

## 19. Case Study of Aircraft Wing Manufacture<sup>1</sup>

*“Yeah. If that alignment is off, engineering comes down and designs us a shim. We have to wait 24 hours while they do the calculations. When the line is supposed to move every three days, that’s a disaster.”*

### **A. Introduction**

This chapter brings together most of the knowledge contained in prior chapters and shows how it was applied to the design of a proposed new assembly technique for a wing subassembly for a commercial aircraft. We will see in this chapter the application of Key Characteristics, the Datum Flow Chain, analysis of constraints and tolerances, and economic analysis. The processes proposed in this chapter have not been applied to the assembly described here, but many of the underlying principles have been applied to other products.

#### 1. How Aircraft Structures are Made<sup>2</sup>

Aircraft structural design is a subset of structural design in general, including ships, land vehicles, bridges, towers, and buildings. All structures must be designed with care because human life often depends on their performance. Structures are subject to one-way and oscillating stresses, the latter giving rise to fatigue. Metal structures are subject to corrosion, and some kinds of corrosion are accelerated in the presence of stress.

Aircraft structures are designed with particular attention to weight, for obvious reasons. If we could see beneath the interior fittings of passenger aircraft, we would see numerous lightening holes in the frames as well as regions where the skins have been thinned by chemical milling. On Boeing aircraft, it is not unusual to find regions as small as the palm of your hand with their own thickness, and four or more individual thicknesses are often found on a single skin. These regions differ in thickness by as little as a millimeter or two, indicating that considerable effort is expended to find regions that are too lightly stressed. Such regions are deliberately made thinner to remove metal that is not doing its share of load-bearing.

The first aircraft had two wings made of light weight wood frames with cloth skins, held apart by wires and struts. The upper wing and the struts

---

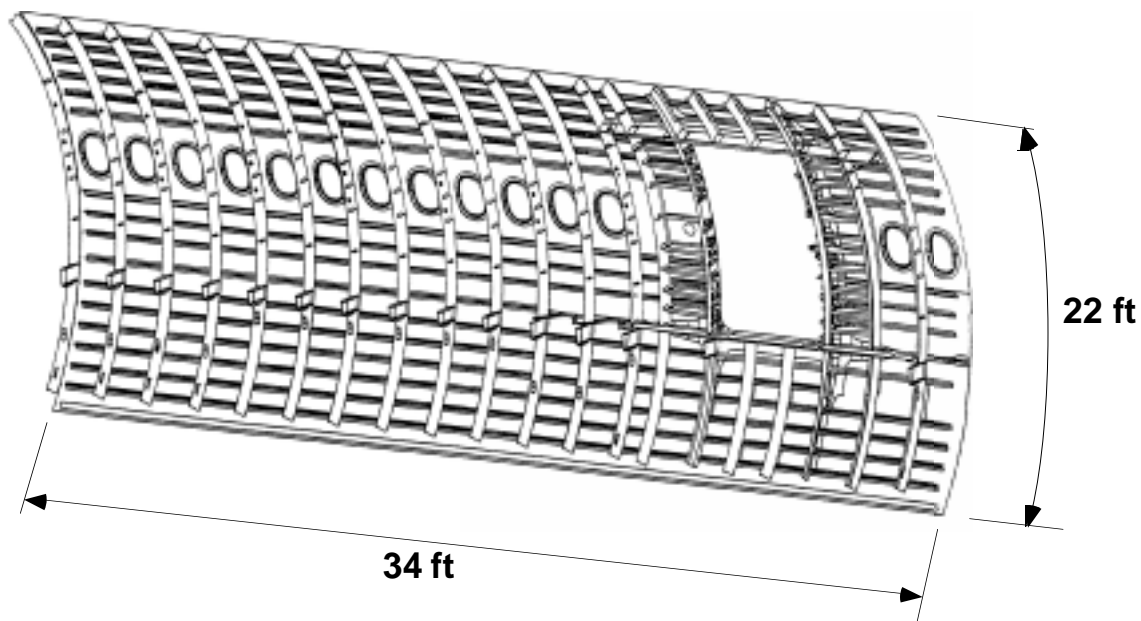
<sup>1</sup> This chapter is based in part on [Cunningham, et al]. The cooperation of Vought Aircraft and Boeing Commercial Airplane Company is gratefully acknowledged. The work reported in the above-referenced paper was supported by the U S Air Force Materials Laboratory, whose support is also gratefully acknowledged.

<sup>2</sup> [Niu a] and [Niu b] contain examples of many kinds of aircraft structures.

provided compression support while the lower wing and the wires supported tension loads.

In the 1920s, metal began to be used for aircraft structure. A metal wing is a box structure with the skins comprising the top and bottom, with front and back formed by I-beams called *spars*, interior fore-aft stiffeners called *ribs*, and in-out stiffeners called *stringers*. In level flight, the lower skin is in tension while the upper skin is in compression. For this reason, this design is referred to as *stressed skin* construction. During turbulence, upper and lower skins can experience both tension and compression. This box structure is able to support the above-mentioned moments, making single wing aircraft possible. The elimination of the struts and wires so dramatically reduced air drag that aircraft were able to fly twice as fast as before with the same engine.

While steel was used for a few aircraft in Germany in the 1930s, the metal of choice was, and still is, aluminum. Figure 19-1 shows an aluminum aircraft fuselage skin subassembly.



**Figure 19-1. Typical Metal Skin Aircraft Fuselage Assembly.** This structure consists of a skin to which have been riveted longitudinal stiffeners (along the 34 ft direction) called stringers. Along the circumferential (22 ft) direction, there are stiffeners called frames. Each stringer-frame intersection is joined by a small piece called a clip. (Drawing from NASA CR-4730.)

While automobile structures are spot welded and ships are arc welded, bridges, buildings, and aircraft are riveted or bolted together. Rivets are the preferred fastening method in bridges and buildings mainly because such joints provide some structural damping via internal friction in the rivet-hole and plate-plate interfaces. This damping reduces vibrations and oscillations.

Spot welding is practical for automobile bodies. It is fast, repeatable, and strong. Laser welding is sometimes used on long edge-edge joints in auto subassemblies because the weight of the overlapped regions of conventional joints is saved and such joints are easy for a laser to access via line-of-sight. Arc welding is rarely used in aluminum because the region around such joints reaches a high temperature and this destroys desirable material properties created by prior rolling and heat treatment. Spot welding is also rare in aluminum because the ever-present tough aluminum oxide on the surface prevents good electrical contact. As a result, rivets and bolts are used exclusively for aircraft structural joints.

Rivet and bolt joints in aircraft are the critical element in airframe integrity. Great care is expended on creating these joints because they are subject to high stresses. The holes are drilled with keen attention to making their axes normal to the skin surface and their diameters correct. In highly-stressed regions of the wing, each hole is manually reamed out to pre-stress the region around the hole. Each rivet or bolt is compressed or torqued precisely in order to achieve the stress-carrying capability intended by the structural engineers. Rivet diameter and compression are calculated to ensure that the installed rivet not only completely fills the hole but also creates compressive stress in the surrounding material. If there is any possibility that drilling a hole will leave a burr on the back side, this burr must be manually removed because it could puncture the corrosion-resisting paint when the skins are pulled together by the fastener.

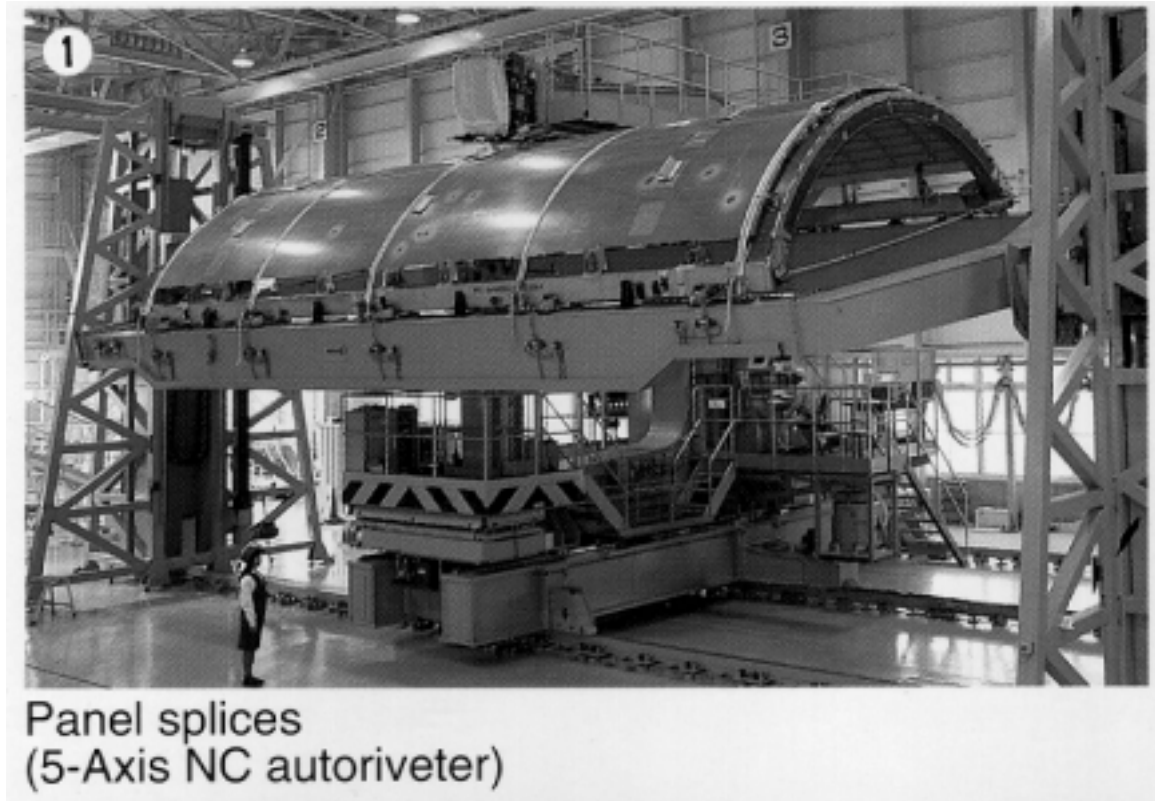
Structural engineers take care to choose the size of the fastener to support the stresses it is expected to bear. The same is true of skin thicknesses, as mentioned above. On an aircraft wing, the skin may be as much as ten times thicker at the root than it is at the tip. The diameter of fasteners varies similarly, with diameters as large as your thumb at the root and as small as 3 or 4 mm at the tip. Such specialization raises the cost because it reduces economies of scale in purchasing and inventory control, but it saves considerable weight.<sup>3</sup>

Rivets and bolts are two-side fasteners, meaning that some operations required to install and tighten them require a tool on both ends of the fastener. While one-side rivets exist, they are not used in high stress applications. Machines exist that can apply both bolts and rivets to aircraft structure as long as both sides are easily accessible. Examples are in Figure 19-2 and Figure 19-3. They are most applicable to flat or nearly flat

---

<sup>3</sup> In automobiles, analysis of the tradeoff results in the opposite conclusion. If every fastener is engineered to be exactly the right size, costs rise because quantities of any given size are low. If a fixed catalog of fasteners is put in place, every chosen fastener will be the next size larger than what is really needed, but huge quantity buys will drive down the price. For one US car firm, the savings amounted to \$1B annually and increased the weight of each car about 1#. [Gordon Willis, private communication.]

subassemblies such as wing skin and fuselage panels. These machines have a C-clamp or traveling beam architecture that can reach around or surround the structure and apply sufficient force for compressing a rivet. The machines have working heads with multiple tools that drill, chamfer, and ream the hole, then lubricate, install, and tighten the fastener.



**Figure 19-2. An Automatic Fastening Machine for Aircraft Manufacture.** A skin subassembly similar to that shown in Figure 19-1 is being riveted together after being assembled in a fixture and tacked together with temporary fasteners. (Photo courtesy of Kawasaki Heavy Industries.)

To complete the assembly of wings and fuselage structures, people must drill each hole and insert each fastener individually, deburring when necessary. Tens or even hundreds of thousands of fasteners are installed this way on every airplane. The work is tiring and noisy, and is one of the main cost components of aircraft manufacture. A good deal of thought, including the work in this chapter, has been expended trying to reduce this cost and speed up this phase of aircraft manufacturing.

