Assessment of Airplane Design, Fabrication, and Repair

by

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ABSTRACT

Engineering programs are most often classes dedicated to how to design things, while the topic of reverse engineering or problem solving is rarely discussed. This unequal presentation of two sides of the same discipline limits the student's ability to completely understand the engineering process. This paper discusses all stages of airplane design, fabrication, and repair, and attempts to provide a comprehensive view of the overall procedure instead of just one aspect. In most cases, the Boeing 747 is used as an example, though most commercial aircrafts are built in a similar fashion.

Once it has been decided to build a new airplane, the design stage can begin. The progression through conceptual design, preliminary design, and detail design can take anywhere from a few to several years depending on the complexity of the model. The fabrication stage slightly overlaps the detail design phase as coordination between engineering and manufacturing occurs. With one exception on the wing panels, the entire airplane is put together manually. This type of build process naturally leads to mistakes by human error. In order to remedy these problems, engineers inside the factory take responsibility for restoring the airplane to its original designed capacity. In this paper, each stage of airplane development from initial concept to final certification is presented in detail to offer a well-rounded assessment of the airplane construction industry.

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Title: Professor of Civil and Environmental Engineering

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1. Introduction

Most often, the study of structures includes learning a variety of different methods for how to design something. Individual components are analyzed under different types of load cases, and students learn how to repeat this process from the ground up until an entire structure is designed. There are hundreds of books in the library explaining everything from analysis methods to final construction stages. However, there is rarely anything that discusses the steps in between the original design process and the final product. What happens if there is a problem between those two stages? There is an entire branch of engineering – product review engineering – that goes largely undiscussed, but there are many people who perform this kind of work. In structural engineering firms, the original designer might handle problems that arise during construction, but other companies have whole teams of engineers dedicated to the "build" stage, and they use their expertise to troubleshoot. The problem is that no one is ever taught how to engineer backwards. In design work, you determine a set of loads and design a structure to resist them. This is quite difficult in its own right because the engineer must figure out and account for every possible scenario, but students have a lot of practice with that process. However, in product review you are given a structure without knowing the load cases or the design choices and are tasked to fix any problems that might occur. Learning through experience is usually the only method used to become proficient. While engineering curriculums are typically quite standardized, it would be beneficial if there was more exposure to the stages after design.

One field where there is a huge disconnect between design and construction is airplane manufacturing. The design engineers are completely separate from the product review engineers, and there is almost no interaction between the two groups unless there is a problem. The separation can make working together difficult because neither group completely understands the other's specific job challenges. The purpose of this paper is to give an overall view of the entire airplane manufacturing process using the Boeing 747 as an example. Each step, from initial design to fabrication to product review is discussed. The hope is to present a complete picture of how an airplane structure is designed and built instead of the typical one-sided view.

2. Overview of Design and Fabrication

2.1 Design Process

The design process begins when a manufacturer decides that there is a need for a new airplane. This new plane might only be an updated version of a plane that already exists or an entirely new model. There are specialists who try to forecast what the market will want or need in the future so that the company can decide which route to take. Creating an entirely new model is a very lengthy and expensive ordeal, so there must be a real need for a type of plane that does not already exist. For example, The Boeing Company is currently finishing up production of the first 787 model. While the size is similar to some of their other models, this plane is being designed with brand new technology that will provide a lighter and more fuel efficient plane. Once the decision has been made to go forward with a new design, the process can be divided into three separate phases: conceptual design, preliminary design, and detail design. The concept design stage can take anywhere from a few months to a few years. This first phase is when the basic configuration is decided, overall size, weight, and performance determined, and general criteria established. The preliminary design phase, which takes a few years to complete, is when the major components are designed more thoroughly. The configuration will not change further and the individual engineering groups can begin analyzing their sections of the plane. Detail design is the longest phase in the process. At this point, every single piece needs to be designed so that the plane can actually be built. Each of the three design process phases will be discussed in more detail below. [1]

2.1.1 Conceptual Design

Basic Requirements

Design criteria are a list of requirements that must be considered for all airplane design. Some of these guidelines are imposed by regulatory agencies such as the FAA and some of them come from the manufacturer. The major components of Boeing Commercial Airplanes design criteria are design loads, materials/fasteners, stiffness, static strength, durability, damage tolerance, crashworthiness, producibility, maintainability, and environment/discrete events. [2] These categories can be defined as follows:

Design Loads

The first step to designing any type of structure is determining the types of loads that will be applied. While specific loads will be discussed in the next section, this paragraph outlines the different loading scenarios that must be considered. In the case of airplane design, the load cases are broken into three categories, operating loads, limit loads, and ultimate loads. Operating loads are the typical loads an airplane will endure in one ground-air-ground (GAG) cycle. This would include standard flight maneuvers, take-off, landing, and taxi and ground handling. Figure 1 shows a typical flight profile and the random cycling for one GAG cycle. [3]

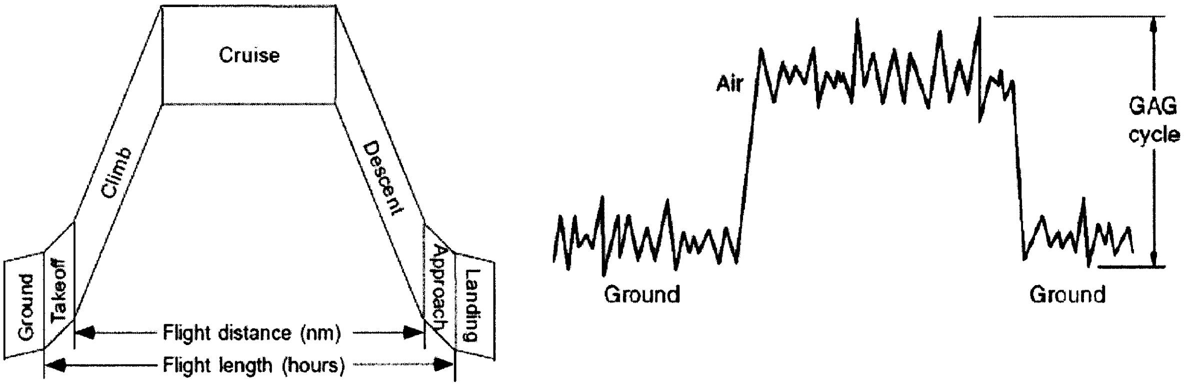


Figure 1: Ground-Air-Ground Cycle [3]

Limit loads are the maximum possible operating loads an aircraft might encounter. It is a requirement that the structure be able to sustain limit loads without deformation. Finally, ultimate loads are the limit loads multiplied by a safety factor. Each of the following design criteria use one or more of these loading cases to establish their designs. For example, static strength uses both limit loads and ultimate loads for sizing different members.

Materials/Fasteners

Each material has its own set of properties, which means that each part on the airplane needs to be analyzed for which material should be used. This does not only apply to differences between types of metals but also to differences between alloys. For example, aluminum 2024 has higher fatigue properties and is usually used for fuselage skin panels, which sees high fatigue loading. Aluminum 7075 has higher strength capabilities and is used for fuselage frames and floor beams which require high strength to act as the airplane's skeleton. [4] However, selecting materials is not quite as simple as determining the loading and durability requirements for a specific part. Manufacturing processes, cost, and joining capabilities, for example, also play a role in choosing between materials. Another factor is that new metal alloys are constantly being created, and composites are becoming more and more popular. With each new airplane program, the list of available materials expands.

Stiffness

The airplane must be designed so that there are no vibrations in flight. In order to predict, and, subsequently, control flutter characteristics, the stiffness and mass distributions of the structure are important parameters of the design. The overall stiffness will also dictate interior deflections of primary structure, such as floor beam or frame deflections, which in turn affect the internal load distribution. Adequate stiffness and flutter control is proved by analysis models and later verified by testing. [3]

Static Strength

According to the FAA regulation FAR 25.305, "the structure must be able to support limit loads without detrimental permanent deformation. At any load up to limit loads, the deformation may not interfere with safe operation." [5] As stated previously, limit loads are the maximum possible loads an aircraft will see in flight. The static strength requirement also stipulates that the structure must be able to withstand ultimate loading to a certain degree. Much of the validation for static strength can be done by computational analysis. However, for each new airplane model the FAA requires ultimate failure testing. For example, the Boeing 787 Dreamliner is a new model made mostly out of composite materials and underwent destructive testing in November 2008. [6] The Wing Box, which was the section being tested, was loaded until failure. Figure 2 below shows the 787 inside the testing rig.

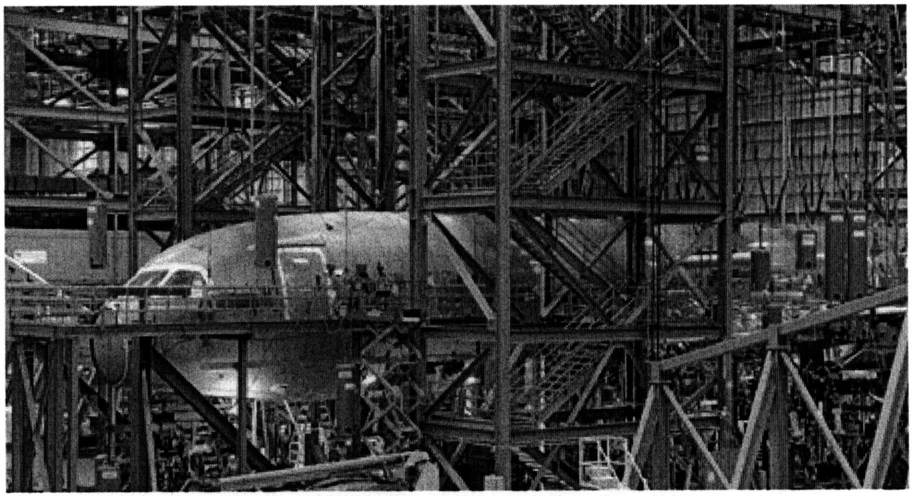


Figure 2: 787 Wing Destruction Test [6]

Durability

Durability can be broken down into two categories, fatigue and corrosion. Each of these two factors affects the long term service life of the aircraft, and is the primary concern for all maintenance programs. For each airplane program, there is a desired design service objective (DSO), which outlines the minimum number of flights the airplane is expected to complete without problems. For the 747, the minimum DSO was 20,000 flights and 60,000 flight hours. [7] Realistically, airplanes can last much longer than the minimum DSO, which is why designing for durability is so important. As new models are designed, fatigue testing results and fatigue flight history are used to improve the design process by incorporating detail fatigue ratings. Maintaining these detail fatigue ratings during the repair process will be discussed later. Preventing corrosion also plays a significant role in prolonging the life of the aircraft. Typically, corrosion is the result of moisture getting trapped between two parts of the airplane. Moisture can come from either external sources such as rain and snow, or internal sources such as spills in the galley or liquid cargo. Galvanic corrosion, which is corrosion due to dissimilar metals coming in contact, also occurs. Proper finishing and sealing of parts is the best way to protect against corrosion, but it is imperative that high risk areas be continually checked and maintained to increase the service life of the aircraft. [3]

Fail Safety/Damage Tolerance

In relation to durability design which affects the overall lifespan of the airplane, fail safe design is the concept that the airplane can sustain major structural damage and still be able to fly and land safely. All primary structure must be designed to be fail safe, which essentially means that all primary structure must have multiple load paths. In order to accomplish this, all of the existing load paths, material choices, fastener capabilities, and damage containment features must be analyzed so that the loss of a major structural component does not result in the catastrophic loss of the airplane. [3]

While fail safe design has been incorporated into Boeing design practices from the beginning, it was not until some major accidents occurred that damage tolerant design became a requirement. Damage tolerance means that the structure must be able to sustain damage until the damage can be detected. In other words, the growth rate properties of the damage must not decrease the overall strength of the airplane until the damage can be located and repaired by routine maintenance. This type of design not only sets requirements for overall airplane strength but also requires an inspection program to continuously monitor the health of the aircraft. Like fail safe design, all primary structure must be damage tolerant. There are some cases of primary structure where damage tolerant design is impractical. In this instance, a third alternative, safe life design is used. Safe life design limits the numbers of flights a specific part can be used before being replaced. An example of safe life design is the landing gear. After a certain number of take-offs and landings, the landing gear must be replaced even if no damage is readily visible. [3]

Crashworthiness

The main concept of crashworthiness is that the airplane must be designed to protect all occupants in the event of a minor crash that is survivable. The FAA outlines the requirements in FAR 25.561 as follows: [5]

(a) The airplane, although it may be damaged in emergency landing conditions on land or water, must be designed as prescribed in this section to protect each occupant under those conditions.

