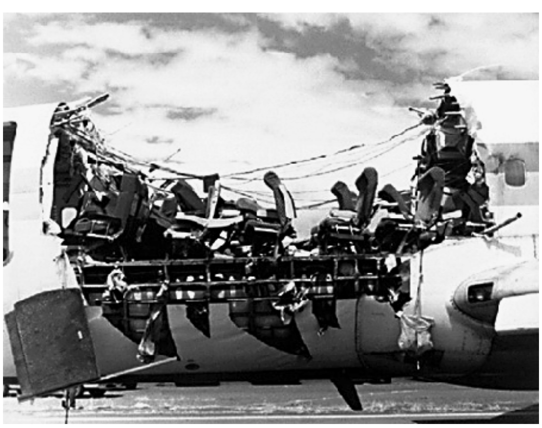


Fig. 8 Aloha incident.

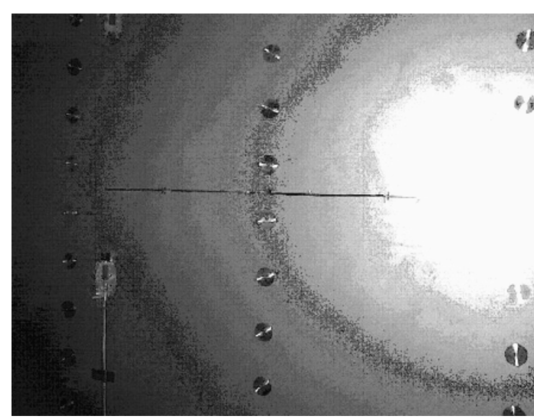


Fig. 9 Two-bay crack in wing lower surface test panel.

Table 1 FAR 25.571 amendments related to fail safety and damage tolerance

Amendment level (date)	Title	Summary of changes to FAR 25.571
25–0 (24 Dec. 1964)	Fatigue evaluation of flight structure.	(c) Fail safe strength. “It must be shown by analysis, tests, or both that catastrophic failure or excessive deformation, that could adversely affect the flight characteristics of the airplane, are not probable after fatigue or obvious partial failure of a single principle structural element (PSE).”
25–45 (1 Dec. 1978)	Damage-tolerance and fatigue evaluation of structure.	(b) Damage-tolerance (fail-safe) evaluation. “The evaluation must include a determination of the probable locations and modes of damage due to fatigue, corrosion, or accidental damage. The residual strength evaluation must show that the remaining structure is able to withstand loads corresponding to. . .”
25–96 (30 April 1998)	Damage-tolerance and fatigue evaluation of structure for WFD.	(b) Damage-tolerance evaluation, for WFD. Initial flaw of maximum probable size from manufacturing defect or service induced damage used to set inspection thresholds; sufficient full-scale fatigue test evidence must demonstrate that WFD will not occur within DSO (no airplane may be operated beyond cycles equal to one-half the cycles on fatigue test article until testing is completed).

members, for example, heavy frames; material toughness and slow crack growth characteristics; and low stress levels.

Service experience around the world has shown that the fail-safe philosophy has made a vital contribution to structural safety. Dozens of incidents have demonstrated safe flight and landing with considerable structural damage. Two examples for fuselage and wing are given in Figs. 10 and 11. However, fail-safe design by itself does not always ensure failures will be obvious and safe for further operation. Damage must be both detectable and detected to ensure continuing safety. This was dramatically illustrated in 1977 with the loss of a 707 near Lusaka, Zambia. This accident resulted from fatigue failure of a horizontal stabilizer rear spar that had a fail-safe "mid chord" as part of the design configuration (Fig. 7). There were many contributing factors to the accident, but lack of a timely inspection that would have detected damage to the upper chord was a prime factor. This was one of the significant events that initiated supplemental structural fatigue inspections to address continuing airworthiness concerns for aging jet transports.

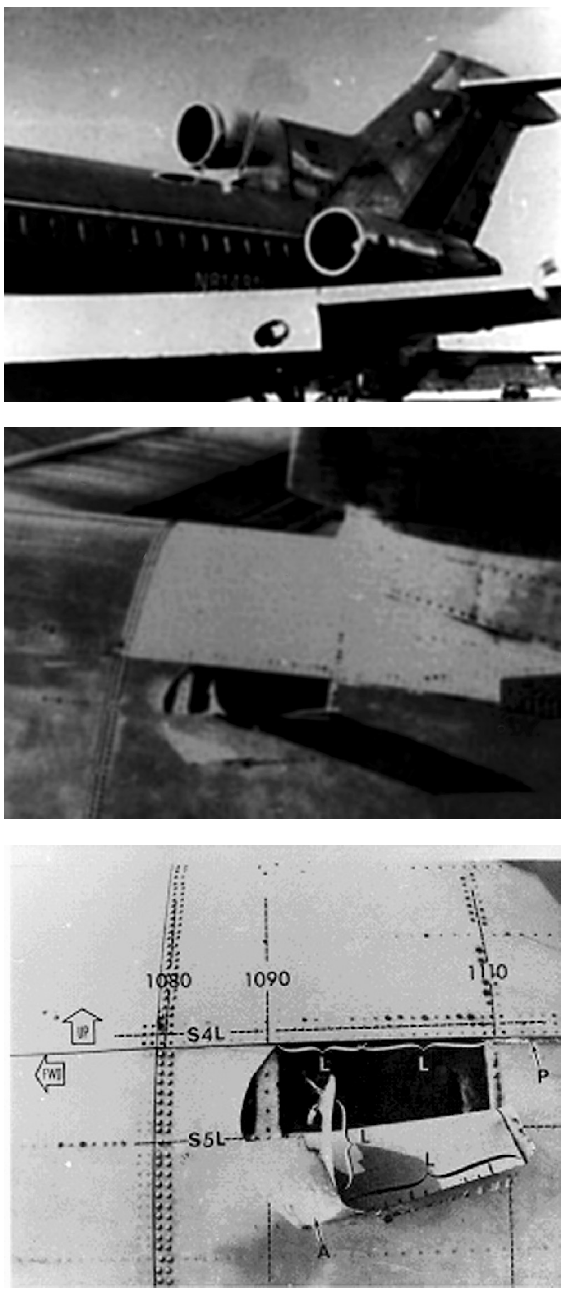


Fig. 10 Safe fuselage decompression examples.

E. Damage Tolerance

Regulatory requirements were revised in 1978 to mandate use of damage tolerance methodologies as part of the Amendment 45 changes to FAR 25.571 (Table 2).

Damage tolerance is the ability to sustain operating loads (up to limit load) in the presence of unknown fatigue, corrosion, or accidental damage until such damage is detected through inspections, including nondestructive inspection (NDI), or safe malfunction, and then it is repaired (Fig. 12). All primary flight-loaded structures must

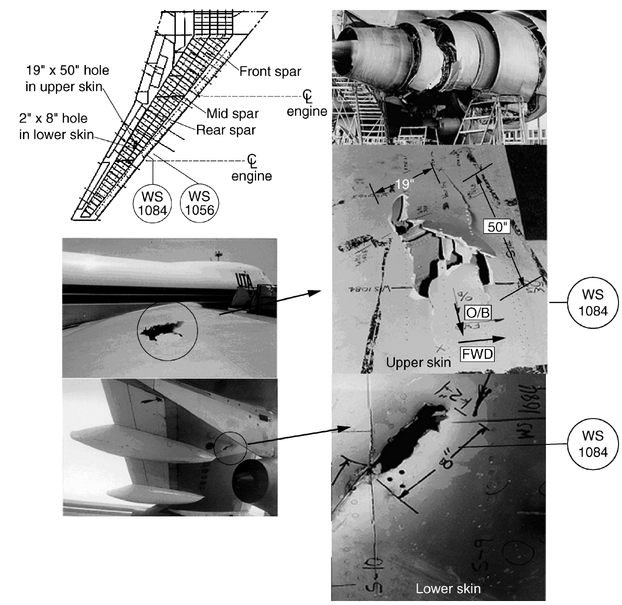


Fig. 11 Example of safe wing penetrations.

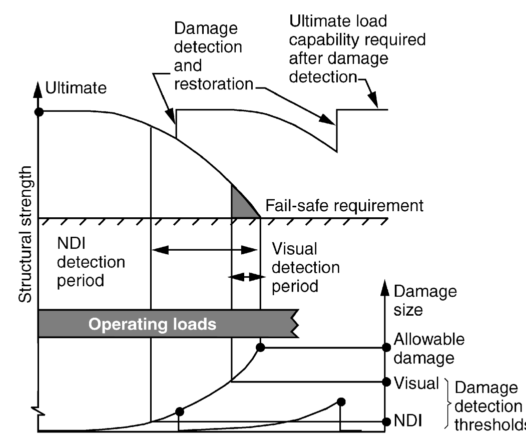
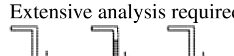


Fig. 12 Strength requirements for damage tolerant structure.

Table 2 Damage tolerance regulation comparison

Analysis	FAR 25.571 (before 1978)	FAR 25.571 (after 1978)
Residual strength	Single element of obvious failure	Multiple active cracks
Crack growth	No analysis required 	Extensive analysis required 
Inspection program	Based on service history FAA air carrier approval	Related to structural damage characteristics and past service history Initial FAA engineering and air carrier approval

be designed to be damage tolerant. This requires that the structure have sufficient damage growth properties and detection characteristics so that if damage were to develop at single or multiple sites, normal specified airline inspections would ensure that the damage is found before it reduces the residual strength capability below the limit load. This requirement, in conjunction with the fail-safe requirement, is essential to provide the most comprehensive assurance of continued safety throughout the service life of an airplane.

With continued safety reliant on inspection, it is essential to know where to look and how large a crack or damage may be missed. To aid in developing reliable inspection programs, tear downs of older airplanes and fatigue test articles and large-scale component tests have been conducted to develop fundamental data to calibrate fracture mechanics techniques. In this way, it has become possible to relate detectable damage, damage growth, and critical damage size to establish the proper inspection methods and frequency required to maintain safe operation up to and beyond the original design service objective. Boeing published damage tolerance standards in 1979 and applied them to the design of the 757, 767, 777 and the next generation 737s. Use of these techniques during design has significantly influenced structural arrangements, materials, working stress levels, accessibility, inspectability, and repairability.

Airplane structures are grouped into various categories, as shown in Table 3. Secondary structures such as fairings are designed for safe separation. Primary structures are designed for damage obvious or malfunction evident to the largest extent possible. The remaining primary structure is designed for damage detection by planned inspection. Primary structures that cannot practically be designed to be damage tolerant are designed to be safe life. Table 3 also shows analysis requirements and structural examples for all categories.

F. Fatigue (Durability)

Durability [the avoidance of fatigue damage (FD)] has long been a prime goal of the designer inasmuch, it is essential to provide the customer with a long-life, trouble-free airplane, with reasonable maintenance costs. Full-scale fatigue tests have been conducted by Boeing on nearly all models since the 1950s as an economic measure, with the intent of discovering any unanticipated fatigue problems caused by design or manufacturing processes, fixing them, and continuing to one or more design service lives to validate the airframe long-term durability. However, with the 757 and 767, Boeing elected to test full-scale airframes to 100,000 flights, or twice the design service objective. This was done in recognition that many airlines would want to operate these aircraft well beyond 50,000 flights or 20 years and that the test data gathered in the second lifetime could be invaluable in building confidence for extended life and also exposing any potential aging problems.