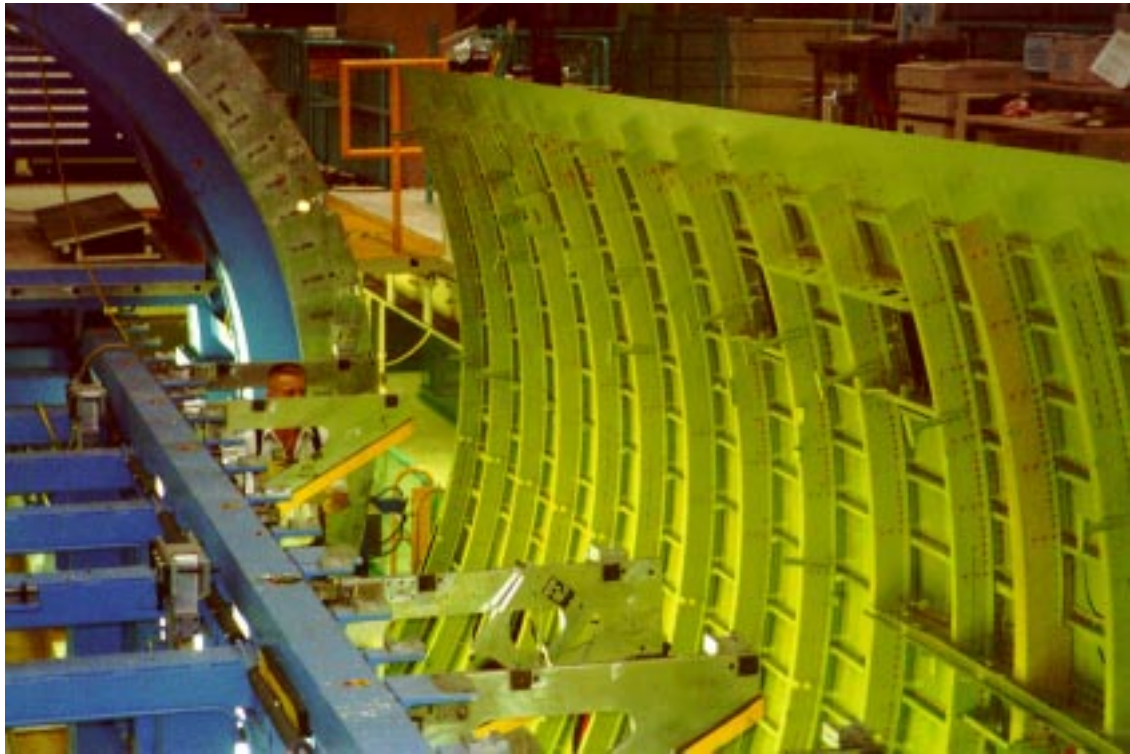


**Figure 19-3. Closeup of Automatic Drill and Rivet Machine.** (Photo courtesy of Gemcor Systems)

As indicated in Chapter 8, assembly of aircraft (as well as other shell structures like ships and automobiles) is accomplished in part by means of fixtures. One such fixture appears in Figure 19-4. These fixtures hold the parts in position while at least a few fasteners are installed or welds are made. These are often called *tack fasteners* or *tack welds*. In many cases, they are removed in the process of installing the final fasteners or welds. Tack fasteners are able to keep the parts in their desired relative locations when they are removed from the fixtures and taken to the fastening machines. The tack fasteners are installed in aircraft structure by drilling through precisely



located drill bushings that are part of the fixtures. When the assemblies become too large to move while only tack fastened, they are given their final fasteners while attached to the fixtures.



**Figure 19-4. Typical Aircraft Assembly Fixture.** This fixture aids the joining of several fuselage skin subassemblies. Portions of the fixture are blue. (Photo by R. Mantripragada. Used by permission.)

These fixtures provide the mates that comprise the DFC for these parts, subassemblies, and final assemblies. As such, they are required to be very accurate. Heavy assemblies are placed on them by overhead cranes several times a week, causing an inevitable amount of shock and wear on the mate surfaces. It is therefore important, and costly, to measure and adjust them frequently. The fixtures are obviously large for large products like ships and aircraft, and manufacturing space is limited. The fixtures are also specialized to the subassembly or assembly they build, so they represent a fixed cost and have what economists call *asset specificity*. All this means that their owners are at a disadvantage. They cannot use the fixtures for anything else, meaning that they are dependent on their customer for continuing business. The space taken up by these fixtures cannot be used for anything else, and a dedicated crew of people is needed to learn and operate each one. Hence the fixtures represent another target for process improvement, and this is the main focus of the case study in this chapter.

Bridges and buildings are assembled by riveting or bolting together beams that have pre-drilled holes in them. Figure 19-5 shows the end of one such beam. These beams are often multi-part assemblies that have been cut out by numerically controlled flame cutters and welded together at a factory. The assembly holes are drilled there as well, and form a square or rectangular array containing as many as a dozen holes that are drilled all at the same time by cluster drills. These beams are transported to the construction site, often hundreds of miles away, where they are hoisted into position by cranes and the holes are nudged into alignment by steel-workers using thin tapered rods. Once the holes are aligned, the bolts are inserted and tightened.



**Figure 19-5. End of Typical Beam Used in Construction of Tall Buildings.**  
(Photo by the author. Thanks to Bovis Corporation, Marr Corporation, and Ironworkers Local 5.)

## 2. Remarks

The foregoing may appear to be general knowledge of only passing interest, but we can relate it tightly to what has gone before in this book as well as to the case study that follows. The connections we will make include Type-1 and Type-2 assemblies as well as integral and modular product architectures.

It should be clear that aircraft structures are Type-2 assemblies because fixtures are required. There are many reasons for this, mainly due to the prohibitive cost of trying to make such large and temperature-sensitive assemblies to tolerances as small as  $3 \times 10^{-4}$  on a relative basis. Such fine tolerances are needed in many cases in order to achieve, or try to achieve, low levels of locked-in stress. The structures are relatively stiff, and any small deformations are usually eliminated by bending the structures, a process that naturally induces stress. These stresses detract from flight loads, so they are avoided if possible. Boeing seeks to avoid such stresses by building the structural elements with many slip joints and by ensuring that there is empty

space at maximum material in many joint locations. These spaces are filled by peel-apart shims (similar to Post-It<sup>tm</sup> Notes but made of thin sheets of metal) until the gap is so small that it can safely be pulled together by the fastener. Airbus makes its structural parts by NC machining them from solid aluminum blocks. These are supposed to be sufficiently accurate that they fit without shimming, but occasionally some liquid shim is used. The objective of reducing locked-in stress is the same.

It should also be clear that bridges and buildings are Type-1 assemblies. The materials are thick and rugged, and the thermal expansion coefficient is half that of aluminum. The requirement to fill the fastener hole is not as critical as it is on aircraft, so a little clearance is permissible. There is also less need to conserve weight, so redundant fasteners and thick material sections can be used to achieve strength and durability. Even so, the accuracy achieved on hole patterns is remarkable. These patterns obviously fill the role of assembly features, and these structures are put together rapidly in true Type-1 style by simply joining the parts at their features.

The stressed-skin wing is an integral design, contrasted with the wood, wire, and cloth wing which is a modular design. In the latter wing, each functional requirement was met by a different physical element: compression resistance was provided by the struts, tension by the wires, and airfoil shape by ribs with cloth stretched over them. The resulting open truss structure created high air resistance, as mentioned above. In the metal wing, compression and tension resistance are both contributed by the skin, something cloth cannot do. The amount of other material needed to support such stresses can therefore be reduced, saving weight. Also, the box structure created by skins, spars, and ribs provides space to carry fuel. There need be no separate fuel tanks as there are on cloth-wire-strut aircraft. It is necessary to carefully seal all the surface-to-surface joints in the metal structure where fuel is to be carried, of course. Thus, in true integral design style, the elements of a metal aircraft wing perform multiple functions.

### 3. Possible Future Manufacturing Methods

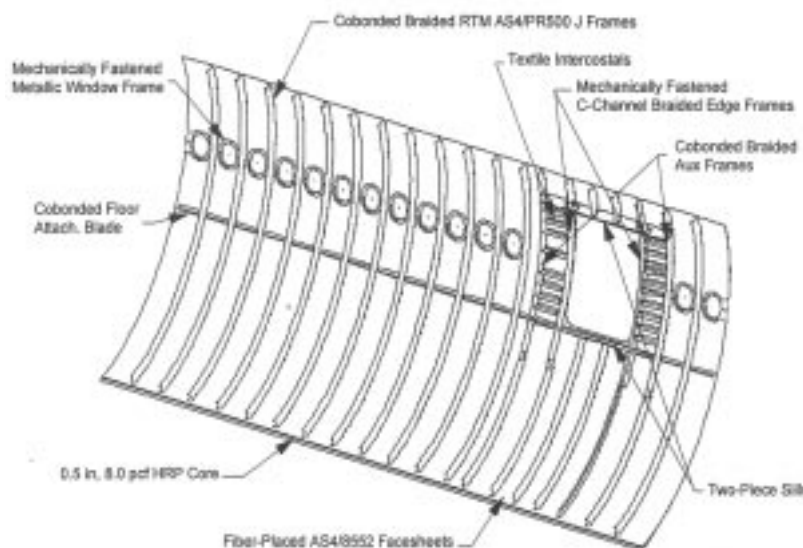
Given what we know about the advantages and disadvantages of current aircraft manufacturing methods, it is not surprising that efforts are under way to enhance the advantages and reduce the disadvantages, mostly by reducing the amount of manual labor and the specificity of the fixtures. The weight of the parts and assemblies requires some kind of support so that they do not collapse, so fixture-like structures will still be necessary, but they might not need to be as accurate or as dedicated to one item as they are now. Two major trends are being pursued. One of these is a shift toward composite materials, while the other is a broad attempt to convert aircraft structures from Type-2s to Type-1s.



### a) Substitution of Composite Materials

Aircraft structures can be made of carbon fiber epoxy composites. Figure 19-6 is a drawing of a fuselage skin subassembly made of composites. These materials are extremely strong and light. They comprise long fine carbon fibers immersed in a so-called matrix of epoxy. In its uncured state, the epoxy is sticky, soft, and pliable. In its cured state, the epoxy is hard and rigid. Curing involves heating the epoxy until a chemical reaction begins. This reaction provides additional heat and converts the epoxy into its final physical and chemical form. The epoxy holds the carbon fibers in place relative to each other and provides some compressive strength while the fibers provide tensile strength.

One of the other important advantages of composites is that they can be assembled into large structures by bonding rather than riveting. In the *co-curing* method, preformed uncured parts are placed surface to surface on a carefully made mold, squeezed together with a vacuum bag, and placed in a large pressure vessel called an autoclave. Here they are subjected to high pressure and temperature while the epoxy cures. In the *co-bonding* process, preformed and pre-cured parts are glued together with epoxy, and the glue joints are cured using the vacuum bag and autoclave method.



**Figure 19-6. Drawing of Example Composite Aircraft Fuselage Skin Assembly.** Note that this structure does not have any stringers. The fibers have been oriented to support the loads normally carried by stringers. (Drawing from NASA CR-4735.)

Cost is the main barrier to use of carbon fiber composites in aircraft. They can cost from \$60 to \$400 per pound, compared to \$0.33 for steel and

\$1.00 for aluminum.<sup>4</sup> The main cost element is the fiber. In automobiles and recreational boats, glass fibers are used with epoxies and other polymers. These support much lower stresses but are sufficiently strong and stiff for those applications. They cost much less and are quite economical for those products.

Another component of the cost is the molds. These are usually made of Invar or another material with very low thermal expansion coefficient in order that the curing process does not introduce size or shape variations.

A third significant cost component is layup, by which is meant placing uncured composite materials onto the mold. This can be done by NC machines if the shape is flat or nearly flat, such as a wing skin, but is mainly done manually.

A fourth cost is rework and repair. Composite parts are made in layers, and a major potential failure mode is delamination, or interior separation of the layers due to such causes as gas bubbles or insufficient bonding. Ultrasonic inspection is used to find such flaws, and increasingly they can be repaired even in thermosets. The process is still very costly, however, and the prospect of generating a flawed large assembly that becomes expensive scrap is a deterrent. This is ironic inasmuch as the ability to produce a large assembly all at once is one of the most attractive features of composite construction.