(b) The structure must be designed to give each occupant every reasonable chance of escaping serious injury in a minor crash landing when—

  (1) Proper use is made of seats, belts, and all other safety design provisions;
  (2) The wheels are retracted (where applicable); and
  (3) The occupant experiences the following ultimate inertia forces acting separately relative to the surrounding structure:
    (i) Upward, 3.0g
    (ii) Forward, 9.0g
    (iii) Sideward, 3.0g on the airframe; and 4.0g on the seats and their attachments.
    (iv) Downward, 6.0g
    (v) Rearward, 1.5g

Producibility

As with the design of any type of structure, the engineers must ensure that the final product can actually be built. Therefore, during the design phase, fabrication procedures and constraints must be considered. Additionally, producibility is reflected by the final cost of the airplane. Designers can try to minimize cost by using repetitive design, i.e. using the same part in multiple locations. They can also take into account the costs of different manufacturing methods before decided how a part will be made. Although this design requirement does not revolve around safety, it is equally important to the manufacturer in terms of being able to produce the product in the first place.

Maintainability

Purchasing an airplane is an extremely large investment for the customer so being able to prolong the lifespan is highly desirable. In order to increase longevity, a good maintenance program is essential. There are three factors that contribute to good maintenance: accessibility, inspectability, and repairability. First, accessibility to all areas of the aircraft needs to be as simple as possible. This means that the designer must consider points of entry after the plane has been completely assembled not just during fabrication. Inspectability is the ease with which someone can look at parts and detect a problem either visually or with non-destructive inspection. It is especially important to retain inspectability during the repair phase because often times repairs require angles or straps which reduce inspectability, and in a high risk area that might not be acceptable. Repairability is the final step in a good maintenance program. Both during fabrication and later in service, certain parts of the plane will need to be repaired. When this happens the repair needs to restore all static strength and fatigue capabilities of the initial part. If the designer does not consider the repair process in the initial design, it is likely that repairs would weaken the overall structure. [3]

Environment/Discrete Events

Environmental or discrete events are specific cases that could happen in flight or on the ground that the plane needs to be able to handle. Some instances of environmental events are lightening strike, hail, and extreme temperatures. Some examples of discrete events are bird strike, which is when the plane collides with a bird between sea level and 8000 ft. Tire burst, which is when the tire explodes and parts of the tread get thrown towards the structure, and engine blade loss, which is when one of the engine blades breaks off and potentially hits the plane. [3]

These main categories described above can be further divided and are shown in Figure 3 below.

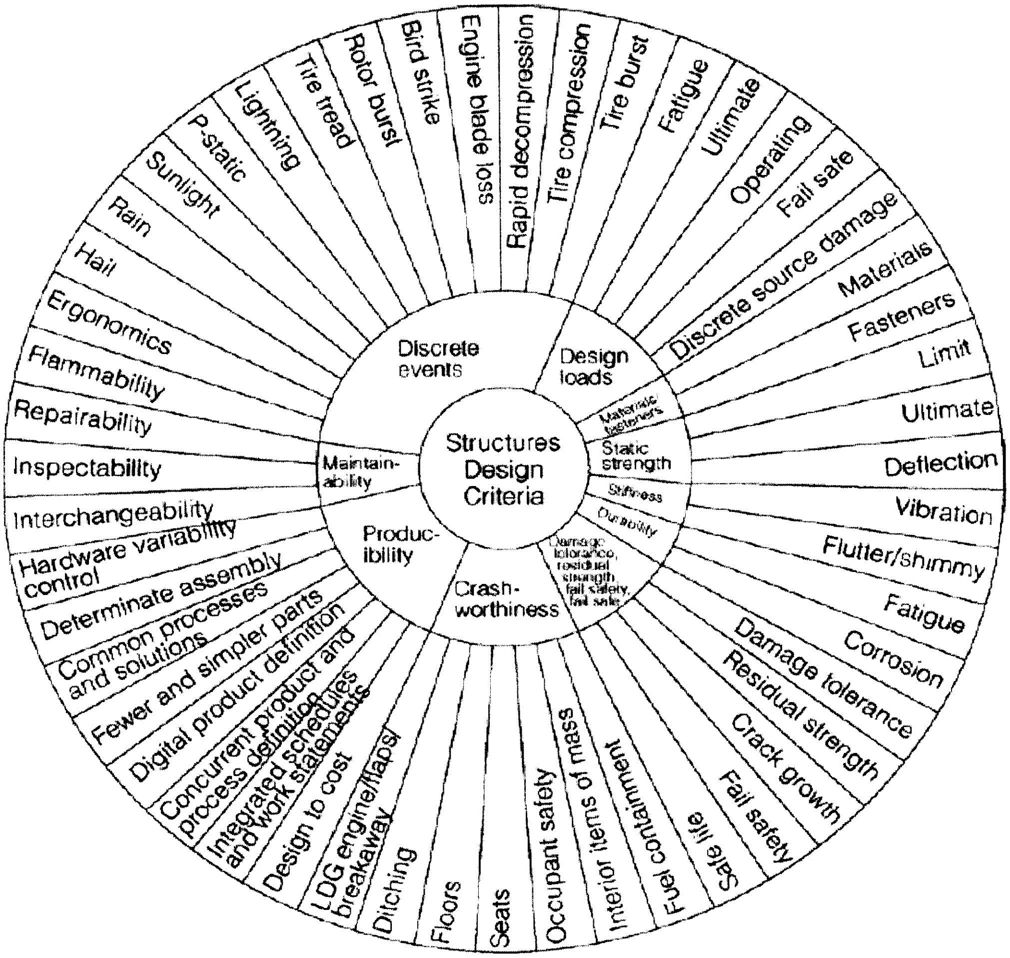


Figure 3: Design Criteria [3]

Loads

As mentioned in the section above, the first step to designing any structure is to determine the different loading cases because it is the loads that ultimately affect how strong, how stiff, and how durable the plane needs to be. When examining the various load cases, one needs to look at not only the in-flight scenario, but the complete ground-air-ground cycle. Table 1 below lists a number of different loads the plane could encounter at any stage of the cycle. [1]

Airloads	Inertia loads	Takeoff/Landing	Powerplant	Taxi	Other
Maneuver Gust Control Deflection Component Interaction Buffet Hailstones	Acceleration Rotation Dynamic Vibration Flutter	Catapult Aborted Vertical load factor Spin-up Spring-back Crabbed One wheel Arrested Braking	Thrust Torque Gyroscopic Vibration Duct Pressure Hammershock Prop/blade loss Seizure	Bumps Turning	Towing Jacking Pressurization Bird Strike Actuation Crash Fuel Pressure

Table 1: Aircraft Loads

Each of these loads will be resisted by the structure in order to maintain balance, thus producing internal forces (tension, compression, shear, bending, and torsion) in the members. Defining the types of internal forces each member encounters is crucial to the design, and, ultimately, controls the detail design, material selection, and fastener choice.

2.1.2 Preliminary Design

Airplane Orientation

Airplanes are built like ships and use a coordinate system of water lines (WL), buttock lines (BL), and station lines (STA) to locate parts throughout the plane. [8] Even though the plane appears symmetric, parts can vary widely from one side to the other. Also when orienting oneself inside the airplane, the directional indicators forward/aft, inboard/outboard, and upward/downward are used. The overall assembly of the plane will be discussed in Section 2.2, but Figure 4 below shows the general layout of the plane.

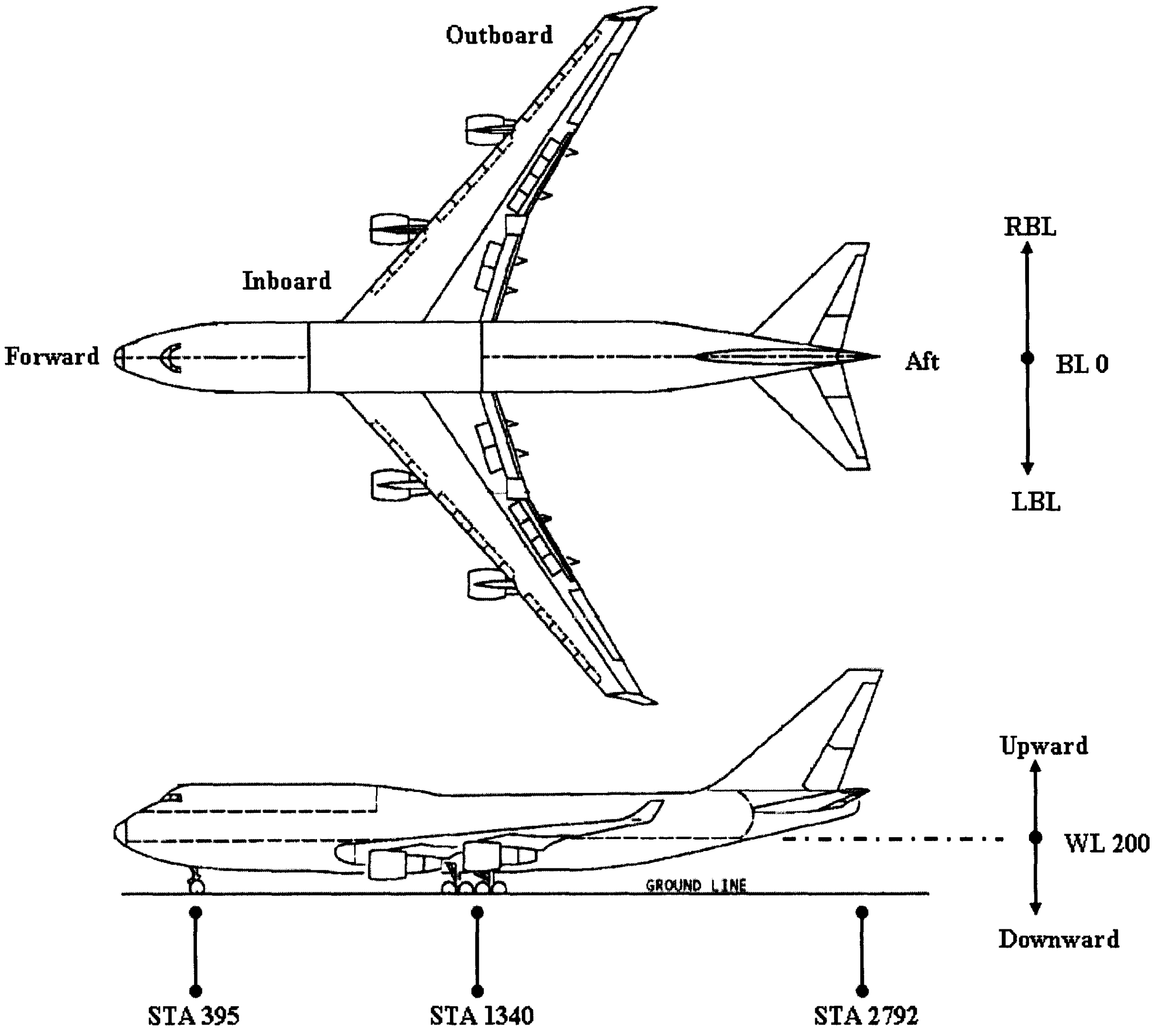


Figure 4: Airplane Orientation [9]

Water lines mark the vertical height of the plane. The main floor of the fuselage is set at water line 200. This means that any component located at a water line less than 200 is part of the cargo area, and any component at a water line greater than 200 is part of the main cabin or crew rest. Buttock lines mark longitudinal cuts along the plane starting at the center (BL 0) and moving outboard in both the left and right direction. The right side is taken when one is standing in the airplane and looking forward towards the nose. Therefore, a passenger sitting in the window seat on the right side of the plane would be located near RBL 124, whereas a passenger on the left would be at LBL 124. Station lines mark circumferential cuts down the length of the airplane. The station numbers start at 0 by the nose of the plane and increase as one moves aft. An example is Station 395, which is where the nose landing gear is located. Complicating matters further, the wings have their own markings called wing buttock lines (WBL) and wing station lines (WSTA), which help during the manufacturing process when the wings are not attached to the fuselage.