With an increasing awareness of potential WFD as a safety issue, it was decided to expand the 777 fatigue test to three times the design service objective. No occurrence of any WFD occurred in any of the 757, 767, or 777 tests. Tests of all three airplanes incorporated damage tolerance cycling for crack growth and validation of proposed inspection procedures. The recent FAA requirements for fatigue testing of new designs to two lifetimes as an element of safety validation is essentially in line with Boeing practice for the past 20 years and is welcomed.

G. Aging Fleet

In the mid-1980s it became obvious that jet transport owners, seeking economic efficiency balance between use of existing airplanes and their maintenance costs, were in many cases starting to operate aircraft beyond the initial design service objectives. Consequently, Boeing initiated an aging fleet survey program in 1986 to gain a better understanding of continued operation of older airplanes. Surveys were conducted to ascertain the condition of structures and systems and to observe the effectiveness of corrosion-prevention features. Prompted by the explosive decompression of a 737 fuselage over Hawaii in 1988, industry working groups took extensive action to address aging fleet structural airworthiness concerns, including (Fig. 13) 1) mandatory structural modifications to lessen dependence on structural inspections, 2) development of mandatory corrosion prevention and control program, 3) development of structural repair assessment procedures to address hidden cracking concerns, and 4) development of new inspection requirements to address WFD concerns in similarly stressed and configured details. As Fig. 13 indicates, concerns included accidental damage (AD) and environmental damage (ED).

H. WFD

As more and more aircraft approach and exceed their original design service objectives, the threat of WFD becomes more acute. WFD is characterized by multiple cracking in adjacent similarly loaded elements and details to the point that the structure will no longer meet its damage tolerance requirements, that is, maintaining the required residual strength after a partial failure or crack linkup.

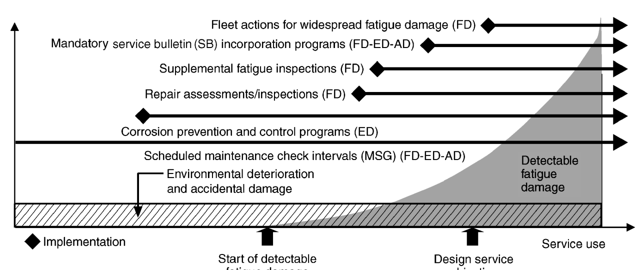


Fig. 13 Aging fleet programs.

Table 3 Structural classifications for damage tolerance

Structural category		Required design attributes	Analysis requirements	Structural examples
Other structure	① Secondary structure	Design for loss of component or safe separation	Continued safe flight	Flap track canoe fairings (safe separation or safe loss or segment)
	② Damage obvious or malfunction evident	Design for failure or partial failure of a principal structural element with continued structural integrity	• Residual strength	Wing fuel leaks
Primary structure (Structurally significant items or principal structural elements)	③ Damage detection by planned inspection	Inspection program matched to structural characteristics	• Residual strength • Crack growth • Inspection program	All primary structure not included in categories ② and ④
	④ Safe life design	Design for conservative fatigue life (damage tolerant design is impractical)	Fatigue analysis verified by test	Landing gear structure

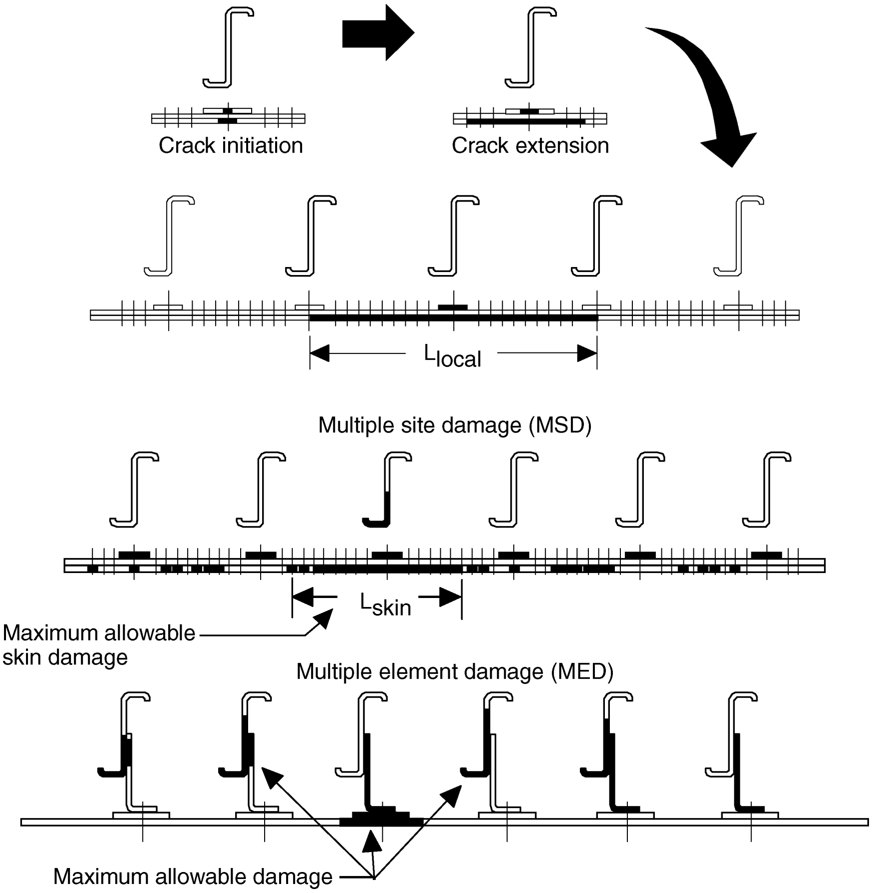


Fig. 14 Local vs widespread MSD vs MED.

Two distinct types of WFD can occur (Fig. 14):

1) Multiple site damage (MSD) is the simultaneous presence of fatigue cracks in the same structural element or panel.

2) Multiple element damage (MED) is the simultaneous presence of fatigue cracks in adjacent independent structural elements.

WFD is most likely in pressure designed fuselage structures with hundreds of adjacent similar details operating at essentially the identical stress each and every flight. Traditional fail-safe structural arrangements cannot fully guarantee safety in the presence of WFD. Therefore, WFD simply cannot be allowed to occur. Regulators and industry are still considering the most reliable actions to preclude its occurrence. As already stated, several options are already in place.

Full-scale fatigue tests to multiple anticipated service lifetimes may either pinpoint the anticipated onset of WFD, or if none occurs on test, a conservative threshold can be reasonably predicted. Likewise, special intense in-service inspections of high-time airplanes can be conducted as well as tear down inspections of high time out-of-service airplanes. Ultimately, however, it may be that safety can only be guaranteed by structural modifications or even retirement from service. One of the new requirements is a concept called limit of validity (LOV). The LOV is a point in the structural life or an airplane where there are significantly increased uncertainties in structural performance and increased probability of development of WFD. Additional fatigue test evidence and validation of the maintenance program for effectiveness against WFD is required to extend an established LOV.

IV. Performance

To be successful in the marketplace, a new airplane must offer superior performance as well as unquestionable safety. The structures contribution to this goal is vital and mandates delivery of the most weight efficient design, coupled with robustness, durability, and ease of maintenance. Once the design service objective (years and flights) is established, the designer must begin the optimization process to achieve the most balanced design that simultaneously satisfies all safety and performance goals, both regulatory and self-imposed. Fortunately, the design task is made more efficient today because of the experience and legacy of the past 50 years, which has brought about a wealth of skills, comprehensive databases, material options, and design analysis tools. These all facilitate accurate and discriminating assessments of competing issues and enable the most informed and optimum balanced solutions. They permit a lean design in which all requirements are met with a minimum weight, complexity, and cost, with no sacrifice in safety or quality.

Principally these assets include 1) a thorough understanding of the operating environment, 2) an accurate external and internal loads prediction capability, 3) the availability of high-performance materials tailored for specific needs, 4) refined techniques for predicting fatigue and fracture behavior, validated by comprehensive test programs, 5) the capability for reliable corrosion prevention and control, and 6) the critical role of maintenance and shared service experience.

Each has contributed greatly to today's essentially seamless design approach for the best possible structural performance. A brief review of some of the key advances is appropriate to appreciate the tremendous progress made in the last half-century.

A. Loads

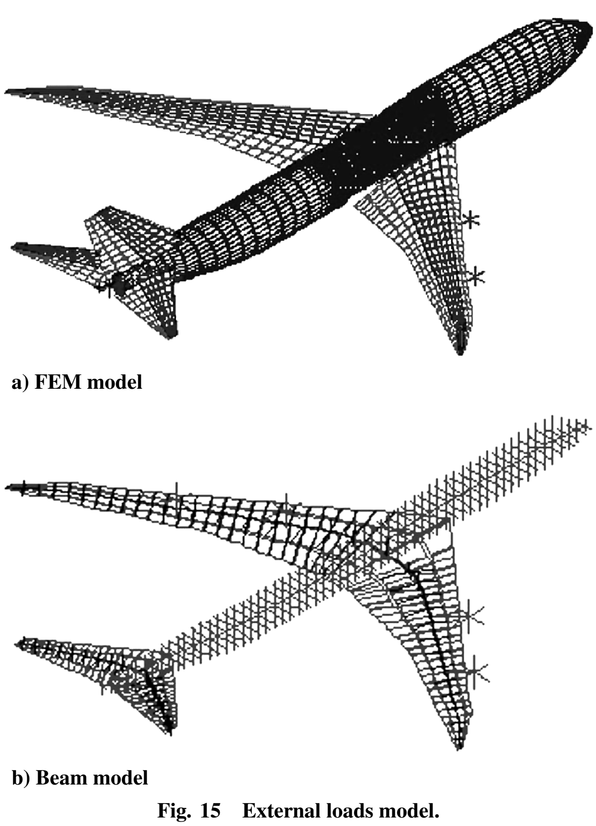
1. External Loads

The ability to predict correctly the airplane loads environment has improved dramatically over the last 50 years. This has led to improvements in safety, while benefiting our customers with enhanced performance and increased levels of passenger comfort. In the early days of jet transport, tools used to predict loads were relatively simple (often based on computational power that was available), and simplified assumptions about the operating environment of the aircraft were used. Conservative assumptions were used to assure safety, resulting in less than optimal airplane performance in the form of increased structural weight. Over the years, as the knowledge, tools, and requirements have matured, the airlines and the flying public have both benefited, not only from the increased levels of safety, but from lighter, more durable airplanes that provide better levels of passenger comfort.

The knowledge base of jet aircraft and their operational environment has evolved over time using a mixture of independent research, government-sponsored projects, industry databases, and Boeing's own internal efforts. Lessons learned from fleet incidents have been gathered and utilized to enhance safety by new criteria and methodologies, as well as new design practices. Collections of in-service fleet data have allowed us to validate or improve our design assumptions. Compilations of fleet utilization statistics and airline reliability and maintainability data have permitted us to improve our durability analysis greatly by focusing on critical flight segments and targeting critical components.