Even though large subassemblies can be made all at once in an oven, final assembly still requires drilling holes and installing fasteners. This is just as critical and costly as in metal structures. Furthermore, the structural engineers worry every time a hole is drilled and fibers are cut. In some cases, the parts can be glued together.

The parts and subassemblies at this stage are remarkably rigid. If they do not fit properly, it is not feasible to use the fasteners to draw them together. While solid or liquid shims are the only recourse, they reduce the strength of the structure and dilute many of the advantages of the method. Only small errors can be corrected this way. Therefore, part and subassembly size and shape accuracy are essential, and great effort is expended on molds and process control to achieve the necessary accuracy.

## **b) Conversion from Type-2 to Type-1**

If aircraft parts could be made the right size and shape, with accurate assembly features on them, they could be tacked together to achieve the desired final assembly dimensions and relationships just by joining these

---

<sup>4</sup> These are typical prices for generic materials in 2000. Aircraft quality aluminum costs more, but nowhere near the cost of carbon fiber epoxy materials.

features. They could then be given their final fasteners the same way as before. The savings would arise from the elimination of the accurate and specific fixtures. While progress has been made on this, no one believes that every fastener hole can be pre-drilled as is done in buildings. The holes in aircraft must be essentially exactly opposite each other or else the fastener cannot fill the hole. It will then wobble when exposed to oscillating shear loads normal to its axis and will rapidly enlarge the hole until it cannot carry any load at all. The only way known to achieve sets of many holes that are exactly opposite each other is to match drill them while the parts are clamped together in the correct relative positions. Thus the focus of attention for new aircraft assembly processes is on tack fastening to create mates that pass dimensional location and constraint between the parts. Achieving this would create Type-1 aircraft assembly.

The advantages would be considerable. Aircraft are made from thousands of structural parts, some as small as a playing card, others as large as 30x6m. With exceptions to be described below, these are all assembled by placing them in dedicated fixtures, match drilling holes using drill bushings in the fixtures, and then installing the fasteners. Thus there are hundreds or thousands of these fixtures, stored in racks, hanging from the overhead, stashed in warehouses and closets. Keeping track of them is a burden, as is inspecting and repairing them.

Over the last decade, most airframe manufacturers have addressed the problem of making the parts with sufficient accuracy that the tack holes line up. All approaches include the use of NC machines of one kind or another to drill the tack holes in the parts. In some cases, the parts involved are made by different companies, adding the usual supply chain issues to the already challenging technical problems. NC equipment is programmable, and an attraction of this method is that different parts for different aircraft or customers could be made on the same equipment, reducing the burden of asset specificity.

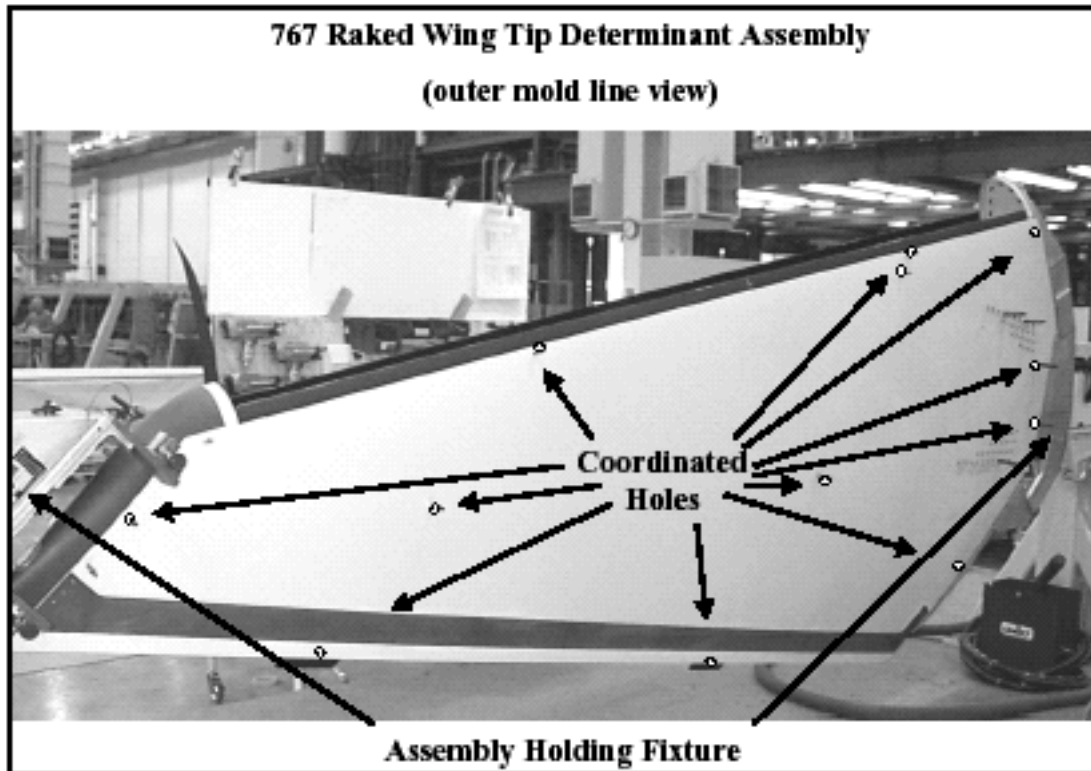
Boeing initiated its efforts some years ago with programs called FAIT and AFPAC. [Munk and Strand] Northrop-Grumman Vought Division had an effort called "precision assembly," while the term "hole-to-hole" assembly has also been used by Boeing and others in the industry. Kawasaki Heavy Industries (KHI), a major airframe subcontractor and equity partner with Boeing on large aircraft, has applied precision assembly techniques to the first few stages of fuselage assembly as well as to assembly of wing parts.

For example, KHI installs longitudinal stiffeners (called stringers) onto aircraft fuselage skins using this method. The skins, already bent to final contour, are placed on an NC drilling machine that is temperature compensated. The machine drills hundreds of tack-mounting holes for the stringers, spaced perhaps 20cm apart along each stringer. A supplier makes

the stringers and drills corresponding holes in them, using another temperature-compensated machine. One hole at one end of each stringer is drilled the same size as holes in the skin, while the other stringer holes are somewhat larger. The end hole thus acts as the main determinant of the stringer's location on the skin, while the other holes, being larger, do not create any over-constraint even if there is some variation in hole position. Small one side aluminum pop rivets are installed to tack the parts together. The tacked assembly is placed in an NC drill-rivet machine that installs the final fasteners, drilling out and discarding the tack fasteners as it encounters them.

Using our terminology, the sized hole at the end of the stringer is a mate while the enlarged holes are contacts. The main KCs evidently are the longitudinal position of the stringer along the skin and the straightness of the stringer. A secondary KC is the circumferential location of the stringer. These are readily achieved by the method used.

Figure 19-7 shows assembly of skins, ribs, and spars of a new wingtip for 767 aircraft. [Swanstrom and Hawke] A fixture is used to drill coordination holes in the skin. These holes, rather than conventional fixtures, are used to locate the ribs and spars with respect to the skins. Additional fastener holes are drilled after the parts are coordinated. Fewer tools and fixtures are needed and assembly is faster, saving a substantial amount of money. A DFA study was also employed to reduce the number of parts and thus the number of coordination holes and fasteners. Part count was reduced mainly by combining large numbers of small composite parts into fewer larger ones. The original design had 236 parts while the final one has 82. Assembly efficiency defined as the ratio of theoretically necessary parts to actual parts increased from 5.9% to 17.1%.



**Figure 19-7. 767 Raked Wingtip Assembled with Minimal Use of Assembly Fixtures.** [Swanstrom and Hawke]. The wingtip skin (white part) is composite with coordination holes drilled using a fixture. Ribs and spars (black parts) join the skin via these holes, which act as mates. Additional fastener holes are added later and act as contacts. In conventional aircraft assembly, these parts would be positioned relative to each other by another fixture; fastener holes would be drilled through all the parts, using this fixture as a guide, while the parts were clamped, and fasteners would be put through these holes. (Reprinted by permission from the Society for the Advancement of Material and Process Engineering (SAMPE).)

All of these efforts, as mentioned, make use of NC equipment plus various temperature compensation techniques. A generous mixture of mates and contacts is also used, as will be illustrated below. NC equipment is used because it can be programmed accurately to make different cuts or drill different holes. Its flexibility reduces its specificity. One machine can make many kinds of parts. This is the original attraction of flexible manufacturing equipment.

The same problems arise, however, as arise with other flexible equipment. It is generally more expensive than dedicated equipment and of course has a maximum throughput limit. When that limit is exceeded, another machine is required. Also, many companies fail to appreciate the cultural, skill, and knowledge differences that lie between use of fixtures and



use of NC equipment. Fixtures are rugged and constant. They can take some abuse and behave the same way all the time. NC equipment is part of the world of software, containing sensors, actuators, and computers. It requires a different sensibility on the part of the shop floor workers than fixtures do. Finally, a Type-1 approach to aircraft assembly requires shop floor workers to be more familiar with what happens at adjacent work stations as well as what happens in the fabrication shop where the assembly features are put on the parts. If the required communication and cooperation do not exist, problems will be harder to find and fix.

With that as the prolog, we are in a position to understand the complexity of the case presented below.

### ***B. Boeing 767 Wing Skin Subassembly Case***

#### **1. Management's Objectives**

Vought Aircraft has been a supplier to Boeing for many years, as discussed above.<sup>5</sup> When the 777 was being designed, Vought bid for production of the tail sections but was not selected. There were many reasons, including the fact that Vought was not considered cost-competitive. However, Boeing had good reasons for sending the work elsewhere, such as strategic outsourcing to countries such as Australia, which wanted to learn about aircraft production and where Boeing felt the long range 777 could be sold. As a result, Vought turned its attention to reducing its manufacturing costs and launched a precision assembly project as part of that effort. Vought had recently committed to lowering its prices to Boeing and this added pressure to lower costs.

Vought makes tail sections and horizontal and vertical stabilizers for Boeing 747, 757, and 767 aircraft. Order quantities for these aircraft are constantly changing, and Vought wanted to be able to shift production capacity, personnel, and floor space from the ones with falling production rates to those with rising ones. In no case are the production quantities large by automotive standards. To date about 1200 747s have been made in about 30 years, with similar numbers of 757s and 767s over about 20 years. A flexible assembly capability would improve Vought's ability to meet shifting demand. Also, it might enhance its image as a technically capable manufacturer. Precision assembly therefore promised to meet several top-level corporate objectives.

Our group at MIT, with funding from the Air Force, made contact with Vought through the Lean Aerospace Initiative<sup>6</sup> at about the time Vought was

---

<sup>5</sup> This company was a division of Northrop-Grumman at the time of the study on which this chapter is based.

<sup>6</sup> The Lean Aerospace Initiative is co-funded by the Air Force and the aircraft industry.

launching its precision assembly project. MIT was generously allowed to carry out its own precision assembly study side by side with Vought's on a non-interfering basis. Both Vought and MIT learned a great deal from each other in this process. The story that follows describes only the MIT process and its outcomes.

## 2. The Assembly and its Key Characteristics<sup>7</sup>

The MIT and Vought projects focused on the 767 horizontal stabilizer wing, with emphasis on the wing skin subassembly. The entire wing is currently made as a Type-2, and current methods generate products that are entirely satisfactory to Boeing. While the focus was on the skin, it soon became clear that this subassembly could not be considered in isolation from the larger assembly of which it is a part, because of the KCs and how they are delivered. This realization caused us to distinguish two kinds of KCs, which we called Product KCs (PKCs) and Assembly KCs (AKCs).<sup>8</sup>

The PKCs are requirements of the final wing assembly, while the AKCs are KCs for the wing skin subassembly. Achievement of the AKCs is necessary for the achievement of the PKCs. However, AKCs are to some degree dependent on the assembly process used to make the skin, while PKCs are customer requirements and thus do not change regardless of the process. Design of the wing skin process therefore included identifying and achieving suitable AKCs in support of the over-arching PKCs. Lengthy discussions with Boeing and Vought personnel plus many plant visits and study of the parts and fixtures over several months were required in order to identify the PKCs as a prerequisite to proposing any new processes.