Design of Major Components

Once the design criteria have been established, the preliminary design phase begins. This is when the major components of the airplane are given initial dimensions to meet any functional requirements set up for the model, such as passenger capacity, fuel efficiency, or distance capabilities. The main components can be broken into five sections: wing box, fuselage, empennage, propulsion structure, and landing gear. Each of these sections is detailed below.

Wing Box

The wing box includes both the wings and the wing center section. Structurally, the wings can be modeled as cantilevered beams that extend from the fuselage. They support the aerodynamic loads as well as loading from the engines and landing gear. The wings also act as the fuel tank, which adds a significant weight component. On a 747, there is an 8.5 ft. height difference to the ground from when the wings are fueled or "wet" and when the wings are "dry." [9] The primary structure of each wing is composed of skins, spars, ribs, and stringers. Figure 5 below shows the layout of a typical wing.

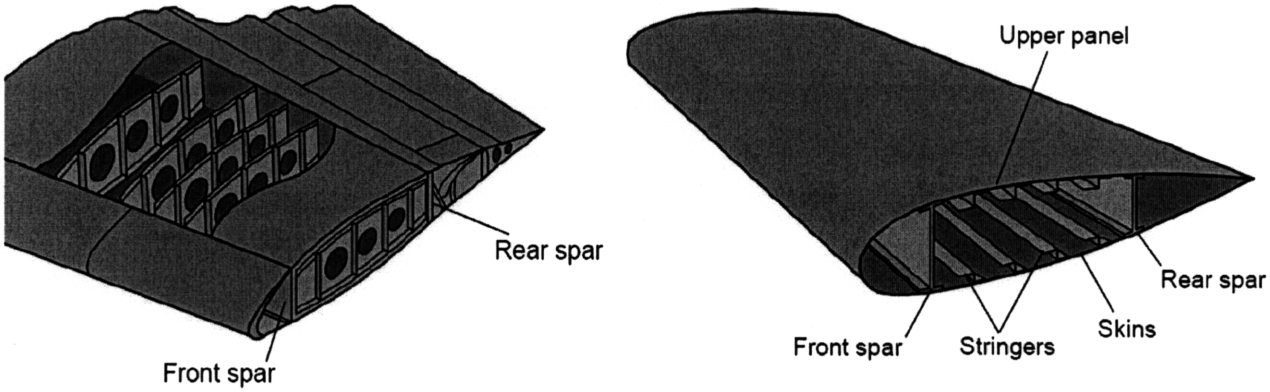


Figure 5: Wing Layout [3]

The skin and stringers work to resist the bending loads and any axial loads that result from bending and pressurization. The stringers also act as stiffeners that increase the buckling capacity of the panels. The spars run along the inboard/outboard direction and help carry vertical shear loads as well as torsional moments. In the 747, there are three spars while the other models have two. The ribs run in the forward/aft direction and are evenly spaced throughout the length of the wing. The ribs help disperse loads through the wing, provide extra stiffness to increase buckling capabilities, and help the skin resist pressurization loads. The wing center section (Figure 6), also called the stub, is what connects the wings to the fuselage, and, therefore, helps distribute loads between the two structures. The overall shape and size of the wing primarily dictates the design for the rest of the airplane. [4]

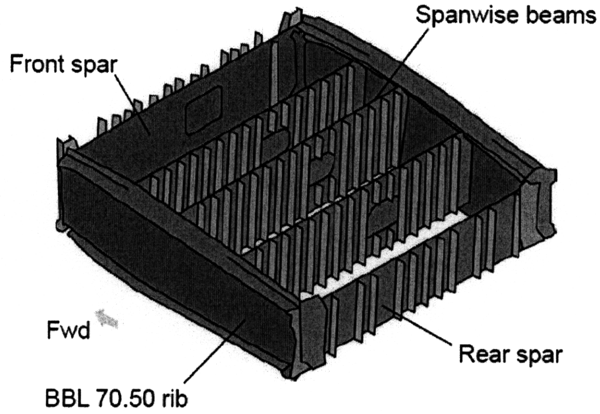


Figure 6: Center Wing Section [3]

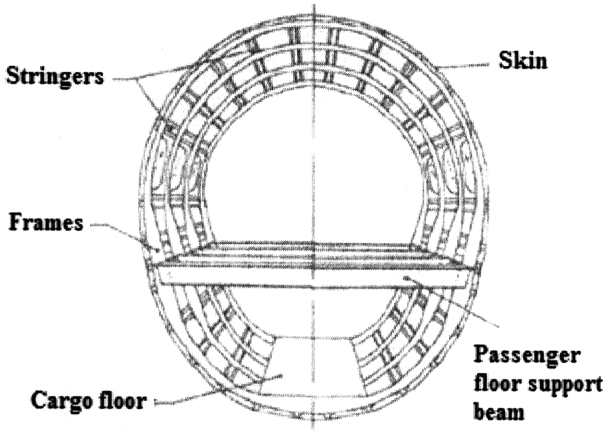


Figure 7: Fuselage Layout [3]

Fuselage

The fuselage or body of the airplane is the section that carries the passengers and the cargo. Portions of the fuselage must be pressurized for human occupancy while other parts are not. The fuselage can be modeled as a simple beam under bending, and also as a hollow tube under pressure loading, shear, and torsion. Skin panels primarily see loading from repeated pressurization. The stringers which run in the forward/aft direction reinforce the skin panels in bending and provide stiffness to increase buckling capacity. The frames run circumferentially around the fuselage to help maintain the shape and provide stiffness to the structure. The floor beams are designed to be high strength members that protect the interior in the event of rapid decompression or extreme static loading. See Figure 7. [4]

Empennage

The empennage consists of the vertical stabilizer and the horizontal stabilizers. See Figure 8. These structures are what steer the airplane. They are constructed similarly to the wings and also contain skin panels, ribs, and spars. However, the individual components tend to be much larger due to the high torsional loading. On the 747, the vertical stabilizer can also be used as an additional fuel tank.

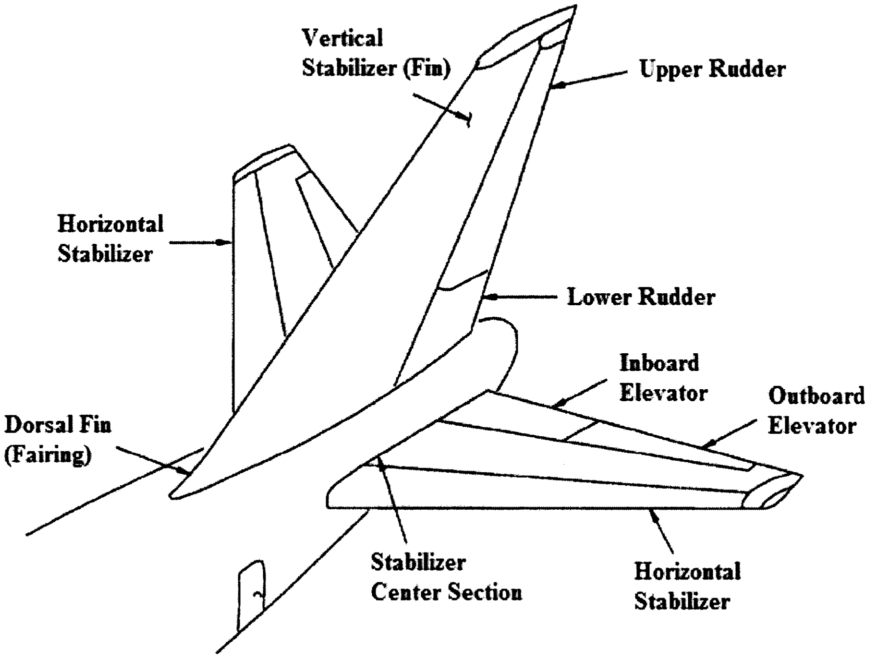


Figure 8: Empennage Layout [9]

Propulsion Structure

The propulsion structure typically refers to the engines which are designed by another manufacturer such as General Electric, Rolls Royce, or Mitsubishi. While the airplane manufacturer is not designing the engines, they do design the mounting structure and must account for all the loading associated with propulsion. The main loading concern to the surrounding structure is vibration. See Figure 9.

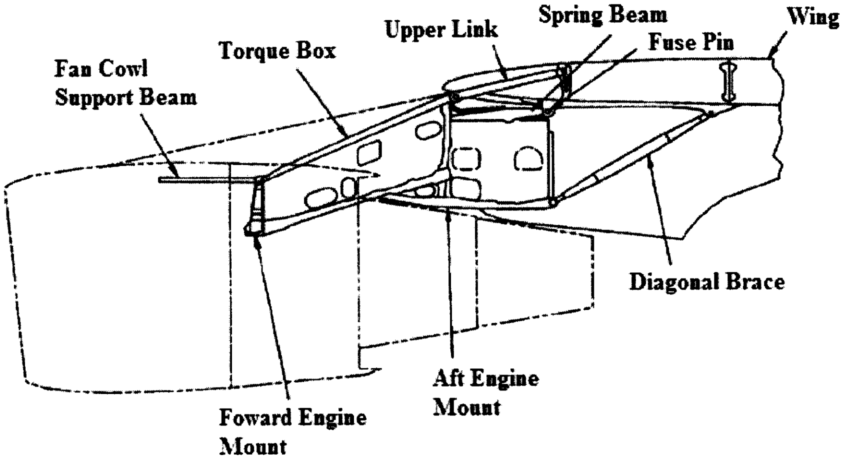


Figure 9: Nacelle Strut Layout [9]

Landing Gear

The landing gear must be designed to sustain large impact loads during landing. They also withstand all ground loading from taxiing to and from the runway as well as provide support to the aircraft while on the ground. Due to the high loading, a number of landing gear components are made from steel, which is a material that is not readily found in other areas of the plane. See Figure 10.