Boeing design loads requirements are derived from both internal criteria and from the regulatory agency standards. Early design requirements were more straightforward than today. They had their roots in a philosophy that mandated criteria that had historically been shown to provide a level of passenger safety. These requirements were continually augmented by additional criteria that were found to be necessary due to accidents, incidents, or new features on the airplanes. Today's trend is toward an increasing reliance on a more probabilistic approach, where fleet statistics are utilized to derive criteria that will produce expected load levels, such as limit load, the maximum load expected in service. An example of this is evident in the recent development of new gust regulations, where new gust intensities have been derived from thousands of hours of in-service airline data.

Improvements in methodologies for loads predictions have evolved simultaneously with the increases in knowledge and computing capabilities. From simple beam models using strip theory for an aeroelastic solution, to highly complex, total airplane finite element models and computational fluid dynamic (CFD) applications, increased computer power has allowed for dramatic advances in how loads are calculated (Fig. 15). The improvements in the accuracy of the tools, the ability to solve more complex problems, and a better understanding of the important parameters have allowed for optimized structural solutions for performance, while maintaining or improving stringent safety levels. Aerodynamics, mass properties, and structural representations have all been improved. Input data such as aerodynamics, which used to be taken strictly from wind-tunnel testing, have been augmented by running CFD, allowing for greater accuracy in the final results. The tools and methods have been validated using data collected during flight testing on the 777 and 737NG programs. These new methods, which allow for better, more accurate loads analysis, are also being used to develop advanced airfoil designs to further benefit aircraft performance. The increase in requirements and the complexity of the analysis has caused a large increase in work required and computing power and has fed downstream customers with increased numbers and variety of load conditions that they have to consider in structural design. The number of design conditions has escalated from less than 100 on early Boeing models to numbers in the thousands on more recent projects.



a) FEM model

b) Beam model

Fig. 15 External loads model.

Boeing continues to lead the aerospace industry in developing advanced computing processes, methods, and tools for the design and response prediction of complex aerospace vehicles subjected to static, dynamic, stochastic, and thermal load environments. The tools, coupled with advanced computing systems, have been used to generate solutions to engineering and scientific problems that were previously not attainable. A wealth of technologies is accommodated in the structural optimization processes that include strength, stability, flutter, aeroelastic static and dynamic loads, acoustic loading, thermal loads, load transfer at joints, and structural manufacturing constraints for advanced composite and metallic structural concepts. This optimization holds the promise of even greater gains in airplane performance as we move into the future.

The same high-speed computational capabilities that have permitted improvements in loads predictions and structural optimization have also been utilized on the airplane itself to improve airplane performance through flight control technology. Modern fly by wire systems weigh less and are easier to maintain than their predecessors. These devices have allowed for reduced pilot workload, have been used as load reduction devices to decrease airplane weight, and have been used to improve ride quality. Today's flight controls offer airlines important enhancements from passenger comfort to reduced cost and weight, but must be reviewed extensively by the loads analysts to assure safety requirements are met, both in normal operation and in degraded conditions.

Advancements in technology, new methodologies, and an increase in knowledge of today's operational environment have all provided for an improved levels of safety in modern jet aircraft, while allowing for better performance and higher levels of passenger comfort. The next generation of airplanes will continue to benefit from new materials and technologies, better airfoils, and increased application of flight controls, all of which require diligence on the part of the loads engineer to also assure passenger safety levels continue to improve.

2. Internal Loads

The objective of performing internal loads analysis is to predict the load levels internal to structural components of an aircraft, due to a set of critical flight, ultimate, fatigue, fail-safe, landing, ground-handling, and selected payload-arrangements loads. The internal loads are then used to predict operating stress/strain levels in the detailed structural components in calculating the respective margins of safety relative to the appropriate design stress/strain allowables.

Aircraft have presented some extremely difficult structural design problems in meeting the relentless objective of minimum weight structure coupled with maximum safety. To this end, aircraft structural engineers have pioneered the development of high-strength, lightweight alloys and have led the research that resulted in refined methods of structural analysis. By the early 1940s, ingenious analytical methods that were based primarily on the truss and frame analysis techniques were available for handling both static and dynamic problems. However, with the advent of jet-powered aircraft with swept wings, the available analysis methods proved to be inadequate.

During the early 1950s, digital computers were being developed, along with advances in matrix algebra representation of the governing equations of equilibrium. During that time, M. J. Turner[1] led a small group at The Boeing Company to address the topic of representing the stiffness of a delta-wing structure in performing structural dynamics calculations. The resulting technical publication in 1956 by M. J. Turner, R. W. Clough, H. C. Martin and L. J. Topp is regarded as a key contribution to the modern day finite element method.

Intense development efforts ensued during the 1960s and 1970s to create special purpose finite element formulations for static and dynamic response, buckling, and material and geometric nonlinearities, which were then incorporated into general purpose computer programs for performing structural analysis. The resulting computational systems have evolved and are now extensively available and used throughout the industry. Application of the finite element method (FEM) during the past 50 years is illustrated in Table 4.

The distribution of external loads through the complex airplane structure is considered internal loads. In the early days of jet transports, simple models of portions of an airplane were used due to solution size constraints. Improvements in computing power and methods have allowed Boeing not only to better optimize structure for improved performance and safety, but also to eliminate expensive testing, from components to full-scale airplanes. Early analysis models were built by hand, had only major load paths, and used overlapping assumptions to assure safety, adding a certain amount of conservatism in the form of additional structural weight. As times have progressed, and computing capacity has increased, finite element modeling has become more complex and the accuracy has increased significantly. Today, total airplanes can be modeled and solved with significant levels of detail. This has given the engineer tools to size structure accurately without having to add unnecessary conservatism, ensuring both safety and airplane performance. Also, major highly complex components can be more accurately modeled to determine detail stresses for ultimate, fatigue, or damage tolerance problems, often eliminating expensive structural tests. Modeling has become increasingly automated and in the future will be tied even more closely to the design tools than today. Other increased capabilities in present day finite element tools such as nonlinear analysis have allowed solutions of extremely difficult structural problems that may have previously only been resolved by some form of test.

Table 4 Application of FEM on Boeing commercial airplanes

Time frame	Airplane	Extent of application
1950s	707	None
1960s	727, 737, 747	Verification only (after drawing release)
Early 1970s	747SP	Drawing release of selected components
Late 1970s	757, 767	Configuration development thru airplane certification of most primary structure
1990s	777, 737X	Configuration development thru certification for all primary structure

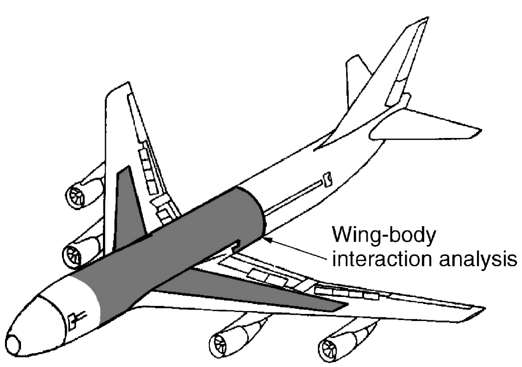


Fig. 16 Interaction model of 747 Wing–body.

The need to predict detailed stresses in regions of major cutouts such as access and cargo doors, and in areas of structural discontinuity in the vicinity of the 747 wing–body juncture necessitated the use of complex, redundant methods of stress analysis. This analysis required a representation of the wing root structure and the adjacent body structure as shown in Fig. 16.

Further analysis of this structural region resulted in the early development of substructered analysis techniques, where a substructure was limited to a maximum of approximately 6000 degrees of freedom (equations) that could be accommodated on the Control Data Corporation (CDC) 6600 mainframe computer at that time. This problem is shown in Fig. 17. Credibility in using the FEM for major structural analysis was developed by validating analysis results with test data such as shown in Fig. 18.

Over time, computing capacity has increased, finite element tools have been enhanced, structural idealizations have improved, and increasing areas of the airplane structure have been covered. These trends have allowed Boeing not only to optimize structure for improved performance and safety, but also to eliminate some expensive testing.

More recently, the FEM models have been used to perform aeroelastic analysis and to predict internal loads within major components of an airplane as are exemplified by the 777 model shown in Fig. 19.

In today's structural design environment, major, highly complex components and mechanisms can be more accurately modeled to determine detailed stresses for ultimate, fatigue or damage tolerance requirements, often eliminating what previously had to be done by expensive structural tests. Furthermore, much of the pre- and postprocessing of the analytical models has become increasingly automated and in the future will also be tied more closely to the design tools than today.

B. Materials

The need for lighter structure has driven the development of higher strength alloys.

1. Aluminum Development

Since the 1940s, many aluminum alloys, some successful, some less so, have been applied to airplane structure. Figure 20 shows

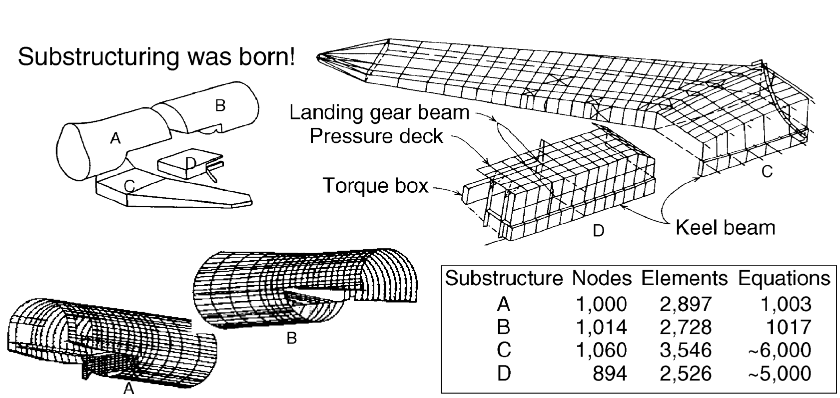


Fig. 17 Large computing problem presented by 747 wing–body interaction analysis.

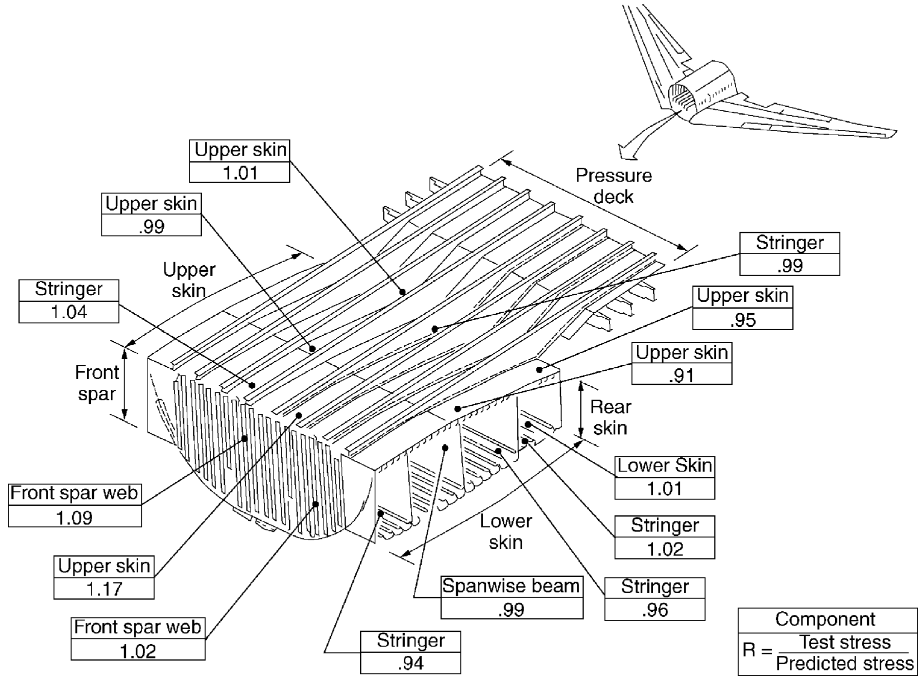


Fig. 18 Validation of wing center section stresses.