Proper design of a new process also includes adequate understanding of the process it is intended to replace, so that the new one will do everything necessary that the original one did, only better. This in turn required us to reverse engineer the existing Type-2 process in order to determine what its AKCs were. None of the personnel who had designed that process or its fixtures 20 years ago were still employed at Vought, and few records of their design intent survived. All we knew was that the fixtures we saw in use were not the originals, which, for some reason related to datum coordination, did not work satisfactorily. No further details about the existing fixtures were

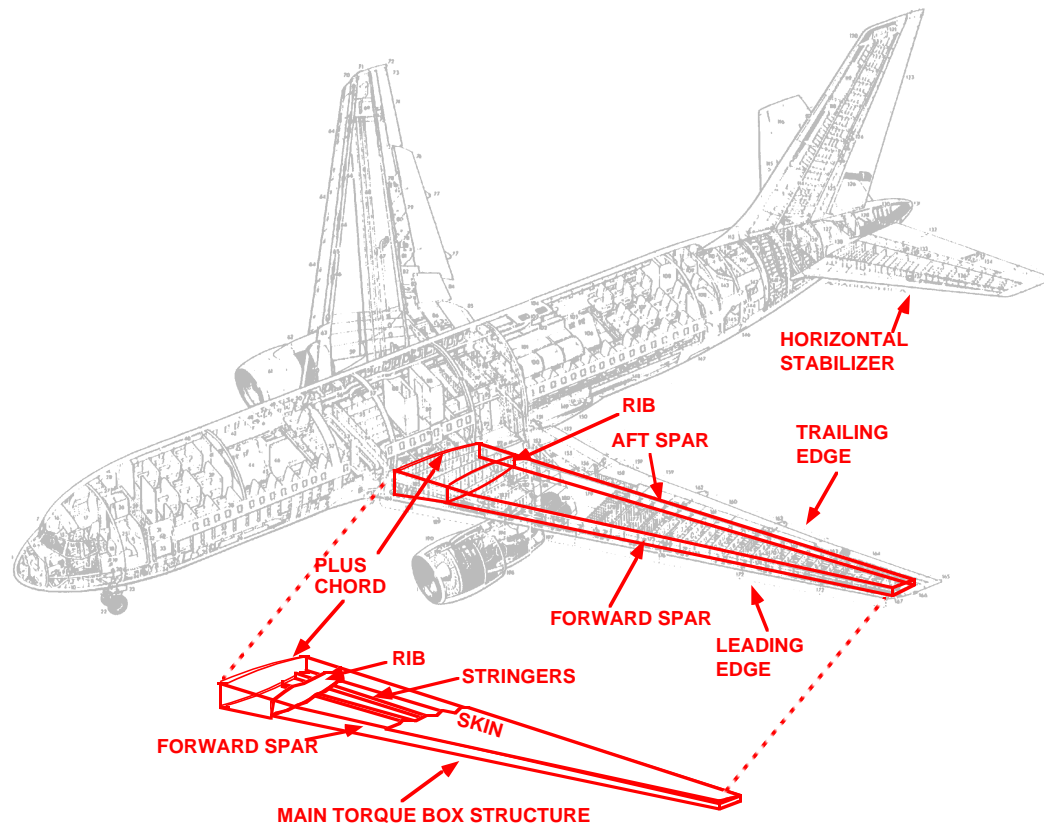
---

<sup>7</sup> This section is based in part on an unpublished study by Don Lee.

<sup>8</sup> At the same time as we were conducting the Vought study, a companion MIT study, also funded by the Air Force, was at General Motors Delphi Saginaw Steering Division (now Delphi Automotive Systems Corp.). Delphi had at that time identified two levels of KC, the KCC or key customer characteristic, and the KPC or key process characteristic. Statistical process control was applied to KPCs in order to achieve KCCs.

available other than their acquisition costs, which were used in our economic analysis.<sup>9</sup>

Figure 19-8 shows a cutaway diagram of a 767 aircraft. The parts of interest to us are called out on the wing for ease of visibility, but the horizontal stabilizer is a scaled-down version of the wing and has all the same main structural parts with the same names. These include upper skin, lower skin, ribs, stringers, spars, and plus chords. These elements form the main torque box, a beam structure that supports the structural loads on the wing. (See Figure 19-14 for another view of how spars, skins, and ribs form the main torque box.) The plus chords are splice elements that connect the wing to the aircraft fuselage. Also shown are the non-structural leading and trailing edges. On this aircraft, the leading edge assembly is called the forward torque box (FTB) while the trailing edge segment of interest is called the fixed trailing edge (FTE). The moving trailing edge, or elevator, attached to the FTE, is not of interest to this case.

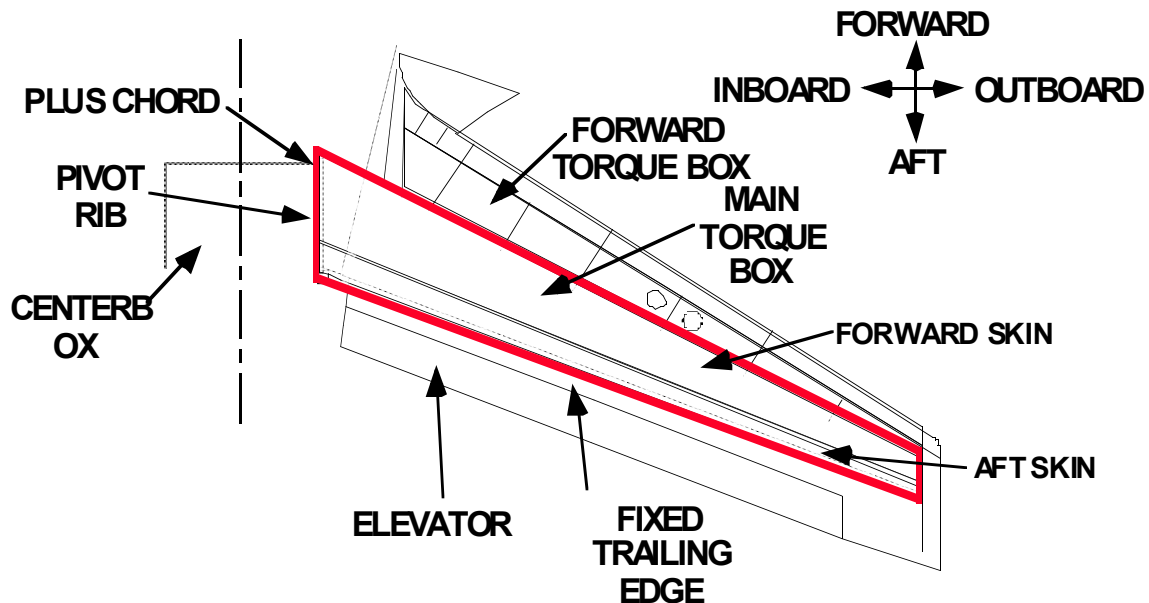


**Figure 19-8. Cutaway Drawing of the 767 Aircraft.** The main torque box structure bears the loads of the wing. It comprises upper and lower skins,

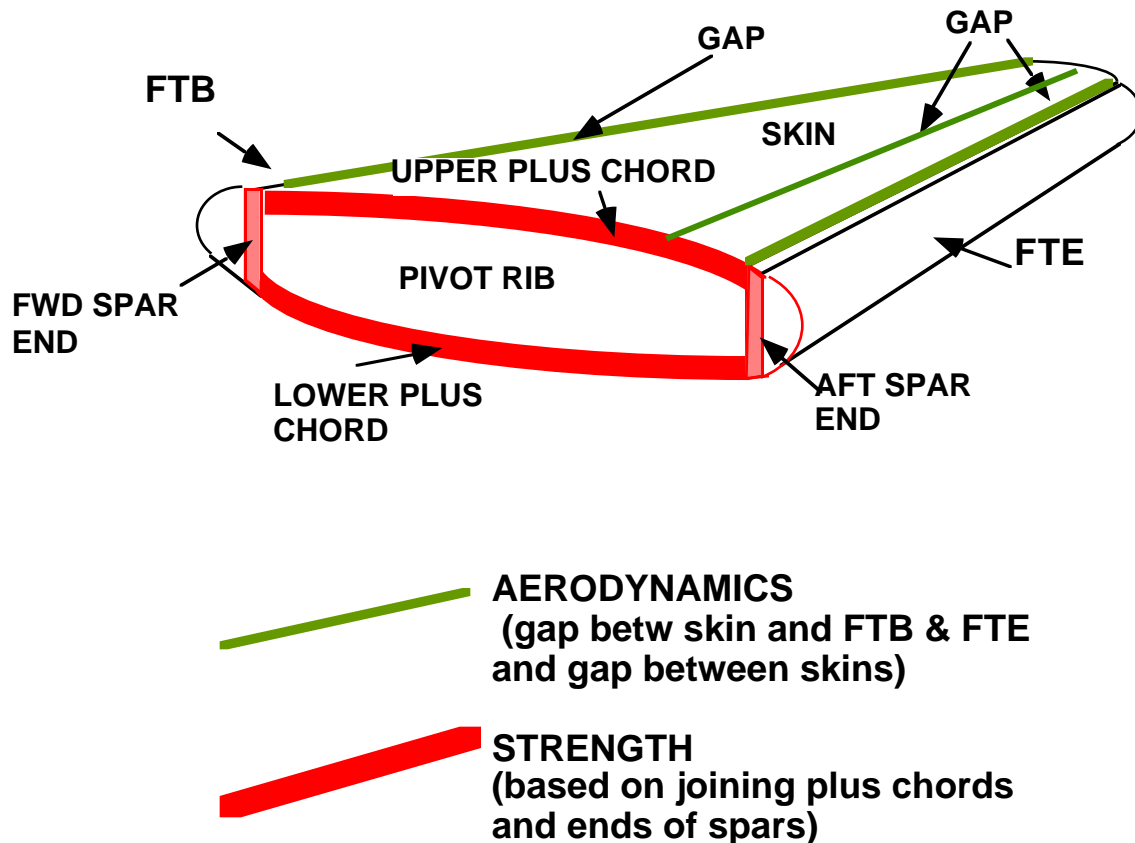
<sup>9</sup> None of these negative-sounding details is unusual. Absence of documented assembly design intent is one of the reasons why this book was written.

forward and aft spars extending longitudinally from inboard to outboard, ribs extending fore and aft, and longitudinal skin stiffeners called stringers. (Drawing courtesy of Air International. Used by permission.)

Figure 19-9 shows the horizontal stabilizer while Figure 19-10 and Figure 19-11 show the main PKCs of interest to us. These PKCs are of two types, aerodynamic and structural. The aerodynamic ones comprise gaps between adjacent pieces of the skin, whose segments essentially wrap all the way around the wing. The FTB and FTE each have skin segments, while the lower skin is one piece and the upper skin comprises two pieces spliced together by one of the stringers. There are therefore five skin gaps. The tolerance on the size of these gaps requires them to be between about 2mm and 4mm wide. The structural PKCs involve the integrity of the inboard rib structure, comprising the upper and lower plus chords, the innermost rib, called the pivot rib, and the ends of the spars. All tension and compression loads from the wing are carried into the center box inside the aircraft by the joints between the center box and the plus chords. Loads carried by the skins go directly into the plus chords at their respective joints, while loads carried by the spars go in indirectly by means of their joints to the plus chords. An important PKC is the alignment of the ends of the plus chords to the ends of the spars, so that splice plates can be installed flush across these joints and transfer the load. The quote at the beginning of the chapter refers to this joint alignment on a wing.



**Figure 19-9. Top View of Horizontal Stabilizer.** The solid (red) outline indicates the boundaries of the structural wing box. The stabilizer is more than 10m long and 3m wide at the inboard end.