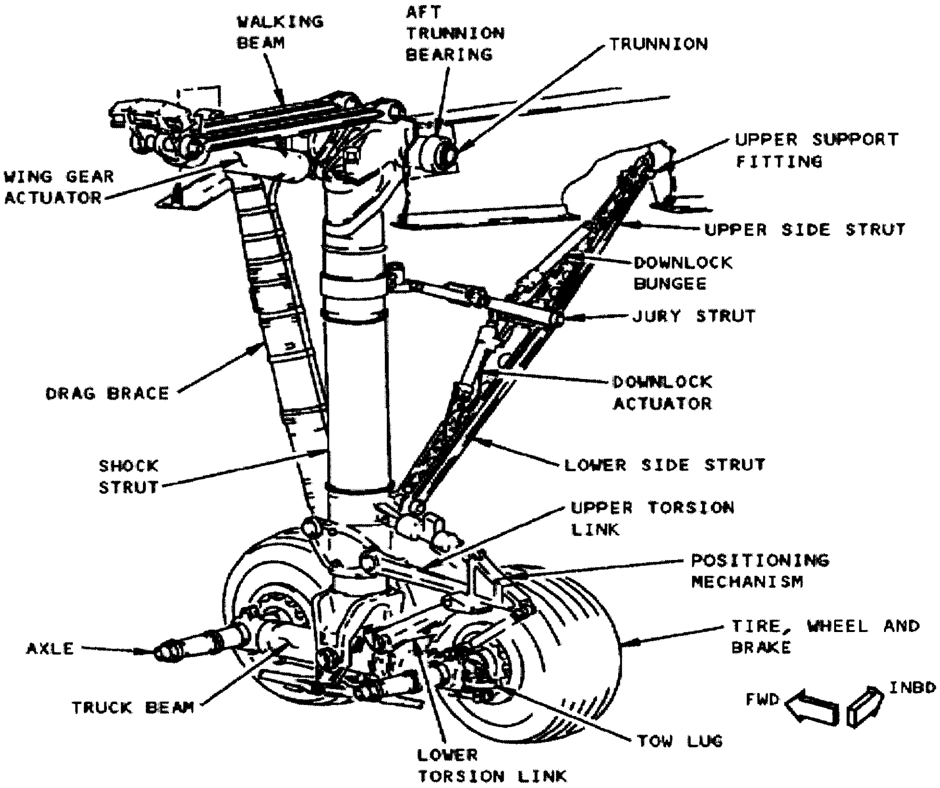


Figure 10: Landing Gear Layout [9]

Sections of a 747 Airplane

Within each of the main sections described above there are many other structural components that go through preliminary design. The following Figure 11 shows an exploded view of principal structural components.

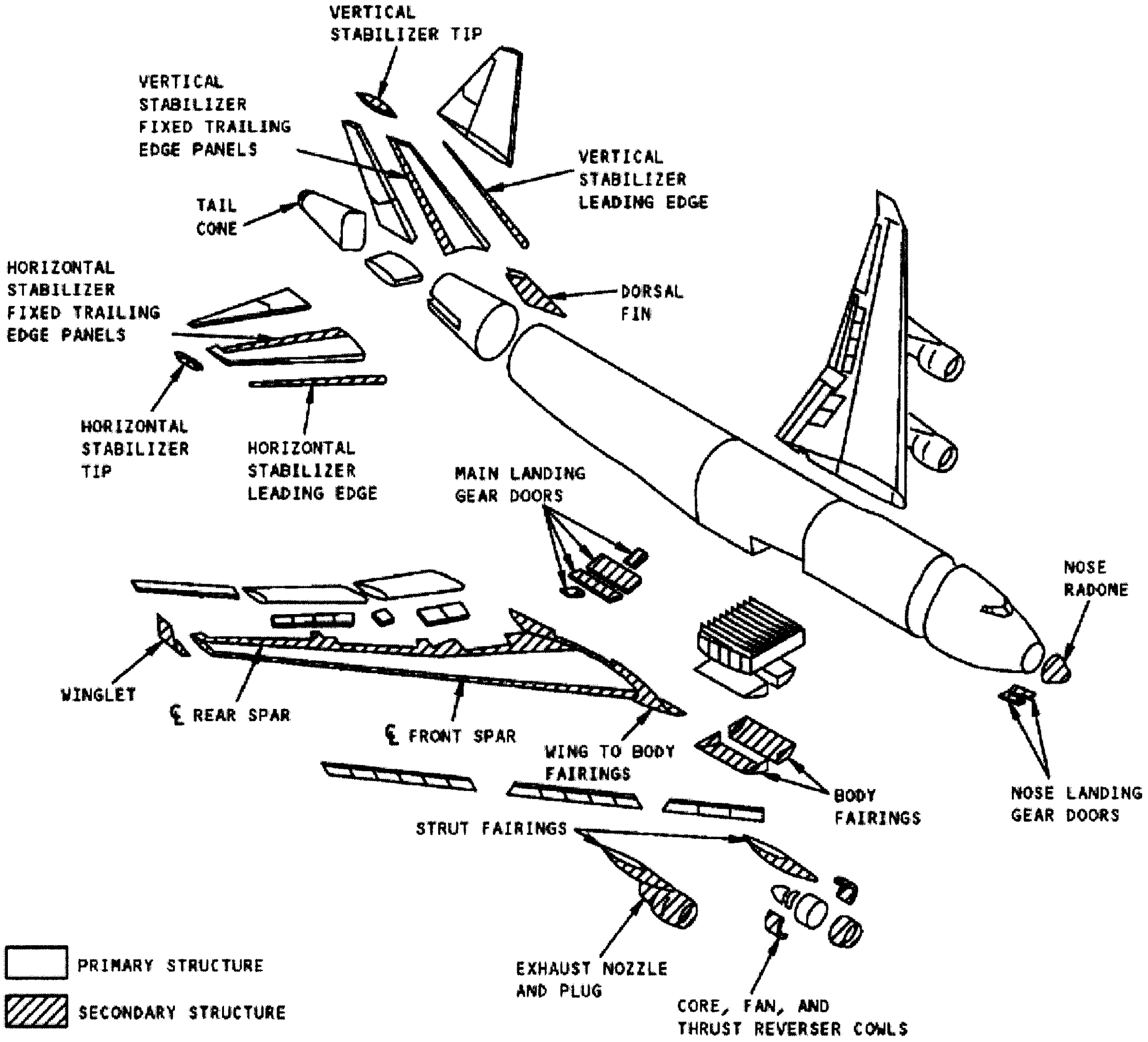


Figure 11: Sections of 747 [9]

2.1.3 Detail Design

The final stage of the design process is the detail design. This phase is the longest and most expensive part of the process because now every single piece of the airplane must be designed, dimensioned, and analyzed. [1] Material selection and fastener choices play a large role in detail design, and there are entire groups of engineers dedicated to researching the best applications of each type of material and fastener. Below, the different aspects of detail design are discussed.

Material Selection

The 747 is made predominately out of aluminum alloy as are most commercial aircrafts. Aluminum has a high strength to weight ratio and is more easily machinable and cheaper than steel and titanium. A variety of different alloys are used which exploit the differing strength, toughness, and fatigue properties depending on where its placed in the aircraft. Even the same metal composition might be heat treated differently to provide different results. In the earliest version of the aircraft, 2024-T3 a copper magnesium alloy, and 7075-T6 a copper magnesium zinc alloy were used most readily. However, airplane materials are constantly being researched and developed to create lighter, stronger, more durable materials. Later versions of this same aircraft started to incorporate some of the newly developed materials such as 2224 extrusion, which has higher tensile strength, fatigue, and fracture properties than the baseline 2024 extrusions. Table 2 below outlines the various aluminum alloys used and their applications. [10]

Alloys	Product Forms	Major Applications	Usage Rationale
2324-T39 2224-T351	Plate/Extrusion	Lower wing surface	Higher tensile strength than 2024-T3 with adequate fracture, fatigue, and corrosion properties.
7150-T6	Plate/Extrusion	Upper wing surface	Higher strength than 7178/7075-T6 with adequate fracture, fatigue, and corrosion properties.
2024-T3	Sheet	Body	High fatigue and fracture properties with adequate strength (tensile, compression and shear) and corrosion properties.
7075-T6	Plate/Extrusion	Horizontal tail Vertical tail	High strength with adequate fatigue, fracture and corrosion properties.

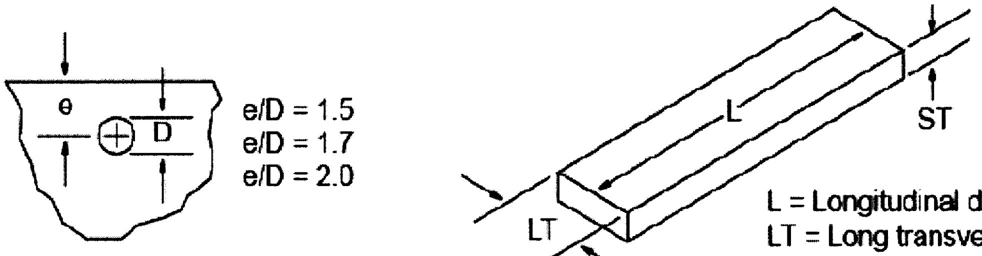
7150-T6	Extrusion	Keel beam chord	Higher compression strength than 7178/7075-T6 with adequate fatigue and corrosion properties.
7075-T73	Forging	Wing and body	Excellent resistance to stress and exfoliation corrosion and adequate strength, fatigue and fracture properties.
7050/7175-T736	Forging	Wing and body bulkheads and fittings	Higher strength than 7075 with equivalent fatigue and fracture properties.
365/A356/A357	Casting	Hydraulic manifold and control linkage	Lower cost than forgings with adequate properties.

Table 2: Aluminum Alloy Uses

In cases where aluminum does not work, titanium or steel may be used. Titanium is light and very corrosion resistant. It is often used when a similar aluminum part would be too heavy or bulky to provide the required strength. However, titanium is expensive and more difficult to machine. Steel, although quite heavy, is necessary when very high strength is required. The landing gear, wing flap and slat tracks, and engine attach fittings are all made from steel. The last main material type is composite. With each new airplane model, the role of composite material has greatly increased, which has led to the 787, a predominately carbon fiber structure. The drive to increase the use of carbon fiber comes from wanting to decrease weight and improve durability. [10]

When evaluating each of these materials, the designers must look at the various material properties such as tensile yield and ultimate strength (F_{ty} and F_{tu}), and shear ultimate strength (F_{su}) to determine if the material will adequately resist the internal forces for a specific part. Refer to Appendix A for a table listing each design criteria and the corresponding critical material property. Material properties are determined through extensive lab testing. Each property has three different values listed which correspond to A, B, or S basis. The A basis means that 99% of the aluminum samples will fall within these values with a 95% confidence level. The B basis is the values for 90% of the samples with a 95% confidence level. The S basis refers to minimum property values with an unknown statistical confidence. Typically, parts that have only one load path are designed with A basis values, and parts with multiple load paths are designed with B basis values. It is not recommended to design using S basis values. Figure 12 below shows an example of aluminum 7075 material properties. [10]

7075															
Form		Bar, rod and wire rolled, drawn, or cold finished QQ-A-225/9						Hand forgings and forged block BMS 7-185							
Material and condition		T6 T651				T73 T7351		T73							
Original thickness		≤2.000		2.001-3.000		≤2.000	2.001-3.000	≤2.0		2.001-6.000					
Heat treated thickness		-		-		-	-	<2.0		<3.0		3.001-4.000		4.001-5.000	
Basis		A	B	A	B	S	S	A	B	A	B	A	B	A	B
Ftu (ksi)	L	77	79	77	7	68	68	65	68	64	67	63	66	62	65
	LT	75	79	72	74		65	64	67	64	67	63	66	61	64
	ST									61	64	60	63	58	61
Fty (ksi)	L	66	68	66	68	56	56	53	56	52	55	50	54	49	53
	LT	66	68	64	65		52	52	55	50	54	59	52	47	51
	ST									47	51	46	50	44	48
Fcy (ksi)	L	64	66	64	66	52	55	53	58	54	57	52	56	51	55
	LT						55	53	56	51	55	50	53	48	52
	ST									48	52	47	51	45	49
Fsu (ksi)		46	47	46	47	41	41	39	40	38	40	37	39	37	39
Fbru (ksi)	e/D =	100	103	100	103	92	92	85	89	84	87	82	86	81	85
	e/D =	109	112	109	112	103	103	95	100	94	98	92	97	91	95
	e/D =	123	126	123	126	109	109	111	116	109	114	108	113	106	111
Fbry (ksi)	e/D =	86	88	86	88	74	74	66	70	65	69	63	68	61	66
	e/D =	88	91	88	91	81	81	7-	74	69	73	66	72	64	70
	e/D =	92	95	92	95	91	91	76	81	75	79	72	78	70	76



e/D = 1.5
e/D = 1.7
e/D = 2.0

L = Longitudinal direction
LT = Long transverse direction
ST = Short transverse direction

e = distance to edge
D = diameter of hole

Note: 'e' is also known as 'EM' or edge margin.
'D' is the average diameter for countersunk fasteners.