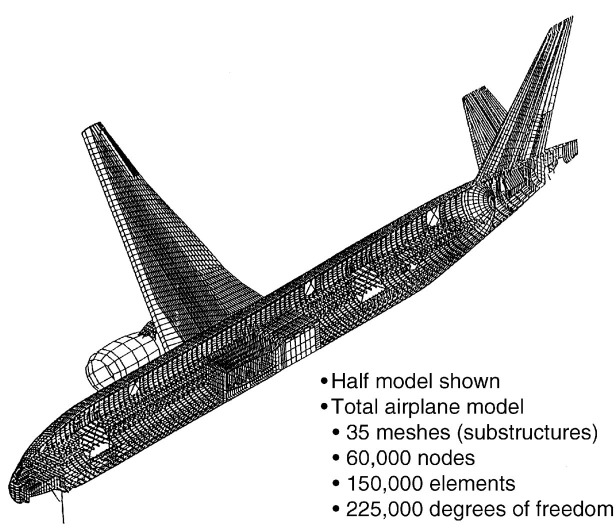


Fig. 19 Internal loads model depicts realism of 777.

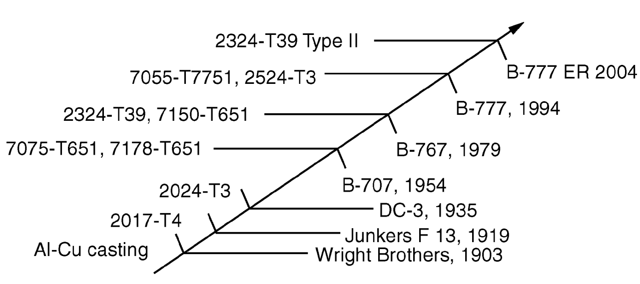


Fig. 20 Introduction of new aluminum alloys.

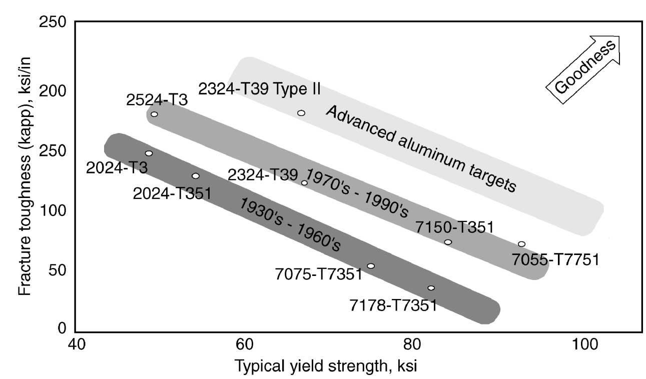


Fig. 21 Aluminum alloy evolution.

the common aircraft alloys along with the year of first flight for the commercial airplane on which they were introduced.

Since 1965, several advancements in aluminum technology have taken place, some of which have been implemented and some of which are still to be brought to market. Figure 21 shows the aluminum technology advancement over time.

Boeing, in conjunction with the major aluminum companies in the United States, developed alloys 2224, 2324, and 7150 in the late 1970s. The application of these alloys led to a 6% more efficient wing structure on the 757 and the 767/747-400 airplanes when compared to previous Boeing model airplanes.

Another major step in the evolution of aluminum was the introduction of the T77 temper, which is a three-step aging treatment that produces very good corrosion properties without the strength drop normally associated with T7-type tempers. The application of the T77 temper to alloy 7150 also made possible the use of this high-strength alloy in the fuselage structure as body stringer material on the 777 airplane. The fuselage skin on the 777 is made from another clean version of 2024, designated 2524. The 2524 alloy has the same strength as 2024, but the high-damage tolerance of 2524 saves structural weight by making possible the elimination of tear straps.

Improved knowledge about the Al–Zn–Mg system, combined with the T77 temper development was taken advantage of for the 777 wing upper surface. The Alcoa-developed alloy, 7055-T77, is a high zinc alloy, 8% stronger than 7150 and more corrosion resistant than 7150-T651.

2. *Steel Development*

There are two other alloy systems used extensively on commercial airplane titanium alloys and steels; some Ni-based alloys are also used, but these are used for specialized applications in the nacelle area and for high-strength fasteners. The steel alloys used today are much the same as those used on the first Boeing commercial transport, the 707. They include the 300 series stainless steels (SS), the precipitation hardened (PH) SS (15-5PH, 17-7PH, 17-4PH and PH13-8Mo) and the high-strength low alloy (HSLA) steels (4330, 4330M and 4340M), which range in strength from 75 to 280 ksi minimum ultimate tensile strengths. The highest usage by weight would be 15-5PH and 4340M with 15-5PH use increasing significantly in the 1980s starting with the 757. The biggest usage of the high-strength alloys is in the landing gear and flap track areas, but they are used throughout the aircraft (Fig. 22).

There has been a lot of activity in the past few years in the development of higher strength SS. The SS with their high corrosion resistance offer some significant advantages over the HSLA steels. The machining of an alloy such as 4340M is highly controlled due to the potential for the formation of untempered martensite, which significantly reduces the ductility and toughness. Boeing is about to develop an ultra-high-strength SS capable of a minimum tensile of 280 ksi. This would be used in replacement of 4340M and eliminate the corrosion problems inherent with the HSLA steels. It could make a significant contribution in reducing life-cycle costs of these HSLA steels, particularly in structures such as landing gear. It would also be better for the environment with the elimination of Cd plating for corrosion protection. The gains anticipated for these alloys in terms of strength and fracture toughness can be seen in Fig. 23.

Fig. 22 HSLA flap tracks and landing gear of 737.

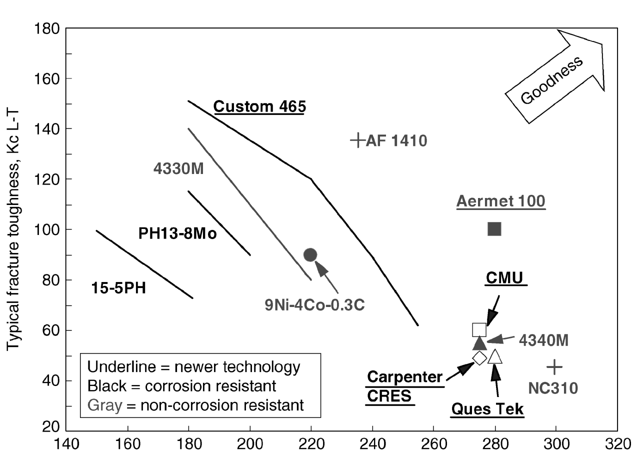


Fig. 23 Strength toughness goals for HSLA steels.

3. Titanium Development

Numerous titanium alloys are also used on commercial aircraft. These are attractive for aerospace applications due to their high-strength, low-density, elevated-temperature capabilities and corrosion resistance, but their use has always been restricted by their high cost relative to the aluminum and steel alloys. They have traditionally been used in corrosion prone areas requiring high strength, such as landing gear support structure, wing actuation devices, and floor support structure in the galley and lavatory areas. Similar to the 2024 and 7075 Al alloys, one of the first alloys developed was annealed Ti–6Al–4V in the 1950s, and it has been the dominant alloy through the years. Figure 24 shows the strength–toughness combinations available with titanium alloys.

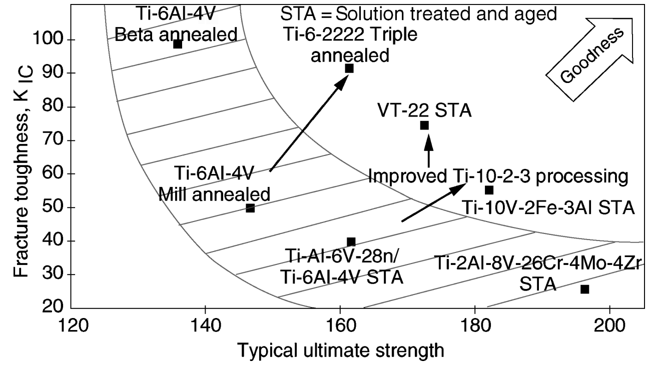


Fig. 24 Evolution of titanium alloys.

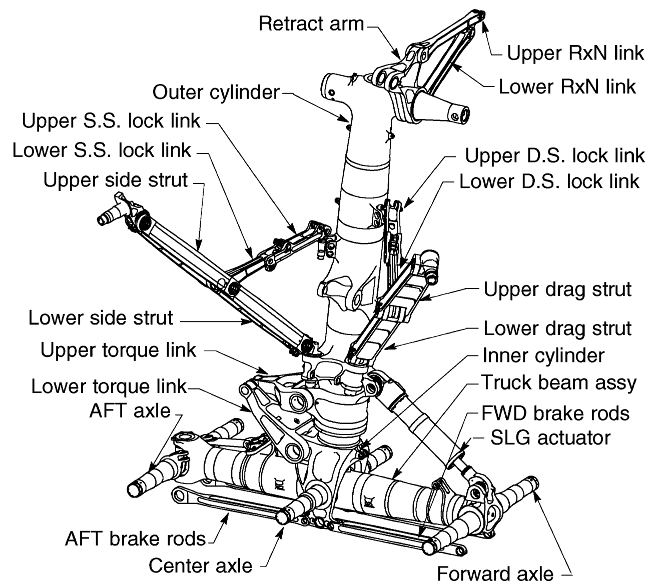


Fig. 25 Titanium forgings for 777 MLG.

If the carbon fibers of graphic composite material were to come into contact with aluminum in an aqueous environment, a galvanic corrosion would be set up that would corrode away the aluminum. There are corrosion-protection schemes to isolate the aluminum from the graphite, but in critical structures that are difficult to inspect and replace, such as the empennage attachment fittings on the 777, beta-annealed titanium is used.

Over the years several near-beta and metastable-beta alloys have been developed because of their higher strength capabilities and, in some cases, processing advantages. Ti–10V–2Fe–3Al is a high-strength-forging alloy that was used extensively on the 777 landing gear, replacing almost all of the 4340M except for the inner and outer cylinders and axles on the main landing gear (Fig. 25).

4. Composite Material Development

All of the early airplanes utilized various forms of composites from spruce spars to doped fabric skins. It took a major catastrophe to eliminate the last vestige of the original structural composites in airplanes. “On March 31, 1931 a TWA wood and fabric Fokker tri-motor went down in Kansas killing all aboard including the legendary Notre Dame football coach Knute Rockne. Up to that time there had been a fierce debate over whether wood or metal was the better material for building airplanes. When wood rot was found in the wing of the Rockne airplane the debate was over and all subsequent airplanes were made of metal.” Figure 26 is a timeline of the composite materials on Boeing commercial airplanes.