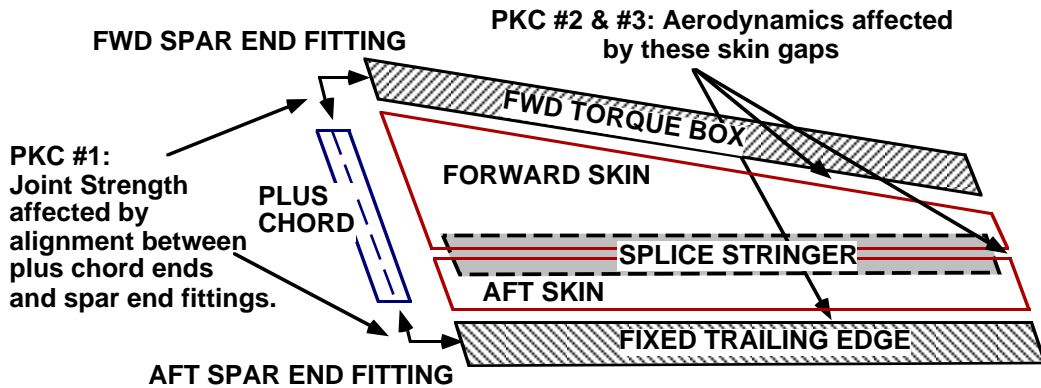


**Figure 19-10. Main PKCs of the Horizontal Stabilizer.** In this figure, two classes of PKCs are indicated using different colors. The green lines represent skin gaps, that is, places where adjacent skin segments meet and where a gap within a certain size range is required. These gaps are controlled for aerodynamic efficiency. The red lines represent the outline of the inboard rib structure, comprising two plus chords, the ends of the spars, and the innermost or pivot rib. The structural integrity of this set of parts is important for the strength of the wing. In particular, the ends of the plus chords must be flush with the ends of the spars so that a splice piece (shown in Figure 19-11) can be installed to tie them together.

Figure 19-11 is a sketch of the horizontal stabilizer's main parts. Each PKC is named and the parts involved in each are indicated. Some detail of the two-piece upper skin is shown, including the stringer (called the splice stringer) that splices these skin sections together. The lower skin, not shown, is made of one piece.

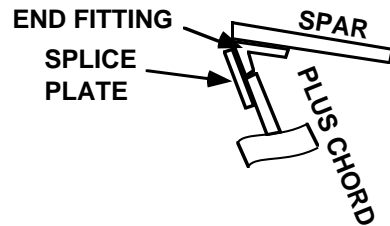
The liaison diagram of the horizontal stabilizer appears in Figure 19-12. In addition to the named PKCs 1, 2, and, 3, this figure alludes to other important alignments between parts such as the ribs and the FTB and FTE respectively without giving them separate names. These will be discussed later.





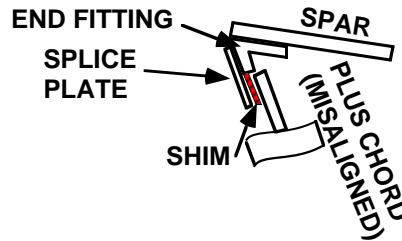
(a)

JOINT STRENGTH PKC ACHIEVED



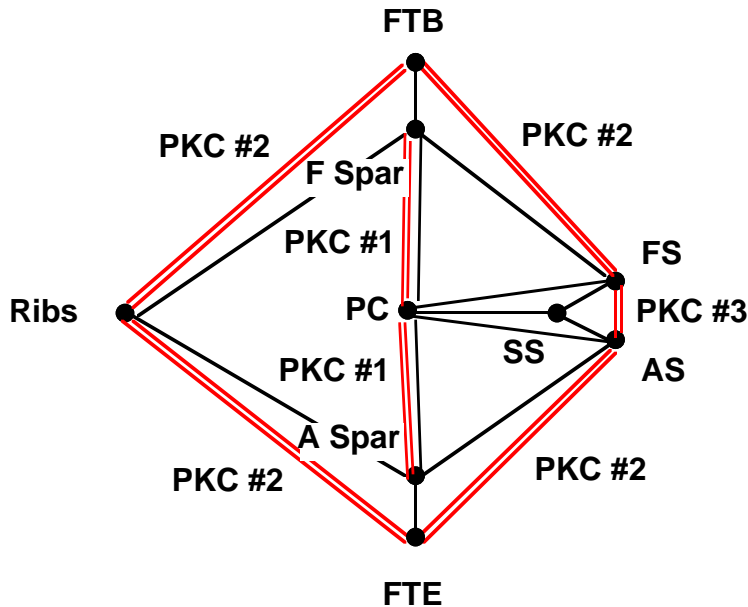
(b)

SHIM NEEDED TO ACHIEVE JOINT STRENGTH PKC



(c)

**Figure 19-11. Sketch of Horizontal Stabilizer Showing the PKCs.** (a): PKC #1 defines alignment of the ends of the plus chord with the end fittings on the forward and aft spars. PKC #2 defines the gaps between the forward skin and the FTB and between the aft skin and the FTE. PKC #3 defines the gap between forward and aft skins. (b): Detail of alignment between plus chord and forward end fitting, showing the plus chord properly aligned to the splice plate that ties these parts together. (c) As in (b) but the plus chord is misaligned. If the skin gaps are wrong, minor repairs are sometimes possible. If the plus chord is not aligned to the end fitting, a shim must be made to fill the gap under the splice plate.



**Figure 19-12. Liaison Diagram of Horizontal Stabilizer with PKCs.** Part name abbreviations are as follows. FTB: forward torque box. F Spar: forward spar. PC: plus chord. A spar: aft spar. FTE: fixed trailing edge. FS: forward skin. AS: aft skin. SS: splice stringer. Double red lines are the PKCs.

Whoever designed the current manufacturing process had to understand all these issues, and all the evidence indicates that he or she did. When we started out to design a new process, we had to understand them, too. It required about a person-year of work of two faculty and two students.

The next section describes our model of this process.

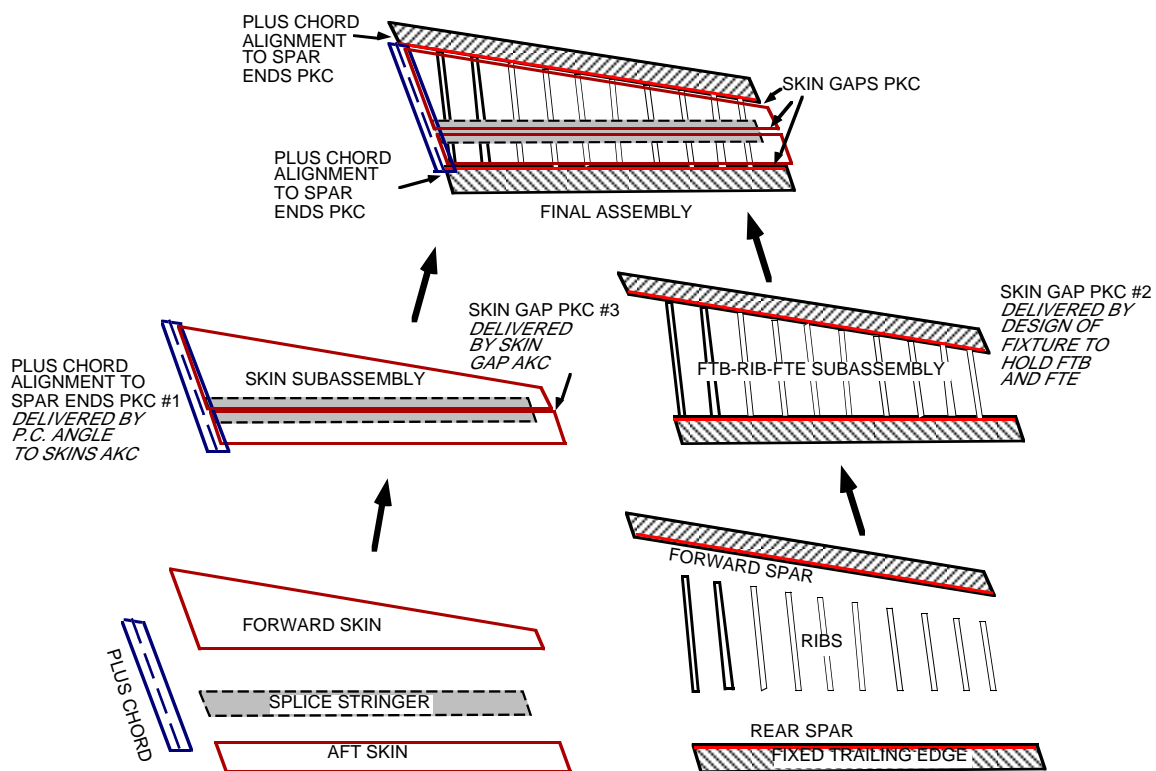
### 3. Existing Manufacturing Method

The existing method of assembling these parts as of 1997 is shown in Figure 19-13. As mentioned above, this method is currently capable of delivering completely satisfactory assemblies. However, it is a Type-2 process, and the envisioned precision assembly process would be a Type-1.

The current method proceeds in several tiers, as shown in Figure 19-13. The right-hand side of this figure traces, from bottom to top, the creation of the FTB-Rib-FTE subassembly. The FTB and FTE are built as separate subassemblies including their respective spars. The ribs are built up from individual structural shapes. These shapes include parts called shear ties that interface the ribs to the skins. The shear ties and ribs are joined by contacts, and a fixture aligns the shear ties to each other and the ribs. The result is that the ribs are enabled to help set the contour of the skin during final assembly. The FTB, FTE, and ribs are placed in a fixture and joined. Ribs and FTE have

a mate joint while ribs and FTB have a contact joint. Thus the fixture sets the fore-aft dimensions of the wing.

The left hand side of Figure 19-13 traces, from bottom to top, how the upper wing skin subassembly is made and joined to the FTB-Ribs-FTE subassembly in the final assembly process. More detail on how the upper skin subassembly is made follows shortly. For now, it is important to understand from this figure how the PKCs are delivered and what the AKCs are. Much detail about these matters is given below, but you should be able to see where in the process the different AKCs and PKCs are delivered. It should be clear that some of these requirements are achieved by cooperation and coordination of several steps in the process that are distributed in space and time over different fixtures and locations in the shop.



**Figure 19-13. Existing Manufacturing Method for 767 Horizontal Stabilizer. (1997)** This figure shows two parallel processes. On the right is the process that creates the skeleton of the wing minus the skin subassemblies. On the left is the process that creates the skin subassemblies. Only the upper skin subassembly process is shown. The lower skin subassembly is similar except that it consists of one skin piece and a plus chord. Each skin subassembly contains many stringers but only stringer #3, the splice stringer, is shown because the others are not involved in any of the KCs under consideration here.

From a product architecture point of view, this process represents one possible decomposition of the stabilizer. As we consider alternate processes, we will refer to them as alternate decompositions to show how architecture, assembly sequence, and assembly method combine to deliver (or fail to deliver) the KCs in different ways. Figure 19-14 shows how the existing process decomposes the horizontal stabilizer. Figure 19-15 is a photo of the upper skin subassembly that is the focus of the case.