F_{tu} = tension ultimate allowable stress
F_{ty} = tension yield allowable stress
F_{su} = shear ultimate allowable stress
F_{bru} = bearing ultimate allowable stress
F_{bry} = bearing yeild allowable stress

Figure 12: 7075 Aluminum Material Properties [10]

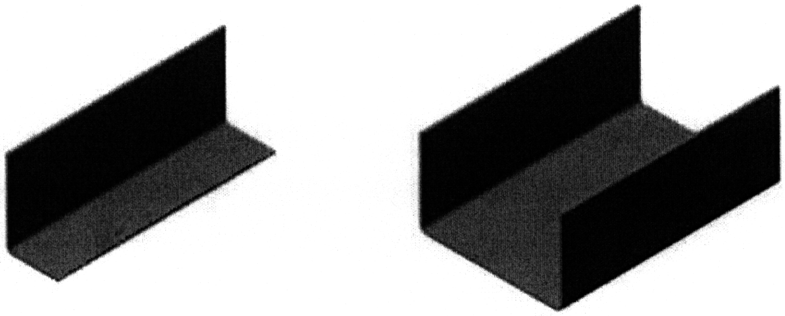
These material charts are very important when it comes to repairing the airplane. Only the original designers know the exact loads that any given part will see, so when a part needs to be repaired, the engineers only have the material properties as a basis for their calculations.

Fastener Selection

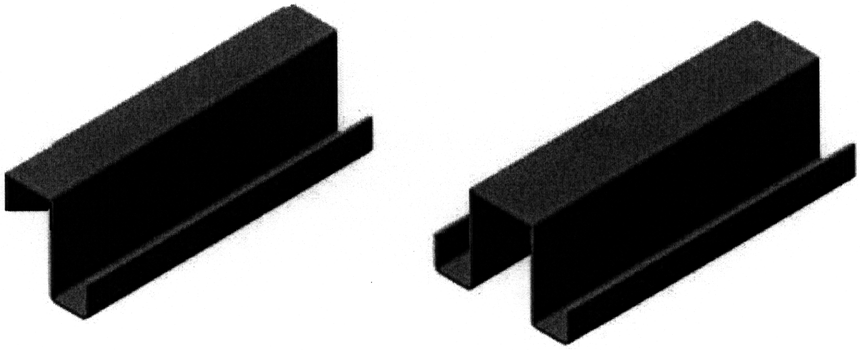
Although some parts of the plane may be welded or adhesively bonded, the majority of joints are fastened together with rivets or bolts. There are many factors that must be considered when selecting an appropriate fastener such as strength, corrosion resistance, removeability, installation access, cost, and weight. Each fastener has its own list of properties that help designers determine the best application. During the repair process, fasteners often play a big role in restoring the strength of the original design. [8]

Types of Details

The majority of detail parts are made from sheet metal that has been bent, pressed, or formed in some way. There are supplier facilities whose sole responsibility is to fabricate these sheet metal parts. The machines can be set to produce completely accurate parts so that when they arrive on-site they are ready to be installed immediately. Some typical shapes for detailed sections are angles, z-sections, channels, and hat sections, which are shown in Figure 13 below.



Angle **Channel**



Z Section **Hat Section**

Figure 13: Types of Sections [11]

More complicated parts are machined from large blocks. This allows for a shape that would be impossible or very complicated to make with sheet metal. As machining processes have improved, more parts have been made this way as it reduces the overall part count, reduces fasteners needed, and eases installation. However, these parts can be more costly, and repairing them is much more difficult.

2.2 Fabrication Process

Once all of the detail designs have been completed, the engineers release the drawings to manufacturing. At this stage, tooling designers, and manufacturing planners and engineers figure out exactly how each part will get built and in what sequence. Often times the design team and the manufacturing team will work concurrently during the detail design stage to make sure the transition is as seamless as possible. [1] Once this step is complete, parts can start being produced either on-site or at a supplier facility. However, before the airplane is actually assembled, the customer needs to decide what options they want since each plane is customized for a specific airline. Even though the majority of the plane is the same, there are differences in parts depending on if the customer chooses one type of engine or one type of cargo equipment over another. Once the customer has selected all the components they want, the customer will be assigned a line number, which is literally the number of the airplane on the production line that belongs to them. As parts get made and shipped to the factory, they will be marked with the appropriate line number and, subsequently, installed on the correct airplane.

The rate of production varies depending on the model. The 747, which is Boeing's largest airplane, takes approximately three to four months from start to finish, with a completed one leaving the factory every two weeks. However, the 777 produces a completed plane every three days, and the 737 has one completed every day.

As mentioned previously, many parts and even whole sections of the airplane are built at supplier facilities and then shipped to the factory in Everett, Washington. For any given line number, the first parts to arrive are the wing spars and floor beams. While the spars are being worked on, the wing skin panels are being riveted by an automated rivet machine, the only automated process during assembly. Once these individual parts are complete, they are brought together in the

"Wing Majors" section. The three spars are placed first, followed by the upper skin panel, ribs, interior components, and, finally the lower skin panel. As the wings are being completed, the individual fuselage sections are being constructed. The fuselage is broken into five sections labeled as the 41, 42, 44, 46, and 48 sections as shown in Figure 14.

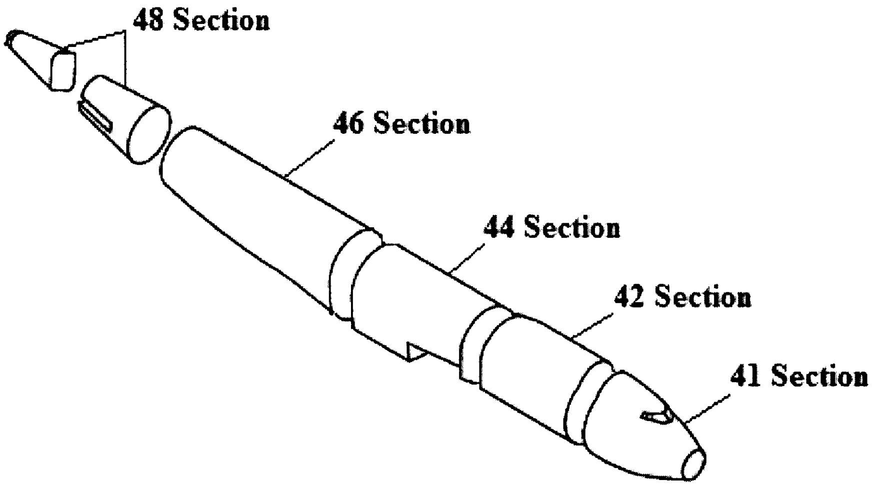


Figure 14: Fuselage Sections [9]

The floor beam grids from before can be put in place as the sections progress. The next stage is called FAIT, Fuselage Accurate Integration Tool, and this is where the 41 section is joined to the 42 section, and the 46 section is joined to the 48 section. While this is happening, the wings move from "Majors" to "Laydown" which is where flaps, slats, and fittings are assembled. Meanwhile, the 44 section is in the systems installation phase, where electronics and insulation are installed. Once those steps are complete, the joined 41/42 sections and 46/48 sections move to systems installation, and the wings and center section begin the joining process. First, is the wing-stub join, which is when the wings are joined to the center wing tank. Next, is the wing-body join, where the 44 section is located on top of the wing center tank and joined. By this time, the forward 41/42 section and 46/48 section systems installation is finished, and they are joined to the center section during final body join. At this stage, the landing gears are installed as well as the horizontal and vertical stabilizers. The plane can now support its own weight and is rolled over to final assembly. Final assembly is the last stop inside the factory. At this point, the engines are installed, interior finishes completed, and all electrical and functional tests run. After the plane leaves the factory, it goes across to the flight line, where it is painted and taken on test flights. Once it has been certified, the customer can bring his own pilots and fly the plane home.

2.3 Validation and Certification

2.3.1 Validation

Validation of the airplane design is a vital part of the process and occurs at all stages ranging from material and component testing to digital mockups and analysis to full scale airplane testing. Each step of validating the design is not only a FAA requirement for certification, but also proves to the designers that parts are behaving as planned. The following Figure 15 represents the building-block approach for validation. This process utilizes the relative ease of repeated testing at the earlier stages of design so that the singular full scale test behaves exactly as predicted. [12]

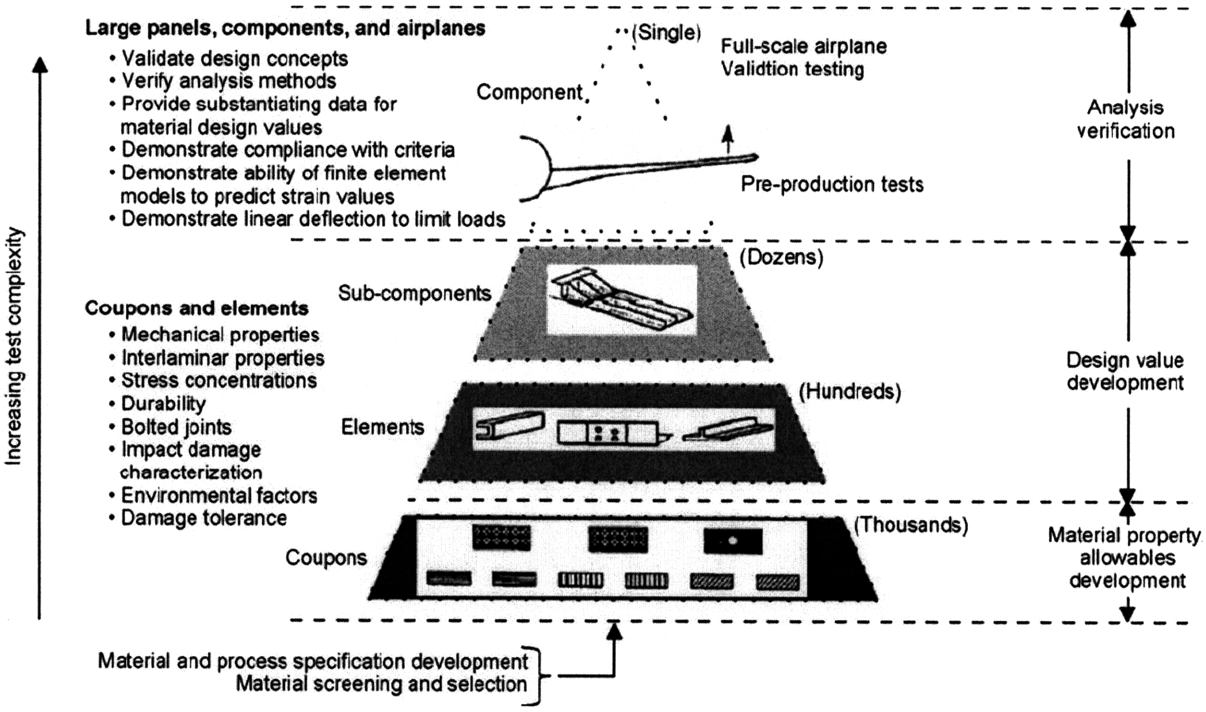


Figure 15: Building Block Validation Approach [12]