The first composites used were wet layup, which impregnated dry fiber with polyester resin, much like boats. Wet layup required considerable skill, and once the resin was mixed, a short-fused process. The 377 Stratocruiser achieved a 20% weight savings for its ducting by using fiberglass composite instead of metal. Supplier preimpregnated fabrics (prepregs), which provide consistent resin content and eliminated the messy process of wet layup, were first utilized in 1961. The 727 utilized a first-generation fiberglass-reinforced 250F cure epoxy composite. This material was used on radomes and fairing panels. The 737 used both a first-generation

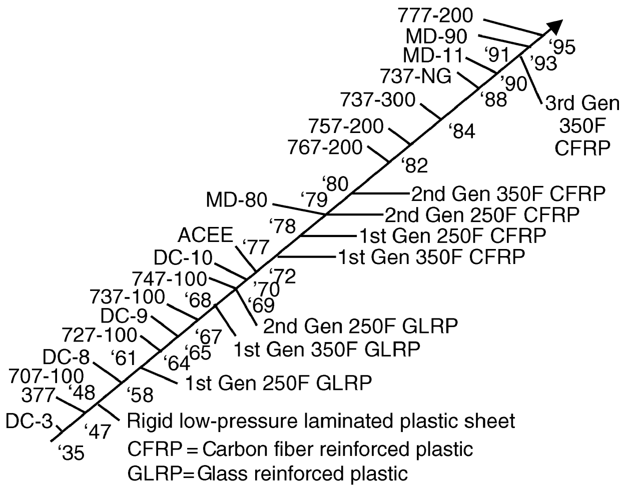


Fig. 26 Introduction of new composite materials.

350F cure fiberglass-reinforced cure epoxy in the hot areas and a second-generation fiberglass-reinforced 250F cure epoxy (rubber toughened/self-adhesive) on radomes, fairings, and control surface cover panels. These materials were mainly used with honeycomb core. The 747 used the same materials in the same locations, only on a much larger scale. The 747 rudder cover panels made with a second-generation fiberglass-reinforced 250F cure epoxy were the biggest composite part Boeing had flown up to that point.

The first Boeing Heritage airplane to use carbon fiber was the 767. The control surfaces (inboard ailerons, elevators, and rudders) used the same form of material and design as the NASA Aircraft Energy Efficiency Program 727 elevator. The spoilers and outboard ailerons used much of the design demonstrated by the NASA ACEE 737 spoilers. The doors and fairings used carbon fiber/aramid fiber reinforcement with a second-generation 250F epoxy. Engine nacelles used a similar carbon/aramid hybrid, except impregnated with a 350F epoxy resin.

The 350F cure resins used in prepregs at that time were designed to make laminates, not thin-skinned, cocured honeycomb structure. The majority of the composite parts on Boeing airplanes at that time were of the latter design. The 757 program, in conjunction with Hexcel, developed a material system specifically for cocuring with honeycomb; the Boeing materials specification BMS8-256 was the outcome. This material has become the de facto standard for secondary structure on nearly all models. Many of the parts originally made with BMS8-212 have been converted over to BMS8-256.

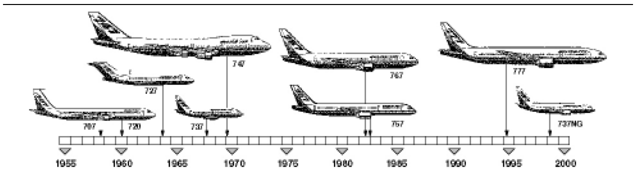
The 777 program, in conjunction with Toray, developed an intermediate modulus (42 msi) carbon fiber prepreg, BMS8-276, for the primary structure. This material was used for the horizontal and vertical stabilizer torque box and the passenger deck floor beams. In addition to the higher modulus, this prepreg had significantly better impact resistance.

Composites have excellent fatigue and corrosion resistance. Development of new materials and processes for fabrication of large structure, as well as improvement to the design and analysis tools, is ongoing. The most significant coupon tests to evaluate critical performance of composite materials consist of hot/wet compression strength and compression strength after impact damage. Figure 27 shows a comparison of these strengths for various generations of composite materials.

C. Fatigue

The minimum design service objective (DSO) for all Boeing structure is 20 years with 95% reliability and 95% confidence. Boeing structures policy for primary structure is to impose a minimum fatigue reliability factor of 1.5 to the 20 year minimum DSO. Hence, all primary airframe structure must be designed with the objective to remain essentially crack free for 20 years of service with greater than 95% reliability. This provides for a DSO of 30 years incurring only minor economic repair, with 95% reliability for typical primary structure. The DSO in flights and cycles corresponding

Table 5 Boeing commercial jet fleet summary[a]



Model	Total airplanes (active)	Minimum SDOs		High-time airplanes	
		Flights	Hours	Flights	Hours
707	734	20,000	60,000	39,800	96,900
720	153	30,000	60,000	45,000	69,300
727	1,823	60,000	50,000	87,700	93,700
737	4,407	75,000	51,000	96,500	97,500
747	1,333	20,000	60,000	39,100	11,650 0
757	1,038	50,000	50,000	34,800	71,700
767	908	50,000	50,000	39,600	78,800
777	459	44,000	60,000	16,300	34,700
737NG	1,311	75,000	51,000	13,800	34,800

[a]As of 30 Nov. 2003.

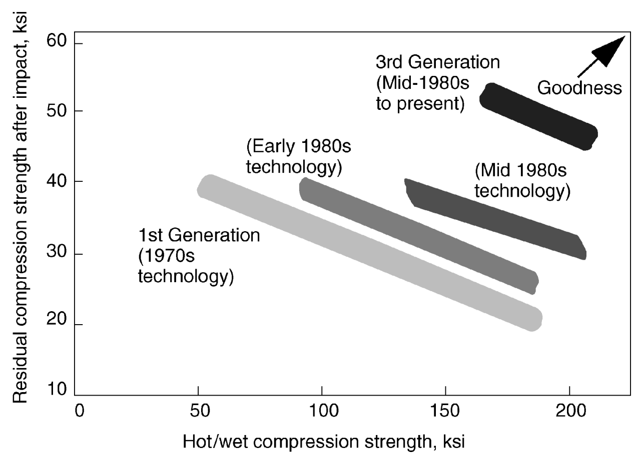


Fig. 27 Composite matrix improvements.

to the 20 year DSO for heritage Boeing Commercial Airplanes are given in Table 5.

Fatigue and consequent cracks have been a challenge for the airplane industry since the time of the Wright brothers. Improvements in static strength design and analysis outpaced understanding of fatigue performance. After World War II, as military planes were converted to airliners, the typical number of flight cycles increased, causing fatigue concerns. Early repeated load testing, such as on the Comet I in 1950, yielded important lessons. For example, fatigue failures in the fleet could occur at less than one-quarter of the test-demonstrated life. These fatigue failures led to gradual changes in design practices.

Methods used for fatigue assessments throughout the 1950s and mid-1960s were a life-oriented analysis procedures, which had limited success. The analysis was complex and generally resulted in postdrawing-release modification. The end results were numerous design improvement changes, service bulletins, and structural repairs.

In 1970, Boeing developed a fatigue design method that could be applied directly to detail design, was generally stress oriented, and was easily understood by every design and stress engineer involved in new airplane design (Fig. 28). The method had to relate to fleet experience and provide the design working tools in a form that was usable in the early layout stages of details.

Background information was obtained from all major fatigue test programs (707, 727, and 747 fatigue tests and component tests of flaps, landing gears, stabilizers, and nacelles). Service experience from all 707, 727, 737, and 747 models was cataloged to provide the historical database. At the time, 30 million commercial flight hours of fatigue design experience had been accumulated, which

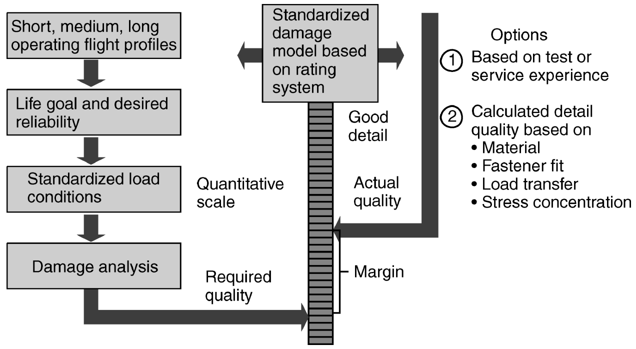


Fig. 28 Durability design evaluation.

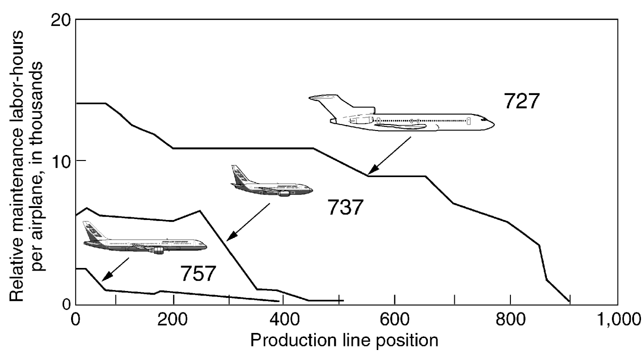


Fig. 29 Comparison of service bulletin labor hours (727, 737, and 757) over 10 years.

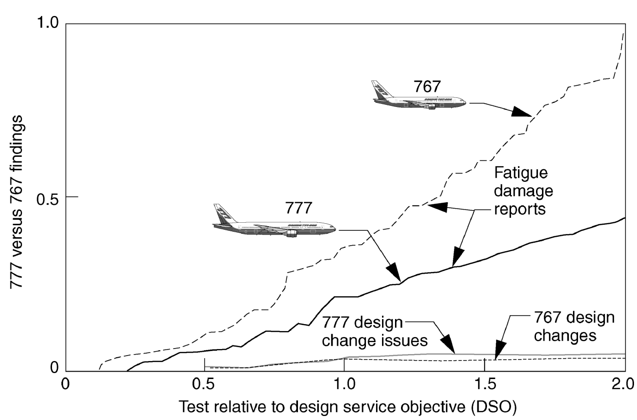


Fig. 30 Comparison of 767 and 777 fatigue test findings.

provided a wealth of experience to be retained and considered for future design activity.

The success of this method became evident during the operation of the 757 and 767 fleets which exhibited significantly less fatigue cracking in service than previous models (Fig. 29). Over a decade later, the 777 full-scale fatigue test showed improvements compared to the 767 fatigue test (Fig. 30).

Today, the durability system serves as a corporate memory of past design. The method has been cross checked and continually updated by fatigue tests and service experience. Fleet surveys continuously provide information that is summarized in terms of service demonstrated fatigue lives of various components. Early experiences showed that incompatibility between operating stresses and fatigue allowables caused a majority of the fatigue problems encountered in service. Standardizing the fatigue analysis process allows the service requirement analysis to be conducted independently of and before structural capability analysis. To achieve fatigue reliability and meet DSOs, Boeing requires durability to be considered early in the design of structure.