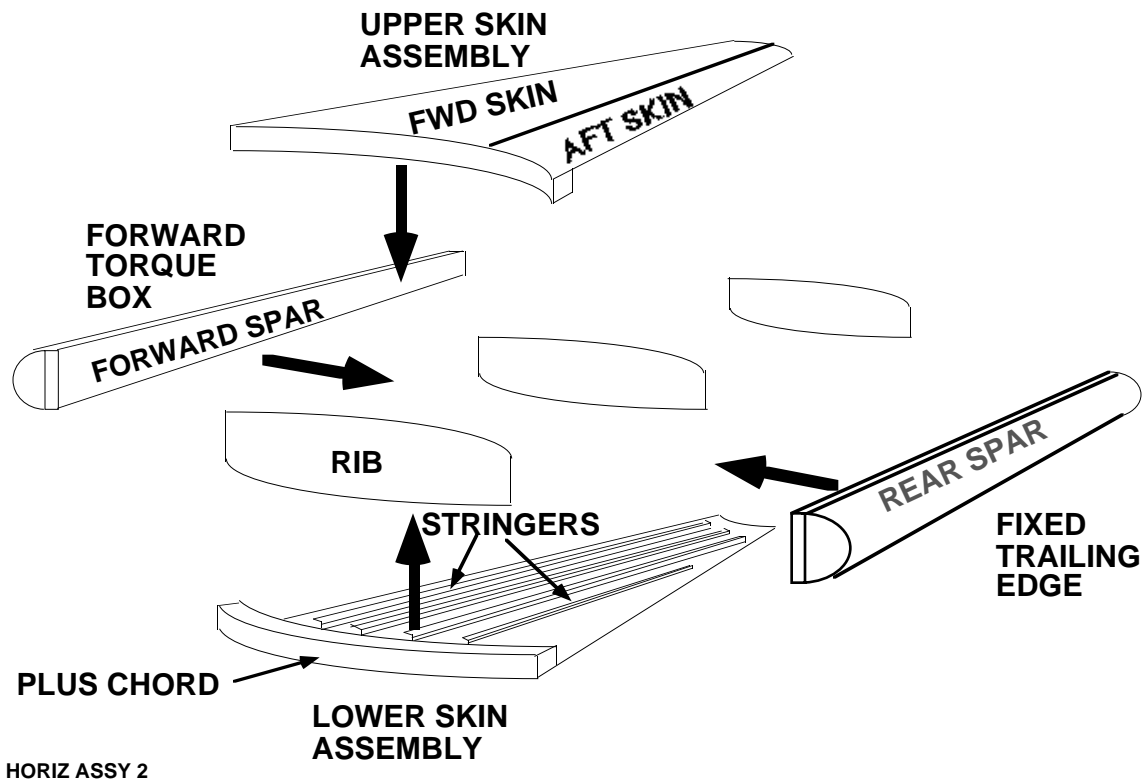
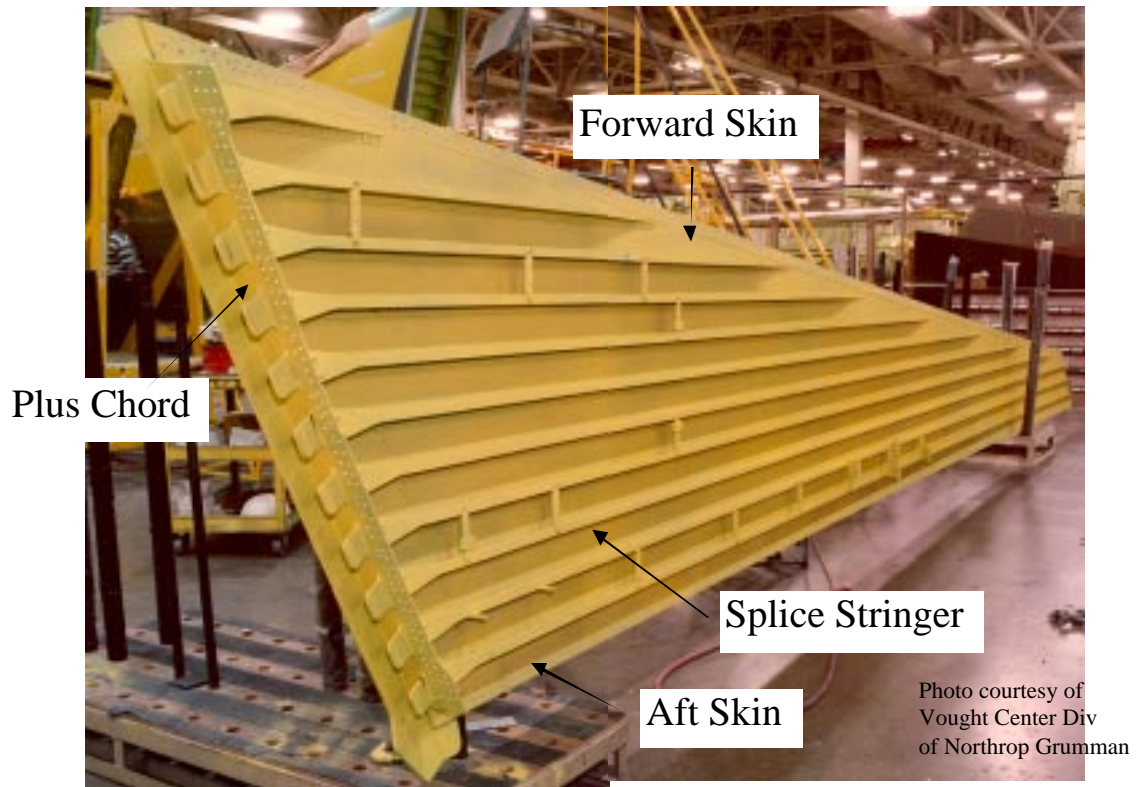


Figure 19-14. Existing Decomposition of the Horizontal Stabilizer.



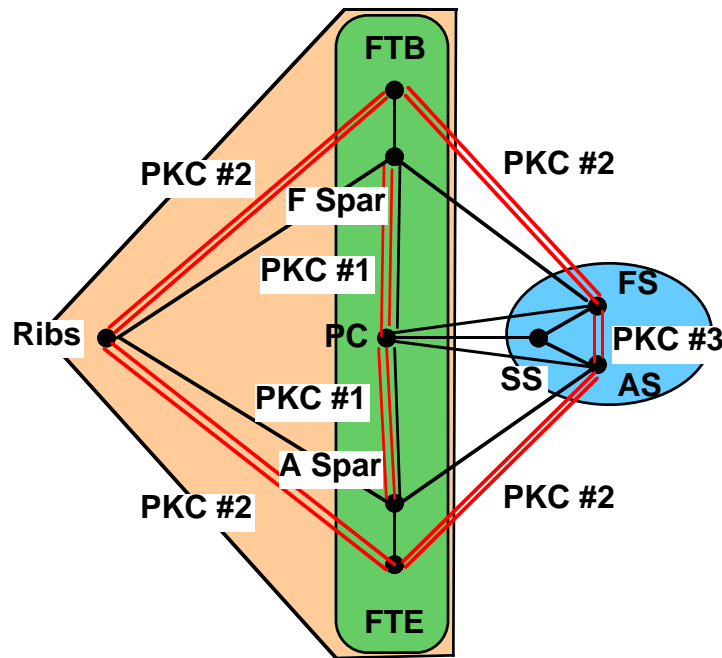
**Figure 19-15. Photo of Upper Skin Subassembly.** (Courtesy of Boeing.)

Is this the best decomposition for this product, or is it even a good one? We know from previous chapters that most products must deliver multiple KCs, and this one is no exception. We also know that the ability to achieve each KC independently of the others is a mark of a good assembly-level design. How does this process look when judged according to these principles?

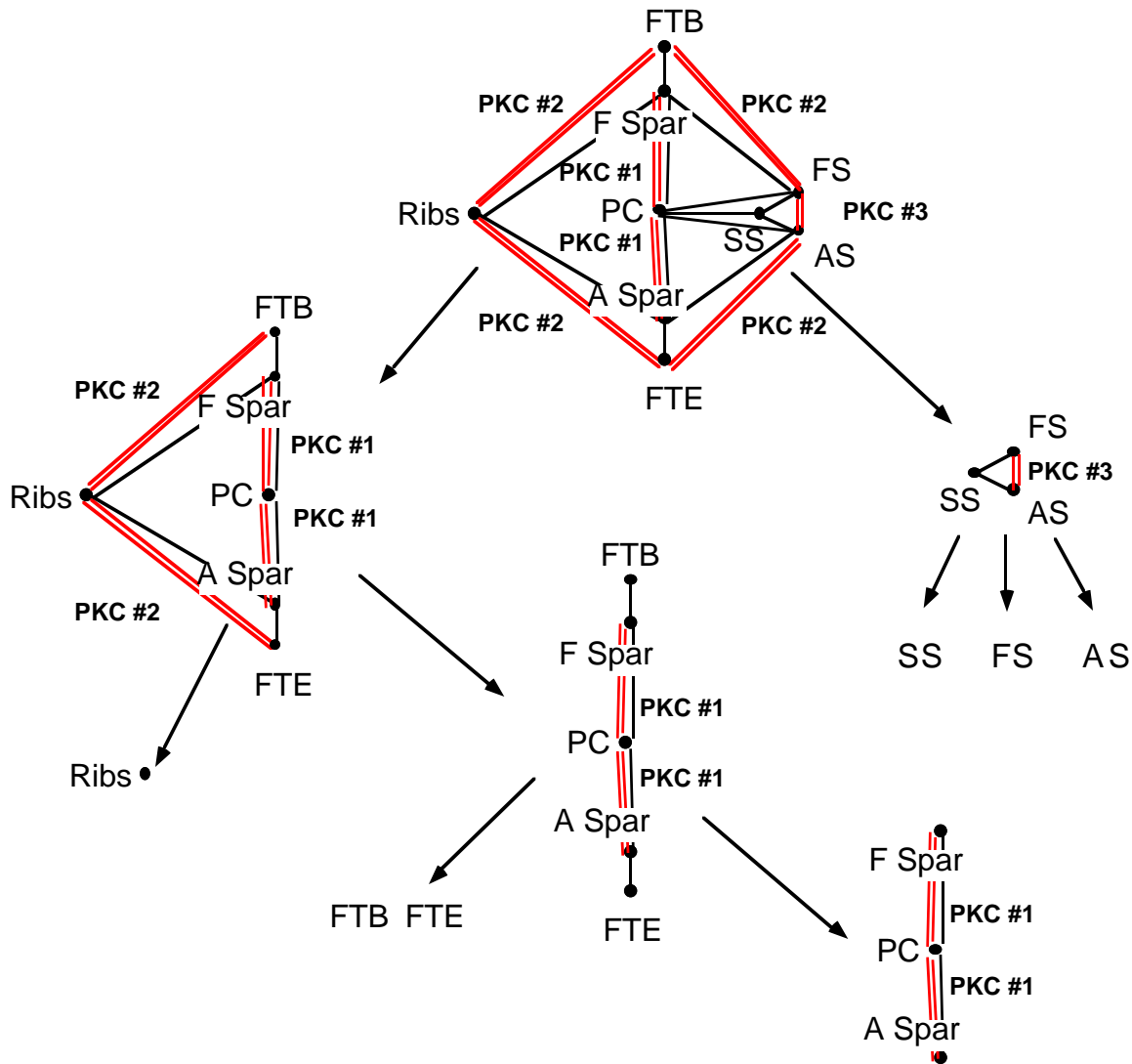
To find out, let's first see what the decomposition would look like if each PKC were achieved independently. We will then compare this ideal to the actual decomposition. Figure 19-16 shows the contents of Figure 19-11 with the addition of blobs that indicate notional subassemblies, while Figure 19-17 traces the delivery paths of the PKCs on liaison diagrams of the various assemblies and subassemblies. PKC #1 is achieved by building the green subassembly in the middle of Figure 19-16 comprising F Spar, PC, pivot rib (not shown), and A Spar. PKC #3 is achieved by building the blue subassembly at the right comprising FS, SS, and AS. PKC #2 is partly achieved by properly joining these two subassemblies. Proper spacing of the FTB and FTE via the ribs is achieved by building the beige subassembly at the left, comprising ribs and the green subassembly. Its proper construction contributes to the achievement of PKC #2.



This decomposition achieves as much KC independence as is possible. Note that PKC #2 involves summing dimensions around a closed circuit that wraps around the wing. This circuit is clearly visible in Figure 19-16. All but one of the gaps can be set independently, but not the last. It will contain the sum of all errors left over after making the preceding gaps and setting the spacing between FTB and FTE via the ribs. At Vought, the blue skin subassembly is built as shown and the forward edge is trimmed to the correct size as part of delivering PKC #2.