The final step of validation for each new airplane model is the full scale testing, which is accomplished by static testing, wing destruction testing, and fatigue testing. The static test is used to prove the structure can adequately perform under specified operating and limit loads. The wing destruction testing takes the loading one step further to test ultimate loading behavior. Typically, the wings are then loaded until failure. Proof of good design is if the wings fail as close to ultimate loading as possible because then the design is fully efficient and not over-designed. The final test is fatigue testing, which is when the fuselage is repeatedly pressurized and depressurized to simulate flight cycles. The requirement is to complete at least twice the intended life cycle of the airplane. While almost all of the final results of these tests can be predicted by analysis, the physical validation ensures complete compliance with all regulations. [12]

2.3.2 Certification

There are three types of certification documents associated with airplane production which are granted by the FAA. The first is called the type certificate. A type certificate applies to a specific airplane model such as a 747 or a 777. The designers will apply for a type certificate once the conceptual design phase is completed, but the actual certificate will not be awarded until the plane has been fabricated and tested. The type certificate approves all designs for a particular model. If a new derivative to an already established model is being designed, a supplemental type certificate will be issued. For example, the original 747-100 was awarded a type certificate. However, when the 747-400 and 747-400 Freighter were designed, only a supplemental type certificate was needed because the basic airplane was the same, but the new changes needed additional certification. The next certificate is the production certificate. This document allows a particular manufacturer to build airplanes with a type certificate. The production certificate proves that all manufacturing and quality assurance programs are adequately established to ensure that each airplane built will meet the type certificate standards. A manufacturer is only awarded production certificate and each new model type certificate is added once acquired. A production certificate can be withdrawn at any time by the FAA, and manufacturers are continually audited to make sure all requirements of the production certificate are being met. The final certificate is the Airworthiness Certificate which is awarded to each individual aircraft that is produced. Once a plane is completed and all of the flight tests are performed, the aircraft is issued an airworthiness certificate claiming the airplane is safe for operation. The certificate and the airplane are then turned over to the customer, and the customer becomes responsible for maintaining the airworthiness of the aircraft. The Airworthiness Certificate can be revoked at any time if the FAA feels the original conditions stipulated by the certificate are not being met. [13]

3. Repair Process

There are two very distinct instances when an airplane might need to be repaired. First is when the plane is still inside the factory, and second is after the plane has been in service. The latter, aircraft maintenance and repair, is an extensive topic but will not be discussed here. This section only refers to repairs made during the manufacturing process.

3.1 Material Review Board

As mentioned previously, once an airplane has been designed and certified, the manufacturer has been granted permission to build airplanes *exactly* as the design drawings stipulate. However, the actual process of designing and building the airplanes is not automated, and, therefore, subject to human error. There are numerous types of problems that arise during fabrication, and each one of those errors means the plane is not compliant with the type certificate. The FAA recognizes this problem and per FAR 21.123 requires that each manufacturer "establish and maintain an approved production inspection system that insures [sic] that each product conforms to the type design and is in condition for sage operation." [14] This production inspection system is called the Material Review Board (MRB) and is comprised of both quality inspectors and engineers. While the FAA outlines some basic responsibilities for the MRB, each manufacturer is required to determine the exact policies and procedures used. The FAA then approves these documents and periodically checks to make sure they are being followed.

The MRB process at Boeing contains numerous checks and balances to ensure a quality product. When a problem, typically called a discrepancy or nonconformance occurs, the mechanic is usually the first to notice. The mechanic will then have a trained quality assurance (QA) inspector analyze and document the discrepancy on a nonconformance record (NCR). If the mechanic does not notice the problem, the QA inspector will find it during routine inspections and initiate a NCR at that point. The NCR must include affected part numbers, dimensions, material and fastener specifications, and any other relevant information. A Material Review Board Designee (MRBD) will review the documentation and check to make sure it is accurate. Next, the MRB Engineer will inspect the discrepancy, review all information provided on the NCR, and conduct his own research of the drawings. The engineer then decides how to repair or solve the problem. Sometimes solutions are straightforward, and sometimes they require consultations with the original design engineers or specialized stress engineers. Once the solution has been decided, the engineer writes out each step the mechanic must take to complete the repair, this is called a disposition. The MRBD will review the disposition to ensure the engineer has appropriately referenced manufacturing processes and drawings, and then provides the instructions to the mechanic. The QA inspector will review the completed repair to make sure it was done properly. The NCR then becomes a permanent design record of the airplane. While there are many people involved in the MRB process, the engineer assumes ultimate responsibility for each repair. The engineer must correctly analyze and apply engineering principles to ensure their designs do not affect the intended strength capabilities of the airplane.

3.2 Typical Repair Considerations

Discrepancies are typically classified as either an engineering error or a manufacturing error. Engineering errors are problems with the original design such as forgetting to specify the type of fastener that should be installed or accidentally referencing two different parts to be installed in the same location. In these cases, the MRB engineer will contact the original designer to determine how the problem should be solved. The MRB engineer will also initiate a corrective action process to fix the drawings so the error will not occur again. The longer a plane has been in production, the engineering errors are less often the source of a problem. Manufacturing errors are usually the cause of a nonconformance. These types of discrepancies can vary widely depending on what stage of the fabrication process the airplane is in. During the initial structural building, typical problems might be holes that were drilled too large or too close together, and scratches, dents, and gouges in parts. During the joining phase there are often gaps caused by misalignment between parts or entire sections. The final assembly stage will create problems such as cut wires, or scratches on floor panels or interior finishes.

One of the main differences between a design engineer and a MRB engineer is that the MRB engineer works backwards from a design that already exists. MRB engineers do not know the loading cases for each individual part or the other criteria that factored into the design. MRB engineers tend to be conservative in their repairs because they do not know what kind of safety factor they have. Therefore, when analyzing any given repair, the goal is to come up with a solution that will restore both ultimate strength and fatigue capabilities. In order to analyze ultimate strength, there are four failure modes that should be calculated to determine the critical case. The four modes are tension failure, bearing failure, tear-out, and fastener shear. The equations are shown below. The following abbreviations apply to all equations:

P_{cr}	Critical Load
F_{tu}	Tensile Ultimate Allowable Stress
F_{su}	Shear Ultimate Allowable Stress
F_{br}	Bearing Ultimate Allowable Stress
$F_{su\|fastener}$	Shear Ultimate Allowable Stress for the Fastener
t	Part Thickness
d	Hole Diameter
EM	Edge Margin (center of hole to edge of part)

Tension Failure

Due to the high tensile properties of metal in comparison to shear, tension failure is not often found to be the failure mode. Figure 16 shows how a part would fail if tension was the critical load case.

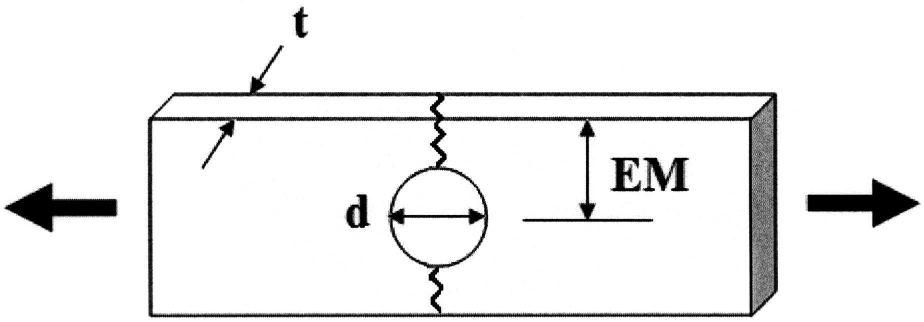


Figure 16: Tension Failure

$$\boxed{P_{cr} = 2F_{tu}t\left(EM - \frac{d}{2}\right)}$$

Bearing Failure

Bearing failure is the most desirable form of failure because it is not catastrophic. The fastener begins to push on the material and enlarges the hole, but there is still some load transfer. In this case, there is time to detect the failure and repair it before something more serious occurs. Most of the time, engineers will design repairs for bearing failure. Figure 17 shows how a part would fail if bearing is the critical load case.

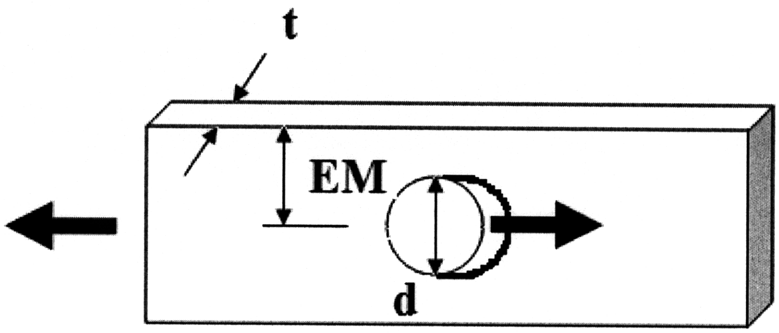


Figure 17: Bearing Failure

$$\boxed{P_{cr} = F_{br}td}$$

Tear Out

Tear out failure is typically a concern when a fastener does not have enough edge margin to the end of the part. The reduced material between the fastener and the edge is not sufficient to transfer the load, and the fastener breaks out from the part as shown in Figure 18. This scenario is the most common concern when holes get drilled too large or are mislocated.

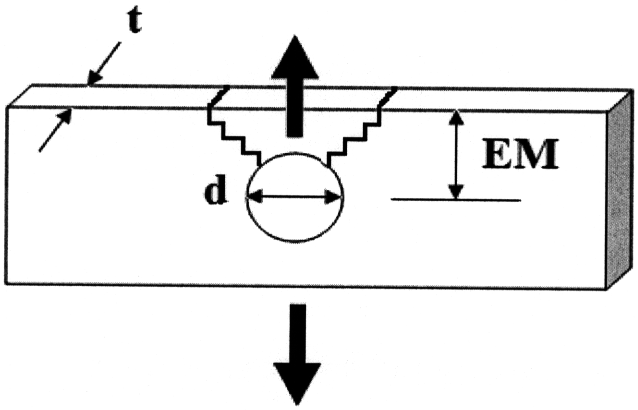


Figure 18: Tear Out Failure

$$\boxed{P_{cr} = 2F_{su}t\left(EM - \frac{d}{2}\cos 40\right)}$$

Fastener Shear

Fastener shear is often not the failure mode because of the high strength of fasteners. However, there are some parts that are designed to be fastener critical. This failure mode would be chosen in cases where the designers would rather have a part become detached and fall away from the plane instead of fail and potentially cause more damage to the aircraft. Figure 19 shows how a fastener would fail in shear.

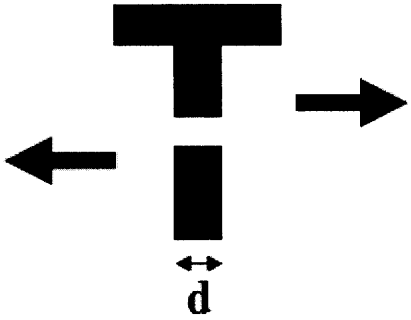


Figure 19: Fastener Shear

$$\boxed{P_{cr} = F_{su|fastener} \frac{\pi d^2}{4}}$$

The second step after ensuring that ultimate strength has been restored is calculating the fatigue properties of the repair. Within Boeing design books, there is a process for figuring out the detail fatigue rating (DFR) of parts and connections. There are different factors that contribute to fatigue capabilities and depending on the type of design these factors are assigned a value somewhere around 1. Each of the factors are then multiplied together to calculate the DFR for a particular design. Ideally, the DFR should equal 1. When analyzing a repair, first the DFR for the original configuration is determined. Afterwards, the new DFR of the repair is calculated. The new DFR value must be equal to or greater than the original DFR to ensure fatigue capabilities are restored. A few of the DFR factors are described below:

Hole Filling/Interference

This factor describes the type of fit between the fastener and the part. Higher inference leads to better fatigue properties. Rivets tend to be better in fatigue than bolts because the entire rivet can deform to have complete contact with the hole, thus providing better interference. When designing a repair, sometimes smaller holes are used to increase the hole filling capability in order to restore fatigue.