A step-by-step procedure for finding the fatigue margin has been developed, along with relevant definitions such as the ground–air–ground stress. Based on a survey of operating loads and the resulting required detail fatigue rating, an indication of high margin by inspection may be adequate. A fatigue margin must be determined for all metallic structure.

Composite primary structure to date has been designed using the no-detrimental-damage-growth approach (FAA AC 20-107A, section 7a). For most composite wing and empennage primary structure, tests have demonstrated negligible damage onset in undamaged structure and the lack of detrimental damage growth in structure containing accidental damages of sizes less than or equal to those considered for regulatory residual strength evaluations.

D. Corrosion

Corrosion control is an important structural performance requirement similar to fatigue, damage tolerance, or ultimate strength. Historically, corrosion problems result from exposure to moisture either from the weather, condensation, or accidental spills combined with designs that trap this moisture in crevices. Improper material selection in addition to inadequate finishes, sealing, drainage, and corrosion inhibiting compound application all contribute to these problems. Areas of the airplane that are particularly prone to corrosion include the leading- and trailing-edge cavities of the wing, lower lobe fuselage structure, floor structure under lavatories, galleys, and doorways, wheel wells, and exterior skins at splices and fasteners.

The responsibility for corrosion prevention starts with the designer recognizing the importance of material selection, drainage, finishes, sealants, and the application of corrosion inhibitors for structural durability (Fig. 31). In addition, it is essential that the designer consider whether the details of a design may affect other areas of the airplane. A thorough design effort will use an envelope of worst-case scenarios to define the environment for each part and assembly being designed.

Corrosion control begins with initial design and manufacturing and continues through the operation and maintenance of the airplanes. Unlike fatigue, which is cycle dependent, corrosion is primarily time, environment, and usage dependent. The fatigue life of an airplane is designed into the structure, and cracks are predictable. Corrosion, on the other hand, is predictable only in that the operator knows it will occur sometime during the life of the airplane. However, the time of initiation and rate of progression is unpredictable, and its presence need not be a life limiting phenomenon like fatigue.

Proper maintenance programs, and in particular, a good corrosion-prevention program, can contain corrosion to an acceptable level well beyond the predicted economic life of the airplane and need not become an airworthiness issue. A maintenance corrosion control philosophy was developed by the FAA, airframe manufacturers, and the operators in the early 1990s to achieve this end. Airplane designs are continually improved based on operator feedback. As an example, Fig. 32 shows design improvements made on the 747 model to minimize in-service corrosion problems.

Typically aluminum alloys comprise some two-thirds of a commercial airframe. Their strength and light weight has been a boon for the industry. Unfortunately, their propensity for corrosion has been a serious headache for the designer and the operator alike. Corrosion detection and repair in service has been probably been more of an economic burden for the operator than fatigue. In fact it is reasonable to believe that corrosion avoidance could be the most compelling reason for greater use of composites in future airplanes.

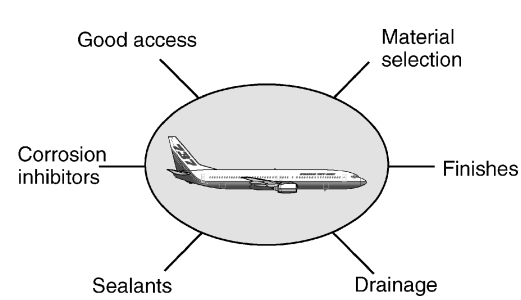


Fig. 31 Design features for corrosion prevention.

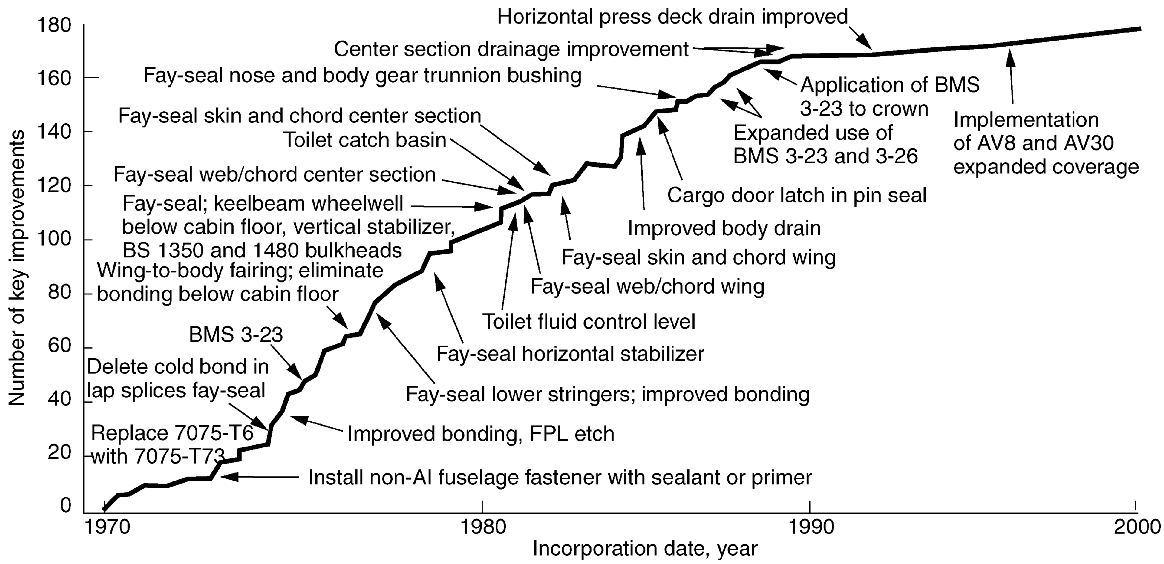


Fig. 32 Corrosion-prevention design improvements of 747.

For current airplanes, it has long been recognized that unchecked corrosion damage, especially in combination with repeated loads, can eventually lead to serious strength degradation. Therefore, designing for corrosion avoidance and control is another critical design goal requiring well-defined criteria and procedures, elements of which are 1) recognition of the corrosion inducing environment for each component of the airframe, 2) selection of the least corrosion sensitive alloys suitable for their function, 3) scrupulous attention to drainage, sealing, and finishes in the delivered airplane, and 4) implementation of comprehensive corrosion prevention and control programs in service.

Today's understanding and practice of design and maintenance for corrosion control has not come easily. It is beyond the scope of this paper to cover in detail all the painstaking step-by-step improvements achieved through several generations of modern commercial airplanes. However, a few major contributors deserve mention here.

Improvements have come because of the focus on better drainage and effective sealing where appropriate, the elimination of stress corrosion through careful alloy selection, development of tough and tenacious primers and finishes, and the use of fay-surface sealants and corrosion inhibitors to deter moisture ingress. Finally, the in-service corrosion control programs developed jointly by industry, regulators, and operators and mandated for incorporation early in each airplane's life will reduce the burden of unplanned maintenance on the operator and will provide increased confidence in long-term safety.

In summary, responsibility for corrosion avoidance starts with the designer, continues with a quality build process, and finally rests with the operator through dedicated surveillance and maintenance. Unless we invent a totally corrosion resistant alloy, all three elements will continue to demand our diligence. Even with greater use of composites, some of these issues will remain, especially at interfaces of dissimilar materials, and will require their own special solutions.

E. Maintainability and Maintenance

In addition to defeating corrosion, prudent inspection and maintenance is also vital to detect and enable timely repair of fatigue cracking or accidental damage from a variety of potential causes. Whereas corrosion onset and growth is mostly time dependent, fatigue damage is a function of flight cycles and flight length.

The dramatic growth in airplane utilization poses yet another challenge for both the designer and the operator. Airplanes only pay for themselves when in revenue use. It is common for an airplane to operate 10–12 h a day (with as many as 10 flights per day), seven days a week for 300 or more days per year. Airplanes like the 757 and 737 log as many as 2500–3000 flights per year.

These high utilization rates have a double impact. First, any damage from whatever source will accumulate more quickly. Second, the readily available down time for scheduled inspection is limited. To ensure that 1) scheduled inspection and maintenance are reliable and effective, 2) surprise unscheduled maintenance is minimized, and 3) the airplane structure remains safe and highly functional, the designer and operator have implemented a three-point approach.

At the outset, the structures designer, recognizing the time constraints on the operator's maintenance team, now places very heavy emphasis on accessibility and inspectability of all critical structure. Access and ease of inspection is always verified by physical or digital mockups and by factory visits to existing similar airplanes. Every effort is made to minimize hidden critical structure and maximize the reliable use of visual inspection. Design details will often be tailored so that, if damage occurs, it will most likely occur first in a readily visible area, thus, signposting the way for wider follow-on inspections. Development and full-scale tests are used to validate expected behavior; the proposed in-service inspection techniques are used in these tests to confirm they are appropriate.

For each new model, the working group from the manufacturer, the customer airlines, and the regulators works for a year or more before certification to establish a comprehensive maintenance program satisfying the structural needs and the operators' maintenance facilities and resources. A basic program addressing accidental, environmental, and potential fatigue damage is approved by all parties and mandated by the regulators. This program specifies inspection locations, types, and intervals and is instituted by each operator at service entry. It typically applies to every airplane of that model in each operator's fleet. At the same time, the working group establishes special directed inspection options for potentially critical fatigue areas, to be incorporated on all airplanes as they approach a high percentage of the DSO flight cycles (typically 75%).

The third element involves open communication between the three parties. All potentially unsafe findings are reported immediately to the manufacturer and to the regulatory authority. The manufacturer will advise all operators of the finding with appropriate remedial recommendations. The regulator may issue mandatory corrective actions, either further inspections or modifications. Finally, the manufacturer usually convenes an all-operators meeting once a year for each model to discuss the three parties concerns. The agenda is mutually set by the manufacturer, the airlines, and the engineering and maintenance branches of the regulatory agency.

Again, the responsibility for long-term success relies on all three parties. The manufacturer must deliver an airframe that is reasonably simple to inspect and maintain. The operator must maintain it diligently. The regulator must monitor the fleet to ensure that all the jointly developed requirements are being met consistently.

V. Cost (Acquisition and Ownership)

The economics of air transport today are heavily influenced by the purchase and/or leasing costs of the fleet. As the fleet ages, inspection and maintenance costs begin to climb and add additional financial burdens to the operator. Decisions made by the modern structures design team must address both the purchase price of the aircraft (recurring and amortized nonrecurring costs) and the life-cycle costs, while still meeting the performance targets for the stated mission. To meet today's cost goals requires a design team working in a collaborative environment that includes all elements of the design, build, and end-user community.

A. Design Environment

The design environment is a key element in reducing the overall costs associated with an airframe. In recent years, manual drawings have been replaced by electronic datasets, physical mockups by electronic mockups, and function organizations by multidisciplinary teams variously known as design/build teams (DBTs), integrated product teams (IPTs) or platform teams as shown in Fig. 33.