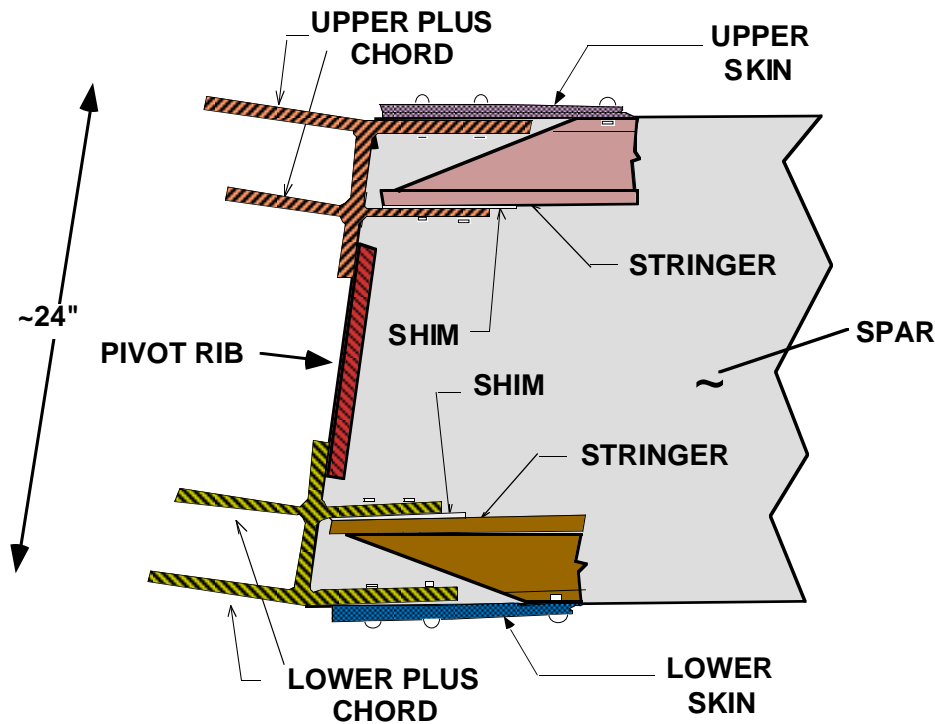
**Figure 19-16. Diagram of Subassemblies that Decompose the PKCs of the Horizontal Stabilizer as Independently as Possible.** As noted above, the skins form a closed loop around the perimeter of the wing, so PKCs #2 and #3 are unavoidably coupled. Thus complete independence of the PKCs is not possible. The best that can be done is that PKC #1 can be decoupled from the others. PKC #2 can be delivered relatively easily because the main determinant of it is set when the beige subassembly at the left is built, creating the opening into which the blue subassembly at the right is placed. PKC #3 can be delivered entirely inside this subassembly and, if necessary, its overall size can be trimmed to fit properly in the opening.



**Figure 19-17. Liaison Diagrams and KCs for a Decomposition that Achieves its PKCs as Independently as Possible.**

If we follow the progression in Figure 19-17 from the bottom to the top, reversing the decomposition, we obtain an assembly sequence for the subassemblies in Figure 19-16. This process builds the PKCs one at a time. Surely it is the one we would want to follow. It creates a subassembly of the plus chords, pivot rib, and forward and aft spars. To this must be added the skin-stringers subassembly, as well as the ribs. *Unfortunately, this sequence is unavailable to us.* The reason may be seen in Figure 19-18. This figure shows how skins, stringers, and plus chord come together. It is a complex joint. The skin and each stringer are joined to the plus chord with multiple fasteners. All holes must be deburred after drilling, requiring the parts shown to be disassembled and later reassembled. Peel shims must be sized and installed between the stringers and the plus chord to prevent over-constraint in the joint. Two-side bolt fasteners must be installed in several places to make up

the combined joint. There is simply no space to accomplish all this if we make a subassembly of the plus chord and spar ends, and then try to add the skin-stringers subassembly, as is required by this decomposition. Even on the much larger wing assemblies, Boeing does not make such a subassembly, even though in principle there might be space for a person to crawl inside with the necessary tools and access all the joint surfaces.



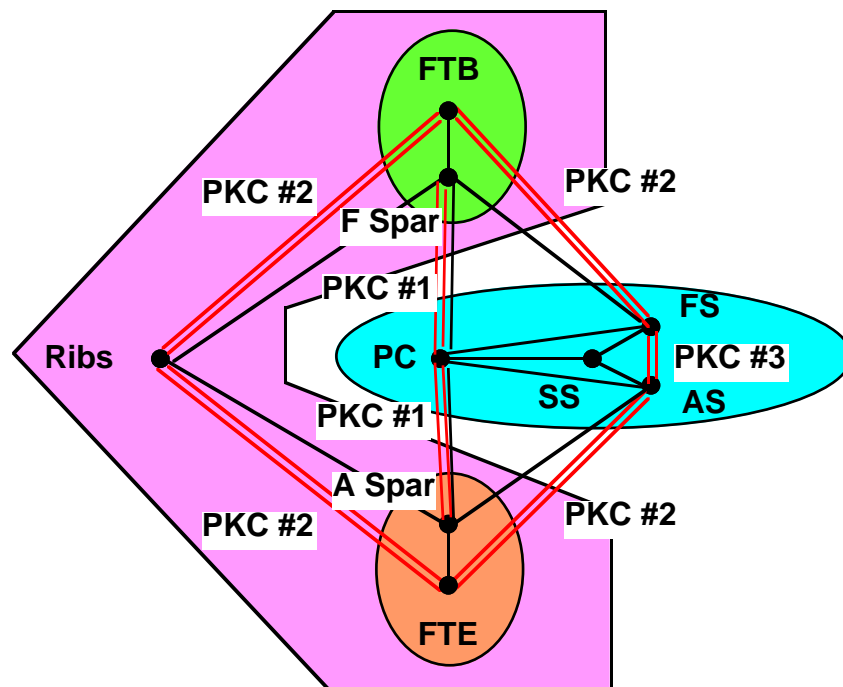
**Figure 19-18. Details of Skin-Plus Chord Joint.** If the plus chords, pivot rib, and spar ends are joined first, then it will be impossible to get inside to drill and deburr the holes for the fasteners that join the stringers to the plus chords and the skins to the plus chords, and then to insert and tighten the fasteners.

Given that the ideal process is unavailable to us, what does the existing process look like, using similar diagrams and symbols? Figure 19-19 corresponds to Figure 19-16 while Figure 19-20 corresponds to Figure 19-17. Here we can begin to see that most of the PKCs are in conflict in the sense that degrees of freedom associated with one PKC are shared with degrees of freedom associated with another. This is particularly true for PKC #1 and PKC #2. Reading Figure 19-20 from bottom to top shows that these two PKCs must be achieved together when the skin-stringer-plus chord subassembly is joined to the FTB-rib-FTE subassembly. In fact, the assemblers who perform this assembly told us that considerable maneuvering is required to obtain a best fit that comes closest to matching all the surfaces.

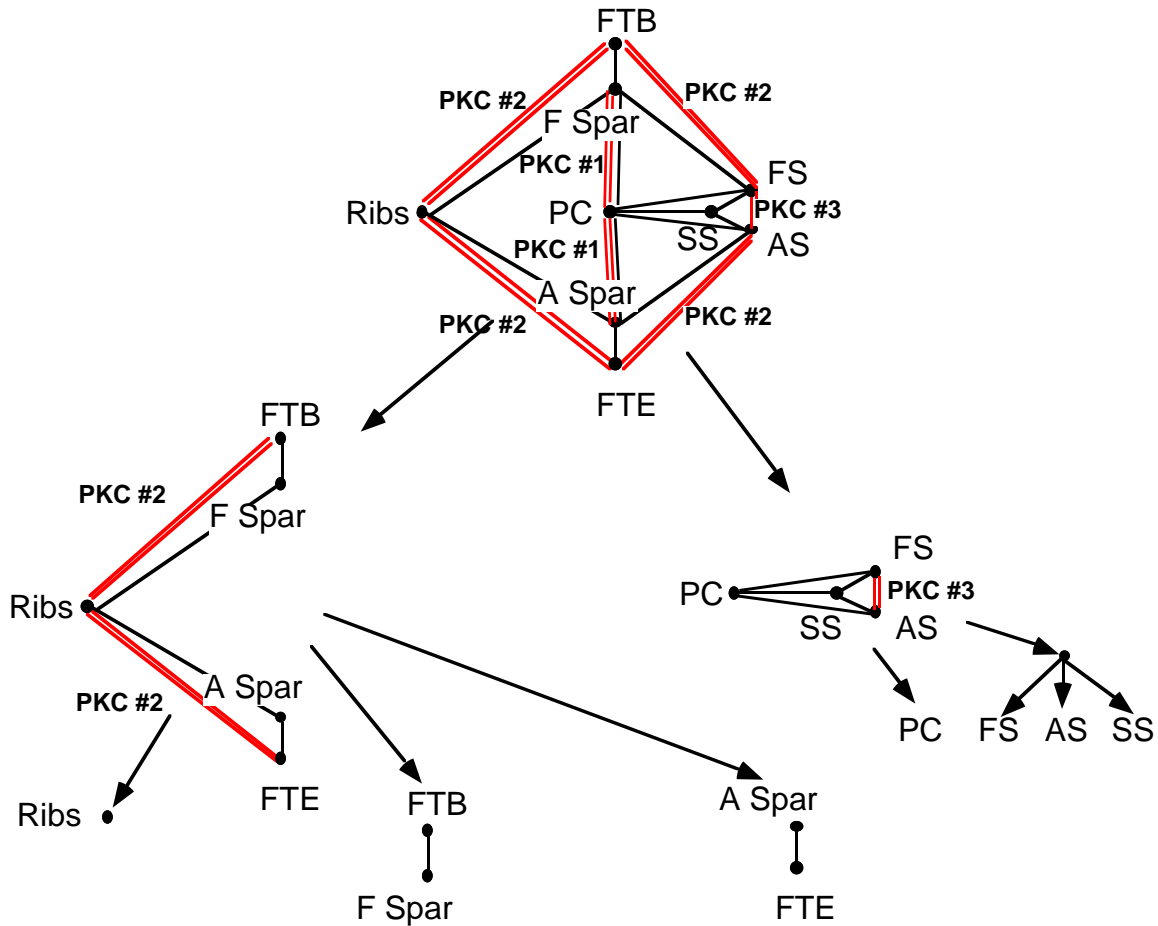
The existing assembly process that joins the skin-stringers-plus chord subassembly to the FTB-ribs-FTE subassembly is as follows:

- At the inboard end, the assemblers align the aft end of the plus chord flush with the end fitting on the aft spar. Then they set the aft skin gap at the outboard end of the skin to the nominal value, which provides a gap of between 0.03" and 0.06"
- The assemblers then rotate the skin as necessary to bring the forward end of the plus chord within 0.005" of the end fitting on the forward spar. They are permitted to slide the skin inboard and outboard while doing this, as long as the aft end of the plus chord stays within 0.005" of the end fitting on the aft spar.
- They then check the skin gaps at the outboard end, fore and aft.

Since this skin is almost 30 ft long and 6ft wide at the inboard end, and rests vertically in the fixture, maneuvering it is not easy. If PKC #1 is slightly out of tolerance, the assemblers are permitted to make their own shim. Otherwise, engineering must be notified.



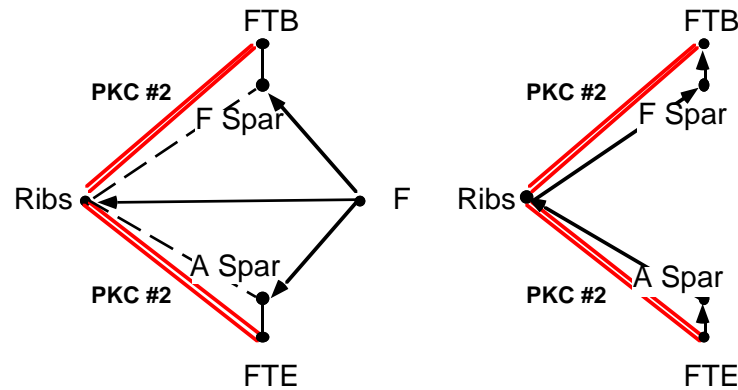
**Figure 19-19. Actual Decomposition of Existing Process.** It is clear from this figure that any adjustment of, or variations in, the subassembly of FS, SS, AS, and PC will affect both PKC #1 and PKC #2. These PKCs are therefore coupled.



**Figure 19-20. Liaison Diagrams and PKCs of the Existing Decomposition.**

The existing decomposition does not deal equally with all the PKCs. As shown in Figure 19-20, the relationship between the ribs, FTB, and FTE, which defines PKC #1 and contributes to PKC #2, flows down cleanly to the subassemblies that are involved. That is, when these parts are assembled, the assembly will contain their contribution to PKC #1 and PKC #2 and no other PKC. Either a Type-2 implementation as used now or a Type-1 implementation discussed later in the chapter in Section 19.C can handle achievement of this alignment, as indicated by the two DFCs in Figure 19-21.