Material Clamp-Up

This factor refers to how tightly the parts are fastened together. Bolts that are designed for tension applications are able to squeeze parts together tighter, and, therefore, have better fatigue properties than bolts designed for shear. In repairs, shear bolts are often replaced with tension bolts to improve fatigue.

Surface Finish/Coldworking

This factor describes any prestressing a part might have had to increase fatigue capabilities. Often parts in high fatigue areas are shot-peened. Shot peening is the process of shooting round metal particles at a surface to produce a layer of compressive residual stress. While this factor is not used as often to improve repairs, it is important to consider if the part being replaced was previously shot-peened. Similarly, coldworking is the process of providing prestress around the edge of a hole. Coldworking is used quite frequently in the wing sections.

3.2.1 Case 1: Mislocated Hole

This first example is used to show how the above failure mode equations can be applied in a repair. A typical scenario to review is the case of a mislocated hole. Since each hole must be drilled by hand, it is quite common for a mechanic to accidentally locate a hole too close to the edge of a part. Figure 20 shows an aluminum angle part with a single row of fasteners. One of the holes was mislocated downwards, which resulted in a short edge margin to the edge of the part. Typically, holes are designed with an edge margin of two times the diameter (2D spacing) of the hole. In this case, the distance 0.36 in. results in a 1.44D edge margin.

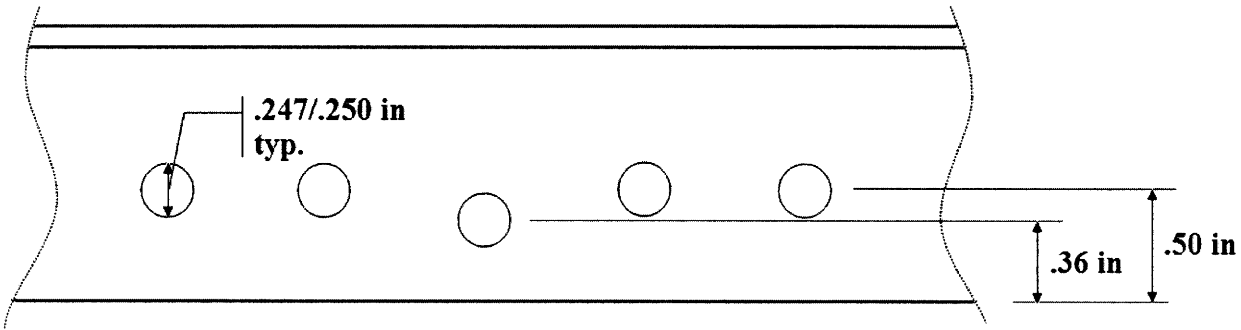


Figure 20: Mislocated Hole

The main concern for this type of problem is the ultimate strength capability. In order to analyze the severity of the problem, the "as designed" condition should be calculated first. The known information about this part is as follows:

7075-T6 Aluminum Angle

Part Thickness	.08 in
Bearing Ultimate Stress, F_{BRU}	110 ksi
Tension Ultimate Stress, F_{TU}	77 ksi
Shear Ultimate Stress, F_{SU}	46 ksi
Fastener Shear, $F_{SU|fastener}$	95 ksi

The "as designed" condition refers to the part's capabilities without any discrepancies. In this case, that means .250 in. diameter holes with a .50 in. edge margin for each hole. Using the four failure mode equations from above, the critical load case for one hole can be calculated. The results are shown in Table 3.

F_{BRU}	(110000psi)(.08in)(.250in)	F_{BRU} = 2200 lbs **Critical Case
F_{TU}	2(77000psi)(.08in)(.50in- .125in)	F_{TU} = 4620 lbs
F_{SU}	2(46000psi)(.08in)(.50in- .125cos40in)	F_{SU} = 2975 lbs
$F_{SU|fastener}$	(95000psi)(.0625π/4)	$F_{SU|fastener}$ = 4663 lbs

Table 3: Case 1, As Designed Condition

The "as designed" condition shows that the critical case is bearing failure at 2200 lbs. The next step is to analyze the part with the discrepant condition of .36 in. edge margin. Table 4 lists the results below.

F_{BRU}	(110000psi)(.08in)(.250in)	F_{BRU} = 2200 lbs
F_{TU}	2(77000psi)(.08in)(.36in- .125in)	F_{TU} = 2895 lbs
F_{SU}	2(46000psi)(.08in)(.36in- .125cos40in)	F_{SU} = 1944 lbs **Critical Case
$F_{SU|fastener}$	(95000psi)(.0625π/4)	$F_{SU|fastener}$ = 4663 lbs

Table 4: Case 1, Discrepant Condition

Due to the discrepant condition, the part will now fail in tear-out, and at a load less than the part was originally designed to handle. One option for fixing the problem would be to replace the part with a new one. However, if damaged parts were continually replaced, the total cost and overall schedule would suffer. Another solution would be to try and draw load away from the discrepant hole by over-sizing the fasteners around it, and thus increasing their load carrying capacity. This second solution is the more reasonable option and will be examined further. In order to calculate the advantage of over-sizing a fastener, the same calculations are repeated, but this time the next fastener size, .266 in. diameter, is used with the original .50 in. edge margin. The fasteners that would be oversized are the ones located on either side of the discrepant hole. The results are in Table 5.

F_{BRU}	(110000psi)(.08in)(.266in)	F_{BRU} = 2340 lbs **Critical Case
F_{TU}	2(77000psi)(.08in)(.50 in- .133in)	F_{TU} = 4521 lbs
F_{SU}	2(46000psi)(.08in)(.36in- .133cos40in)	F_{SU} = 2930 lbs
$F_{SU\|fastener}$	(95000psi)(.0708π/4)	$F_{SU\|fastener}$ = 5282 lbs

Table 5: Case 1, Repair Condition

The above calculations show that even with an over-sized fastener the failure mode is still bearing, which means that the repair method would be valid. For each over-sized fastener, the additional load carrying capacity is 140 lbs. (the difference between the bearing values from Table 5 and Table 3). However, the load capacity required to restore the strength is 256 lbs. (tear- out load from Table 4 minus bearing load from Table 3). Therefore, two over-sized fasteners will be necessary to complete the repair, one on either side of the mislocated hole. The final repair configuration is shown Figure 21.

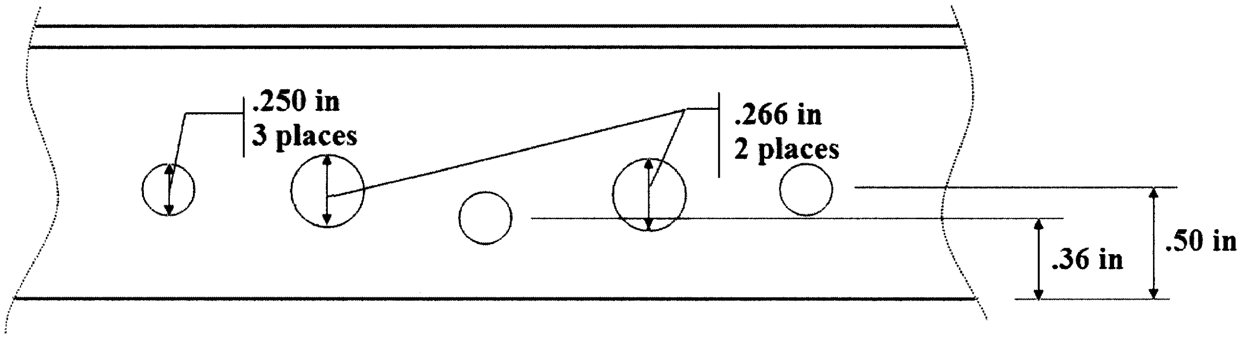


Figure 21: Repaired Mislocated Hole with Oversized Fasteners

3.2.2 Case 2: Repair Parts

The second example is similar to the first except now the short edge margin is at the end of the part instead of in the middle as shown in Figure 22.

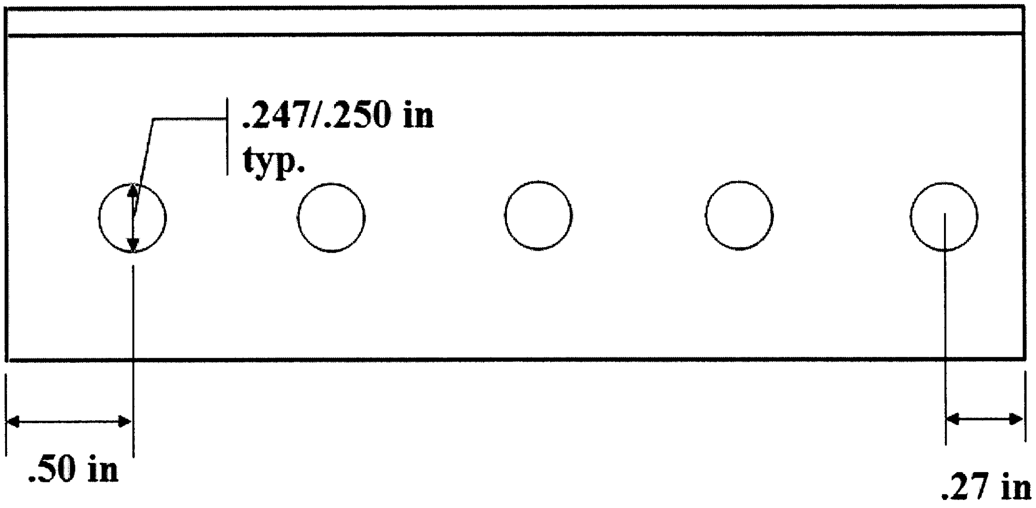


Figure 22: Short Edge Margin

Considering the repair options from Case 1, either replacing the part or over-sizing the surrounding fasteners, neither one is a good solution. Replacing the part will not fix anything because the hole has already been drilled through all of the parts in the stack-up. Therefore, the problem would still exist even if a new part was installed. Over-sizing the surrounding fasteners is also not a good option because the edge margin for this discrepant hole is 1.1D, and leaving a fastener in the hole might create problems with stress concentrations. A third option must be considered in this case which is to fabricate a repair part that increases the length. Within the factory, there are supply areas which store blank sheet metal, angles, channels, and numerous other repairs parts specifically for these cases. For simple problems, the mechanic can use one of these repair parts to quickly fabricate something that works and directly install it on the airplane. The repair part in this example would be an angle that had all the same properties and dimensions as the original except the length would be increased to provide adequate edge margin for the mislocated fastener.

3.3 Standard Repairs

In some instances, a problem comes up that is more complicated than over-sizing holes or designing repair parts, but is still considered relatively common. A standard repair manual (SRM) has been created that contains thousands of pages of allowable damage limits and standard repairs for the entire plane. Typically, this document is meant for the maintenance mechanics of individual airlines but it can also serve as a guideline for engineers inside the factory. These repairs have all been analyzed by a stress group which proves they are acceptable to use under the conditions stated in the manual. Below is an example of a standard repair.