B. Integrated Product Teams

The advent of integrated product teams (IPT), advances in computing tools, and global collaboration, all play a role in the design environment (Fig. 34). Up to 90% of the cost of an airframe is

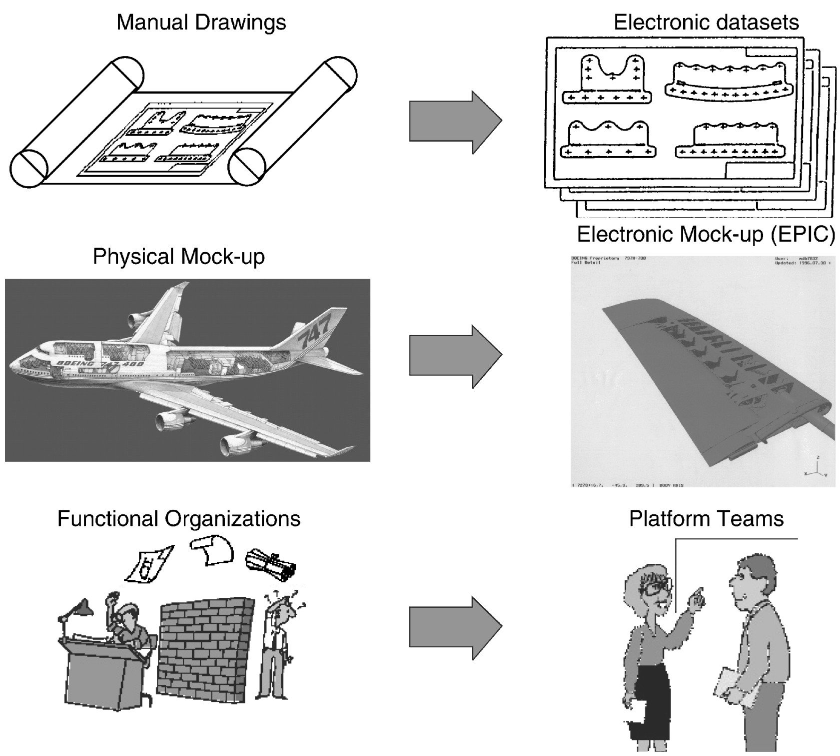


Fig. 33 Design tools and processes have changed.

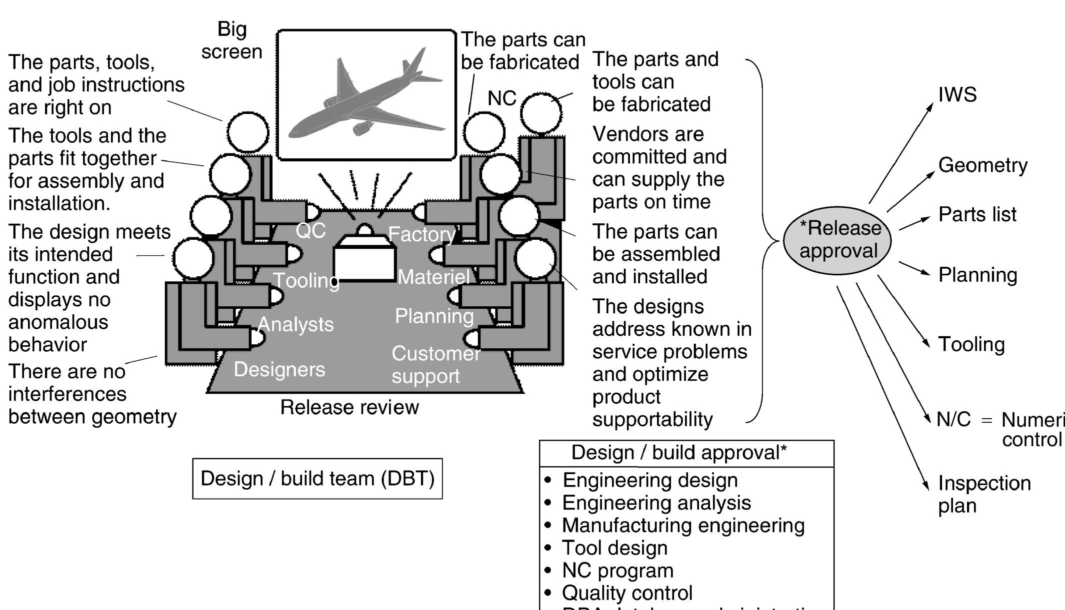


Fig. 34 Design/build teams (DBT) and IPT produce concurrent product definition including integrated work statement (IWS) and digital preassembly (DPA).

established in the initial design. Selection of manufacturing processes, materials, and airplane configuration dictate that cost structure. For many years, engineers worked diligently at optimizing their portion of the airplane, usually along narrowly defined functional specialties. Often the structures design proceeded along one schedule while the systems design followed another. This led to the need to release engineering definition multiple times for each component, adding cost and flow time to the design effort. This in turn had the downstream impact of causing expensive rework to tooling or fabricated parts.

In an IPT environment, the design engineer is an integral part of a product team. Responsible for all design, build, and support aspects of the program, these teams bring together the expertise of all functions to ensure the best possible balance of performance, cost, and in-service functionality. Membership includes the component manufacturer and may include representation from potential airline customers. The teams work to ensure all aspects of the product (materials, finishes, part designs, tooling approach, manufacturing plans, and systems installations) are integrated before the initial release of the engineering drawings. This concurrent work pays off in reduced disruption during the manufacture of the product and in the end reduces the time to market. The team works in a digital environment in which the design team prepares three-dimensional representation of all parts (Fig. 35). These models are shared across the team to enable virtual fabrication, assembly, and maintenance operations. These simulations facilitate optimization of the design prior to manufacture.

Global collaboration is also key in reducing time to market. IPTs are becoming increasingly global, and tools are now in place to enable continuous design work, allowing around the clock productivity on the product. The sharing of digital data sets nearly instantaneously allows designers at the prime manufacturer to work with their partners around the world on various aspects of the design. Improvements in web-based virtual meeting and electronic-collaboration tools will further enhance the ability to share design responsibility around the world.

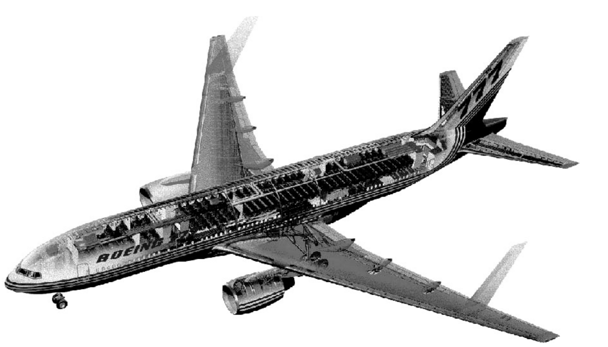


Fig. 35 Digital product definition enables engineers to validate assembly before cutting metal.

C. Knowledge-Based Engineering

Among the methods available to the designer are knowledge-based engineering (KBE) tools. These tools allow key features to be defined based on manufacturing considerations, basic structural design requirements, and geometric constraints of the configuration. Once established, these parametric models allow for the rapid changes to the product definition to meet changes in configuration. KBE is a proven technology and is an integral part in the development of new and derivative airplanes in at Boeing Commercial Airlines (BCA). The use of KBE technologies enables various engineering disciplines to support the BCA reduction initiatives.

First is the reduction of cycle time: The development and implementation of KBE applications allows for a significant reduction in the design cycle of an airplane program. The tools accomplish the reduction by automating numerous tasks including spatial and analytical integration. Both structural and system engineering disciplines realize this benefit.

Second, variability in the design is minimized by the programmatic application of design and manufacturing rules. These rules are external to the KBE applications and can be modified to satisfy a given design constraint.

Third, nonrecurring cost is reduced. The deployment of the KBE tools reduces the manpower requirements to complete the airplane design, thus reducing cost. Cost is also reduced by the use of routines that search for existing designs that satisfy the design constraints removing the need to manage new designs.

Redesign due to changes in loads, manufacturing preferences, and even derivative configurations can all be accomplished in rapid fashion, reducing the product definition time and speeding the product to market. At The Boeing Company, KBE process development continues, as demonstrated in Fig. 36, evolving from a detail design aid to an integrated product design tool of the future.

What about the end product? The design philosophy today is evolving toward one where fewer, more structurally integrated parts are brought together as simply as possible. One must remember that from a cost perspective all designed parts, from the simple clip or bracket to the wing skin panel, require rigorous control of materials, finishes, and manufacturing plans, to conform to the type and production certificates. Simply reducing the number of parts reduces the costs associated with maintaining the design data.

D. Material Selection

Material selection is critical in providing value to the end user. The designer must carefully consider raw material costs, processing costs, vehicle build plans, structural performance, and life-cycle costs when making these decisions.

The first consideration is the selection of the lowest cost materials and processes that adequately meet the performance targets and tolerances required in the build plan. Selection of materials is critical to further integration of the structure into large monolithic bonded assemblies or machined parts. A well-balanced decision must also consider commonality of materials and processes across the vehicle, particularly for composites, to further reduce raw material costs and to simplify maintenance for the operator.

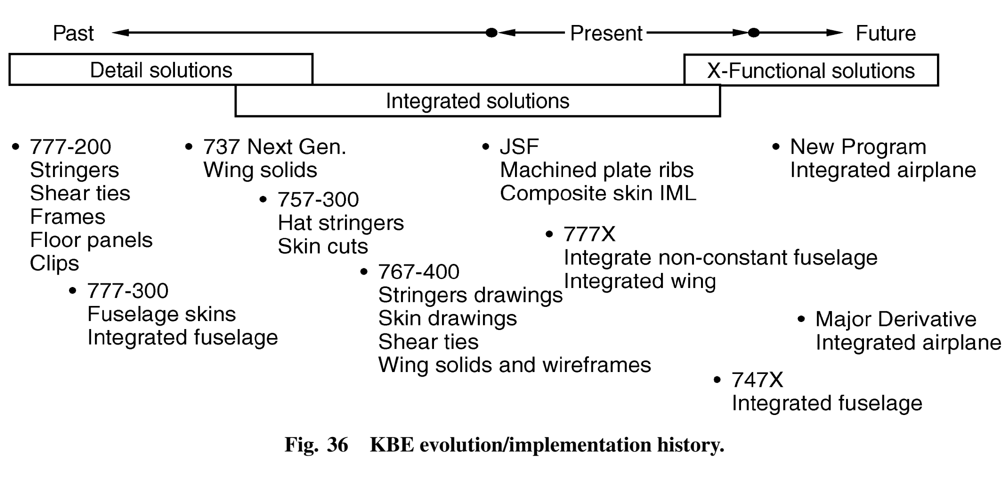


Fig. 36 KBE evolution/implementation history.

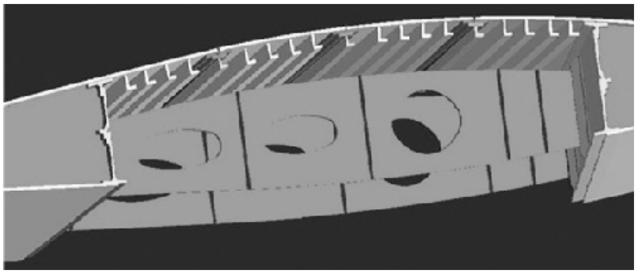


Fig. 37 Advanced metallic structures.

The second consideration is of the vehicle build plans: Balance cost of detail part fabrication against downstream assembly and installation costs. Criteria can include evaluation of tooling plans, producibility evaluations, and integrated structural approaches.

The third consideration is structural performance. Performance has many measures but the evaluation must include ability to meet weight and cost targets for a given component.

Last are the life-cycle costs. Modern materials and finishes, combined with carefully designed details, have delayed the onset of corrosion and fatigue in traditional aircraft structure. Selection of correct materials must include appropriate understanding of damage tolerance, durability, and corrosion. Repair philosophy must also be considered for in-service accidental damage.

As the use of composite materials grow, the potential exists to design and build a composite fuselage structure that would essentially eliminate traditional corrosion and fatigue concerns with the airframe. This has the potential to extend the life of an airframe significantly and reduce overhaul and maintenance costs substantially.

E. Determinant Assembly

One aerospace executive is well known for his goal of making airplane assembly as simple as "Fisher Price toys on Christmas morning." To achieve this, a trend in design philosophy is the move towards self indexing parts. Traditional aircraft assembly methods involve large and expensive fixtures to maintain part to part alignment during assembly. Modern design practice looks to locate parts relative to each other based on carefully defined index and datum systems. The result is simpler, more flexible tooling, with shorter lead times, to support the airplane assembly. A related trend is the replacement of builtup structures, containing dozens of mechanically fastened parts, are being replaced with monolithic machined or integrated structures (Fig. 37). In the area of metals, improvements in high-speed machining, advances in laser beam welding, and development of friction stir welding all potentially lead to a reduction in the costly work involving drilling holes and filling them with fasteners. Less obvious but equally important is the improvement in accuracy for these components, particularly for high-speed machined parts, and fewer hand fit operations involved which reduces the often hidden costs associated with errors and rework. When applying monolithic and welded integrated structures, great care must be taken to ensure that durability, damage tolerance, and fail safety considerations are thoroughly understood and evaluated. However, when used properly, these structures have the potential to reduce greatly the labor involved in fabrication and assembly.

VI. Future Challenges

Today's commercial airplanes are modern marvels of engineering science, and the industry can rightfully be proud of its achievements. However, it cannot be satisfied with the status quo. The flying public deserves airplanes that are even safer, more comfortable, and more economical. Every facet of the industry must contribute to achieve these goals: the manufacturer, the regulators, the airline operators, and the world's airport facilities.

The structures community contribution must be to meet the challenges of providing improved safety; more efficient structural performance; reduced costs of production and ownership; shorter, more agile development flow times; and fully productive use of our resources in-house and with our partners and suppliers. The challenge is often stated as "Do a better job, for half the cost, in half the time and with half the people!"

A. Composite Structures

Commercial aircraft fiberglass composite structures have been used in secondary structures since the 1960s. In the 1970s, carbon-fiber composite structures were initially applied to Boeing commercial aircraft through a series of NASA-funded demonstration programs. These programs involved 737 spoilers, 727 elevators, and 737 horizontal stabilizers. In 1984, the 737 stabilizers were the first certified composite primary structure on commercial aircraft. As a result of these NASA programs, and with the experience with certifying the composite control surfaces on the 757 and 767 airplanes, the FAA issued AC 20-107A, "Composite Aircraft Structure," in 1984. The certification of composite primary structures has followed the guidelines contained in AC 20-107A. For damage tolerance, composite structure certification has been based on demonstrating no-growth of damage of sizes up to the damage limit. Environmental degradation caused by temperature, humidity, etc., must be considered. The residual strength vs damage size criteria is shown in Fig. 38. The airplane is designed to maintain ultimate strength with barely visible impact damage, limit strength with visible impact damage, and 70% of limit strength with large accidental damage.

The quest for lighter, more durable, and more forgiving structures will not be easy. The low-hanging and much of the midheight fruit has been harvested already. Although some further advances in traditional metallic materials can be expected, they are likely to be modest and evolutionary rather than revolutionary. The most promising avenues will likely be composite structures, in their many emerging forms. Satisfactory service experience with primary structure components over more than 10 years has validated the potential for significant weight reduction, corrosion avoidance, and operator acceptance. It is now entirely feasible to pursue composites for both wing and fuselage structures. By getting beyond the "black aluminum" mindset, we should be able to realize their structural advantages and damage tolerance properties at competitive production and maintenance costs.

B. Health Management

Boeing is investigating use of a variety of monitoring techniques for airplane structures. The primary motivation is to reduce the effort required for inspection and repair. Structures health management applications under investigation include the following.

Corrosion inspections, that is, moisture and corrosion monitoring require a large amount of effort throughout the life of an airplane. Electronic monitoring capability could eliminate the need to gain access to an area for inspection (which often takes much longer than the actual inspection) and minimize the extent of the repair (by detecting the problem earlier). One potential monitoring approach uses a fiber optic sensing technique.

Accidental damage occurs from a number of sources, such as vehicles colliding with the airplane at the gate. Monitoring techniques could determine if an area of structure has been

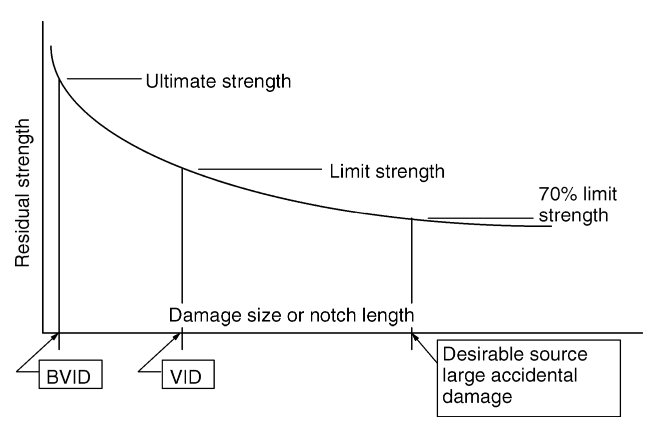


Fig. 38 Residual strength vs damage size or notch length.

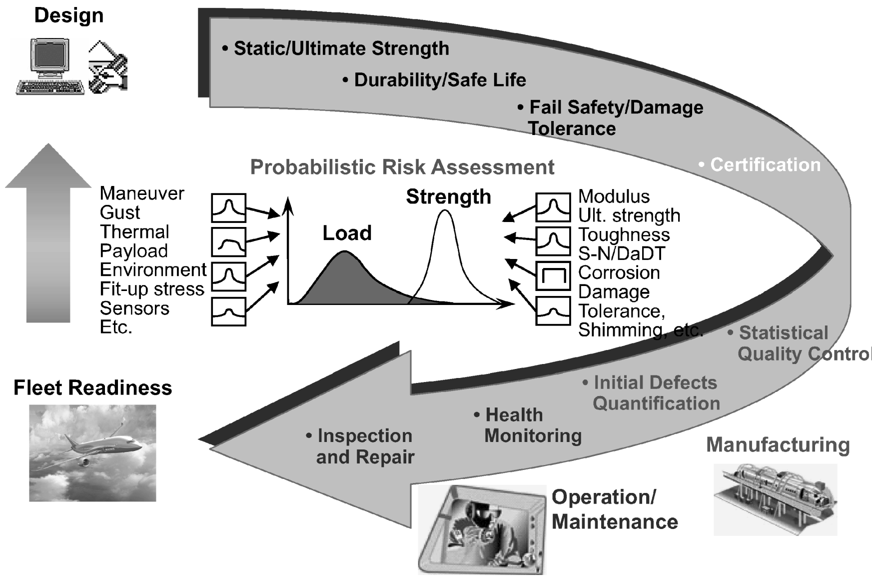


Fig. 39 Probabilistic life-cycle management.

impacted and the extent of the resulting damage. One potential technique is via use of an array of piezoelectric sensors; arrays such as this have been shown to detect location and magnitude of an impact and the location and severity of damage (such as a delamination).

Load exceedance monitoring techniques have been applied to fighters and some other military airplane for years. For commercial airplanes, benefits are expected in some areas, including exceedance monitoring. Load monitoring could characterize each exceedance (such as a hard landing), to focus the inspection effort to areas where there could be potential damage. Load monitoring has traditionally been accomplished primarily with physical strain sensors, but there is increasing evidence that much of this can be accomplished via calculations based on existing airplane parameters (inertial, air data, flight control surface positions, etc).

These approaches will be considered for their ability to reliably identify potential structural issues and reduce maintenance costs.

C. Tools and Processes

Today's design and validation practices are far more sophisticated than they were in the 1950s, resulting in far fewer surprises in service. However, the cost in engineering resources has seemingly increased exponentially. We must find and implement ways to reduce design and development flow times and manpower resources to bring new airplanes to market without any sacrifice in design integrity.

Computer-aided design and analysis tools continue to be improved and will be an essential element in achieving these reductions. The design and analysis disciplines will become more integrated through the use of parametric CAD/CAE processes. Rapidly increasing computing power allows increasingly complex design and analysis operations to be performed in acceptable times. Analysis tools for composite structures are being developed that will allow the analyst to evaluate the strain environment at the lamina level, reducing the time and expense of point design testing. Knowledge based engineering has been used extensively for the last 10 years and will continue to reduce routine design work allowing the designer to focus much more on innovation. The caveat is that these tools must never be allowed to supercede intelligent thinking.

D. Probabilistic Methods

There is considerable effort being applied to probabilistic analysis and design methods for structures, similar to those used for systems design (Fig. 39). The incentive is to better understand and quantify the uncertainties in structural design so that some worst-case conservatism can be avoided while designing to a desirable safety level, especially with new materials. The quantifiable risk or safety level can be treated as a measurement of structural performance and used as a design and maintenance metric to ensure consistent safety throughout the life cycle. The core of this approach is the ability to characterize the uncertainties needed in the design analyses. Availability of data needed for uncertainty characterization so far has been the biggest challenge, especially for new materials and applications. However, it has much to do with the lack of processes and requirement for such data in the past because of the current mostly deterministic design approach. More research is still required in several areas to develop an adequate level of maturity before its full implementation by the industry. One imminent example is how to support certification with the probabilistic design approach. Although there have been some successes, more collaboration between government agencies and manufacturers will be critical to the success of making this revolutionary change of design and certification approach. If validated, this approach may lead to structures that are both lighter and safer at the same time. The use of this approach is expanded on the 787 airplane to include effects like the environment on the allowables of composite structures.

E. Global Partnership

The technical challenges identified above are tough and exciting technical challenges. They will be met with the same aggressive and dedicated efforts characteristic of the past 50 years, and solutions will be found. There is, however, one additional major challenge facing us which is more cultural than technical. This is the challenge to establish successful and effective design partnerships worldwide to produce our next-generation airplanes. An example showing the Tier 1 airframe partners for the 787 program is shown in Fig. 40. Our industry will become increasingly dependent on these partnerships with many customer countries that have mature or developing engineering capabilities. Success will demand a great deal of mutual effort from all parties—respect and trust, communication, education, and well thought out strategies. The responsibility to achieve this success will rest primarily on the day-to-day efforts and attitudes of the structures engineers involved.

As this is written, we are celebrating 100 years of powered flight. Commercial aviation, with its many technological breakthroughs, has had a profound practical and cultural impact on society throughout the world. It is tragically ironic that this milestone occurred at the same time as the industry's biggest downturn, which took

Fig. 40 Airframe partners of the 787.

a staggering toll on manufacturers, operators, and the supporting infrastructure. We must believe that the world's economies and international stability will improve and that the demand for commercial air travel will grow to its previous heights. Our success in meeting the challenges described here will play a significant role in the degree and rate of that growth. We must meet them.

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