3.3.1 Case 3: Stringer Splice

Stringers are the long stiffening members on the interior side of skin panels in both the fuselage and the wing. If any damage occurs in these parts, they are quite difficult to remove and would often cause more damage to the airplane. Instead, the practice is typically to perform a stringer splice repair, which removes only the damaged portion of the stringer and then replaces it with a splice. The SRM provides all types of stringer repairs depending on where the stringer is located in the airplane. For this example, a stringer located at the very bottom of the 42 section will be used. Figure 23 shows the dimensions of the stringer that has been damaged.

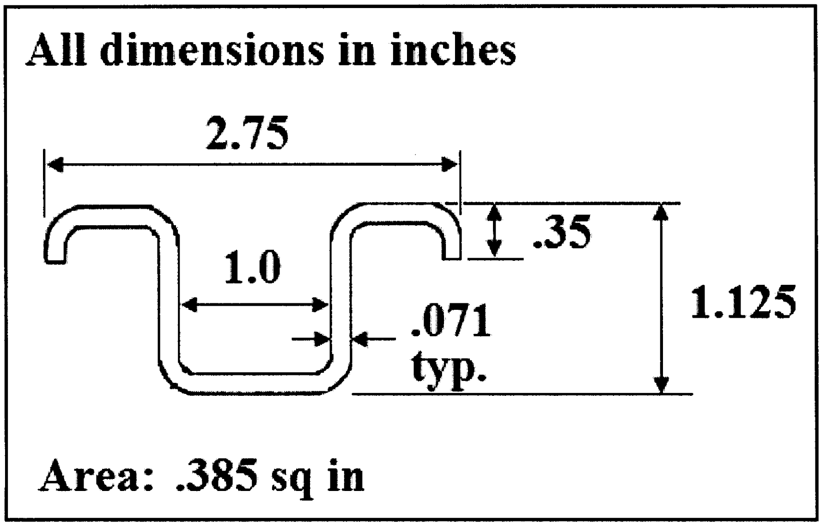


Figure 23: Stringer Cross Section

According to the SRM, for this type of stringer the following repair parts must be fabricated as outlined in Table 6 and located as shown in Figure 24.

Repair Materials		
PART	QUANTITY	MATERIAL
Splice (Hat Section)	1	7075-T6
Filler	1	7075-T6
Shim	4	2024-T3 or 7075-T6
Filler	1	7075-T6

Table 6: Stringer Splice Repair Materials

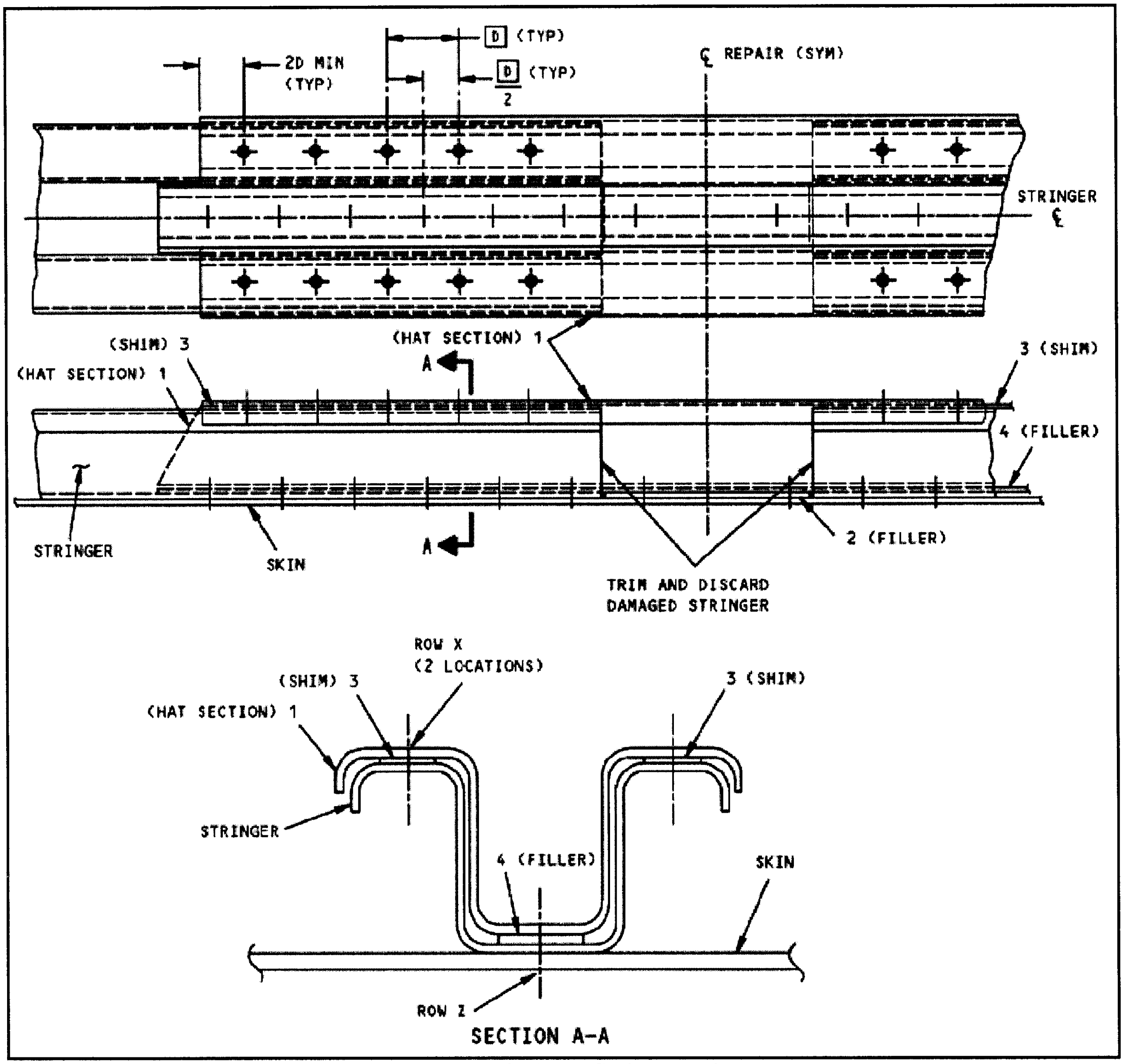


Figure 24: Stringer Splice Repair

Even though this repair has already been approved by a stress group, it is always advisable to check the calculations to make sure it's applicable to the current case. For this example, the damaged portion of the stringer has been cut out, and a replacement splice made of the same material and thickness is being used instead. The question that remains is if the load will be adequately transferred from the original stringer to the splice and back to the stringer through the fasteners. In order to determine how many fasteners are needed to transfer the load, the load carrying capacity of a single cross section is calculated. From Figure 23, the cross sectional area is .385 sq. in. Using the same material properties from Case 1, the ultimate tensile stress is 77 ksi. Multiplying cross sectional area by ultimate tensile stress results in a load carrying capacity of 29,645 lbs. That means that all the fasteners combined on one side of the splice must be able to withstand 29,645 lbs to be able to transfer that load to the other side. In order to calculate the number of fasteners required per side, the total load (29,645 lbs) is divided by the critical load case for the fasteners being used. If .250 in. diameter bolts are being used, the critical load as determined in the Case 1 example is bearing failure at 2200 lbs. This results in 14 fasteners required per side of the splice. As shown in Figure 24, there are actually 16 fasteners used on either side of the splice. The difference is that the SRM is using rivets instead of bolts which have a slightly lower bearing capacity, thus requiring two additional fasteners.

3.4 Significant Repairs

On occasion a problem is so significant that the MRB engineer cannot analyze it himself. The damage is too great and the ultimate strength or fatigue cannot be restored using the information available to him. In this case, a separate stress group is brought in to determine a solution.

Liaison Stress Group

The liaison stress group is a small group of engineers who provide stress analysis to all the MRB groups inside the factory. While a specific MRB engineer will only be responsible for one model airplane, the stress group works on problems for all the different models. The stress group does not have MRB authority, meaning that they cannot provide instructions directly to mechanics or sign off on the repairs. However, the stress group has access to the actual loads on the airplane, unlike the MRB engineers, so they can determine the real severity of a problem and propose an acceptable solution. The stress group is usually called when the area of the plane with damage is critical primary structure. One example might be when the centerline spacing of some fasteners is significantly smaller than the designed spacing on a fuselage skin panel. Another example, was a situation when two holes were drilled too close together to be left as two holes, and too far apart to be combined into one. The damage was located in the highest load bearing section of the wing. Ultimately, the stress engineers decided it was necessary to throw out the entire wing and start over from scratch. That example is an extremely rare case, but shows both the importance of having a stress group available for significant situations, and the commitment of the engineers to providing a safe airplane.

Significant Rework Log

The significant rework log (SRL) is a manual that is given to the customer after completion of the airplane that provides documentation of any significant repairs. A significant repair is one that might alter the configuration of parts as detailed in the SRM, or that requires a separate maintenance schedule. The SRL is crucial to maintaining the safety of the airplane as it brings special attention to parts of the airplane that need to be inspected more often. Not always, but often repairs that have been coordinated with the stress group become part of the SRL documentation.

4. Conclusion

The purpose of this assessment of airplane design, fabrication, and repair was to give an overall view of the entire process. The final stage of repairing problems as they occur during fabrication is rarely discussed, and, therefore, not often considered by new engineers. One of the most common complaints by mechanics is that the engineer was not thinking when they designed something a certain way because the part does not fit well or the installation is very difficult. The more likely explanation is not that the engineer was not thinking but that they simply did not know the problems the design would cause in production or that there might have been a better way. If design teams could spend more time talking with mechanics and the MRB engineers, the whole process might be better understood leading to more efficient designs. Likewise, MRB engineers spend much of their time repairing problems by the "tribal knowledge" method. Very little repair methodology has been explained, mostly because the documentation does not exist. If MRB engineers had more access to the design process, the repairs would become more efficient instead of the typical conservative, over-designed repairs used now. Ultimately, this type of cross discipline study needs to occur at the classroom level. Students should be exposed to both design and reverse engineering to fully understand how something works and to make them better engineers. The learning process could then continue into industry by allowing new engineers to participate in a rotation program that would shift them through different positions. This paper attempts to provide this type of well-rounded view for the design and build of airplane structures.

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6. Appendix A

The table below lists the critical material properties for each of the internal load cases. [15]

Design Property	Criteria Property	Critical Material Property	Property Evaluation
Static strength			
Tension	Structure must remain elastic to limit load and carry Ultimate Load. For composite materials, manufacturing flaws and Barely Visible Impact Damage (BVID) must be included	Fty, Ftu, Fbru OHT, FHT, NT	Fty – small hole out OHT – open hole tension Ftu – large hole out FHT – filled hole tension Fbru – Joint strength NT – notched tension
Compression		Fcy, Ec OHC, FHC, NC	Fcy – short columns Ec – long columns OHC – open hole compression FHC – filled hole compression NC – notched compression
Shear		Ftu, Fty, Fsu NC, NT	Ftu45, Fty45 – thin web Fsu – thick web NT – notched tension NC – notched compression
Durability			
Fatigue	Design service objective with high level of reliability	Fatigue strength, open hole, notched specimen, low load & high load transfer joint coupons	Low load and high load transfer joint coupons data most reliable for material evaluation For composite, cycling to validate no growth.
Corrosion		K1scc, SCC threshold and exfoliation rating	Heavy reliance on service experience
Damage Tolerance			
Crack Growth	Damage must be found before becoming critical. For composite material, structure must demonstrate no detrimental growth with visible flaw.	Fatigue crack growth characteristics CAI – compression after impact	Inspection intervals & methods
Residual Strength	Must carry limit load with large damage	Kapp, Fty, elongation H. - Composite fracture toughness CAI	Kapp for low Toughness or wide panels, Fty for high toughness narrow parts Hc for wide panels, CAI for local areas
Weight/Cost			
	Minimize within constraints	Density, material costs	Fabrication and maintenance costs must be accounted for