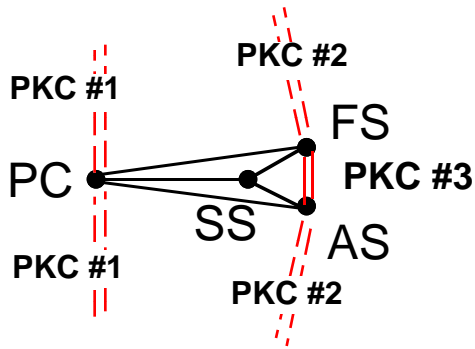




**Figure 19-21. DFCs for Achievement of FTB-Rib-FTE Alignment and Part of PKC #2 at the Subassembly Level.** Left: The existing process is a Type-2 and depends on a fixture. Right: A possible Type-1 implementation.

On the other hand, if we look at the subassembly of upper skin and plus chord (Figure 19-22), we see that the relationship between the construction of this subassembly and the PKCs it contributes to has been lost. No elements of PKC #1 appear in this subassembly even though we know that its proper construction is crucial for achievement of this PKC. Therefore we know that, when building this subassembly, we must provide high quality proxies for the missing parts that participate in this PKC, parts that are made and assembled elsewhere, if we are to have a chance of achieving this PKC. This task falls to the fixture that builds the skin subassembly in the current process, which must provide these proxies.

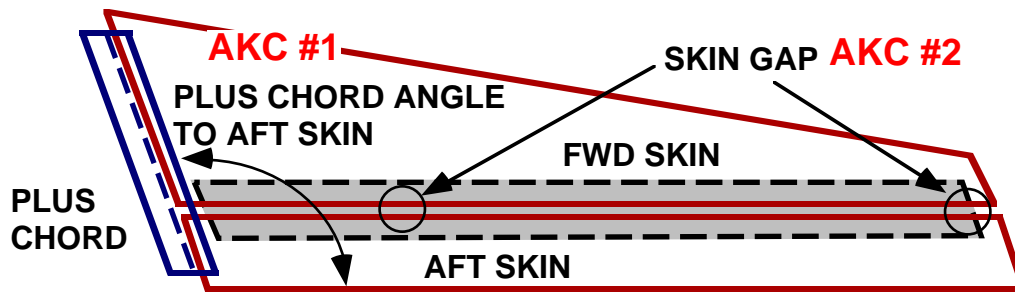
It took us several months to understand these issues. When we did, we asked for a drawing of the subassembly in Figure 19-22 as well as drawings of other key elements. Boeing made these drawings, copies of which were on file at Vought. A search through the files located drawings of most of the parts and some of the assemblies, but no drawing of the skin-plus chord-stringers subassembly as a final unit. In fact, no such drawing was ever made. If it existed, it would be called an “as-built” drawing. Boeing’s job was to make engineering or “as-designed” drawings. So, what we found on file was a Boeing drawing that showed the plus chord, spar ends, and end fittings, a crucial view for the structural engineers but in fact a subassembly that would never exist in the factory. This drawing reinforced our view that the plus chord-spar end joint was an important one. It also showed us that engineers care about a different set of subassemblies than the manufacturing people do, a fact that can cause problems in the supply chain unless there is strong communication of design intent up and down the chain.



**Figure 19-22. Liaison Diagram of Upper Skin-Plus Chord Subassembly.** Even though this subassembly is intimately involved in achievement of PKC #1 and PKC #2, we can see no evidence of these PKCs in this liaison diagram. The missing KC links are shown as dashed red lines. Note that there are many other stringers in this subassembly but they are not shown because they are not involved in delivery of any of the KCs under consideration here.

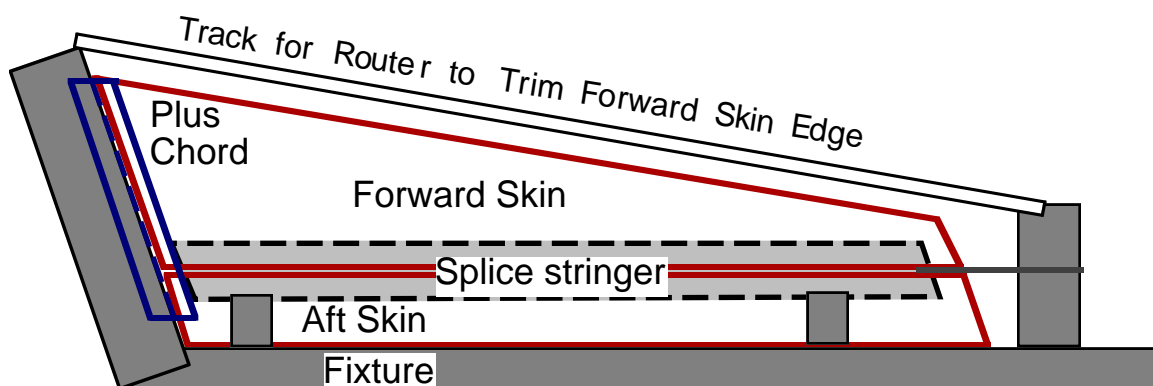
Now that we have identified the PKCs for this assembly, we are in a position to describe the existing Type-2 assembly process for the upper skin-plus chord-stringers subassembly and show how it achieves them. This involves identifying supporting AKCs, drawing DFCs for them, identifying mates and contacts, and showing how the fixture controls the degrees of freedom of the parts. In Section 19.B.4 we will use this knowledge to design two Type-1 methods as possible alternatives. We already know that joining this subassembly to the rest of the assembly will couple the PKCs regardless of whether it is made as a Type-1 or a Type-2.

Let us consider PKC #1 first. Remember that our subassembly is about 30 ft long and the skin gaps between it and FTB and FTE can be adjusted only within a range of 0.04" to 0.08". This means that very little rotational adjustment of the skin is possible in an attempt to align the ends of the plus chord to the spar ends. Either the plus chord is correctly aligned angularly to the in-out axis of the skin or else final achievement of the PKCs will be difficult or impossible. Reasoning this way leads to identification of the first AKC for the skin subassembly according to this decomposition, namely the angle between the plus chord and a reference surface (the aft edge of the aft skin). The second AKC is clearly the one that separates the forward and aft skins to create one of the skin gaps. These AKCs must be provided by the skin subassembly fixture as proxies for the missing parts: the spar ends and the FTB and FTE skins. Figure 19-23 shows these AKCs on a sketch of the skin subassembly.



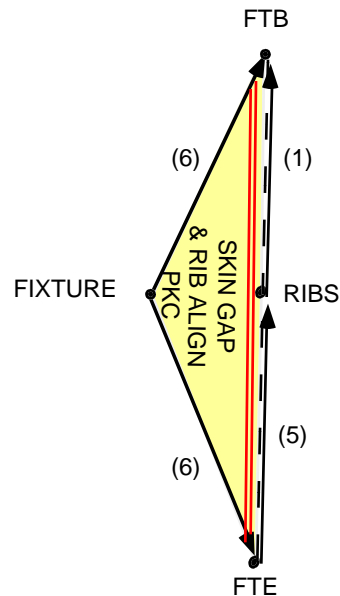
**Figure 19-23. AKCs of the Upper Skin-Plus Chord Subassembly for the Existing Process.** AKC #1 is the angle between the plus chord and the aft edge of the aft skin. AKC #2 is the gap between the forward and aft skins.

The existing fixture that delivers these AKCs is shown in Figure 19-24. The DFC for this fixture and its parts appears in Figure 19-25. The assembly sequence is as shown at the right in Figure 19-20: the aft skin is placed in the fixture; spacers are placed along its upper edge and the forward skin is placed on those spacers, creating the gap for PKC #3; stringers are placed on the fixture and the assembler drills holes for tack fasteners; he then places the plus chord in the fixture and uses a drill bushing fixture to drill holes for fastening the skins, stringers, and plus chord together; he deburrs the back side of all these holes and makes the shims for installation between the plus chord and the ends of the stringers. Then he installs tack fasteners between the skins and the stringers and final fasteners between the plus chord, skins, and stringer ends. Then he runs a routing tool along the track at the top of the fixture to trim off a little excess material deliberately left on the forward skin in order to place the forward edge at the correct distance from the aft edge as part of achieving the skin gap KC. Finally, he takes the subassembly to a drill and rivet machine that installs final fasteners between the skins and the stringers.



**Figure 19-24. Existing Fixture-Based Method Used to Assemble the Upper Skin Subassembly.** This fixture is designed to deliver the two AKCs identified in Figure 19-23. It also permits placement and joining of several stringers to the skin that do not appear in the figure because they are not involved in any

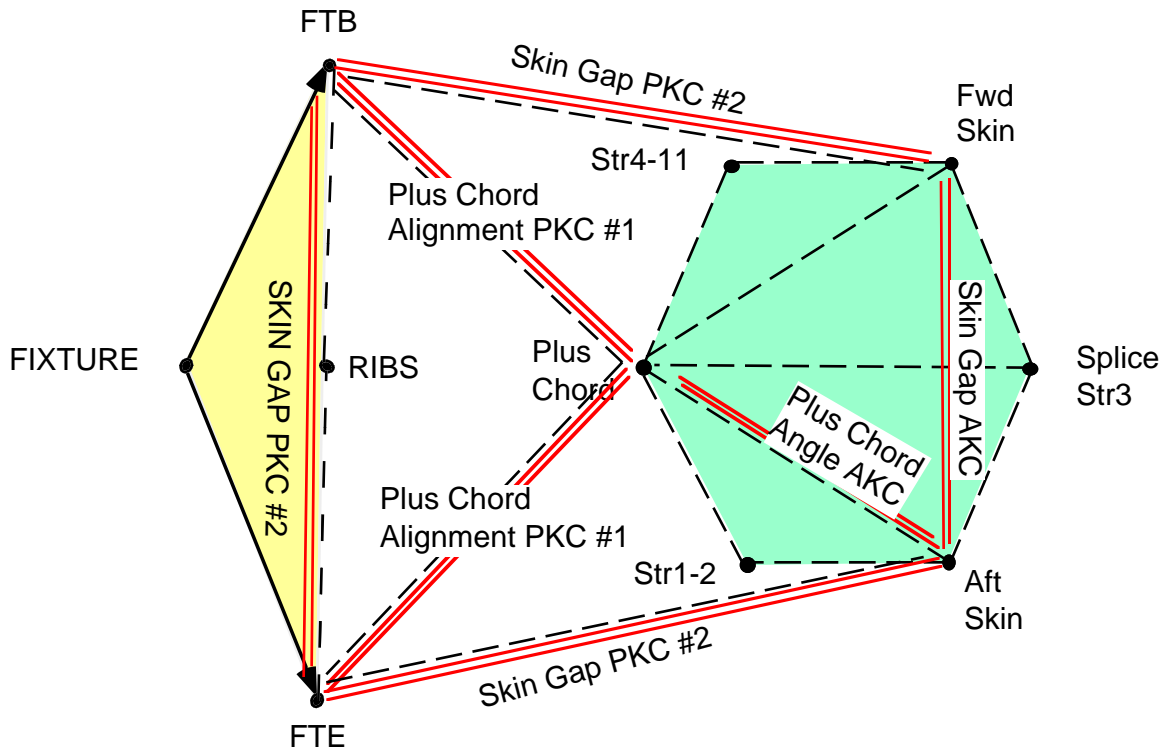




**Figure 19-26. DFC for Existing Fixture-based Assembly Method for the FTB-Ribs-FTE Subassembly.** The fixture controls all the contacts and delivers all the PKCs contained in these parts. This portion of the process and the fixture appear on the right in Figure 19-13.

Once the FTB, FTE, and ribs have been placed in the fixture and joined, the wing skin subassemblies are installed onto those parts. Only the process for installing the upper skin subassembly will be described here, and only insofar as it pertains to delivery of the PKCs discussed so far. A number of other important operations are performed at this time that involve other PKCs. The assembly process DFC is shown in Figure 19-27. On the left are the parts and fixture shown in Figure 19-26. The assemblers place the skin subassembly on the parts, not on the fixture. They adjust the position of the subassembly to best achieve the coupled PKC #1 and PKC #2 as described before. This coupling is clearly visible in Figure 19-27. When they have finished adjusting the position of the subassembly, they drill through the skins, ribs, FTB, and FTE, and fasten the skin onto the assembly.

The existing process is obviously Type-2 at both the subassembly and final assembly level. The next section discusses proposals for substituting Type-1 processes. The discussion focuses on the skin subassembly but brief descriptions of possible Type-1 processes for final assembly are also given.

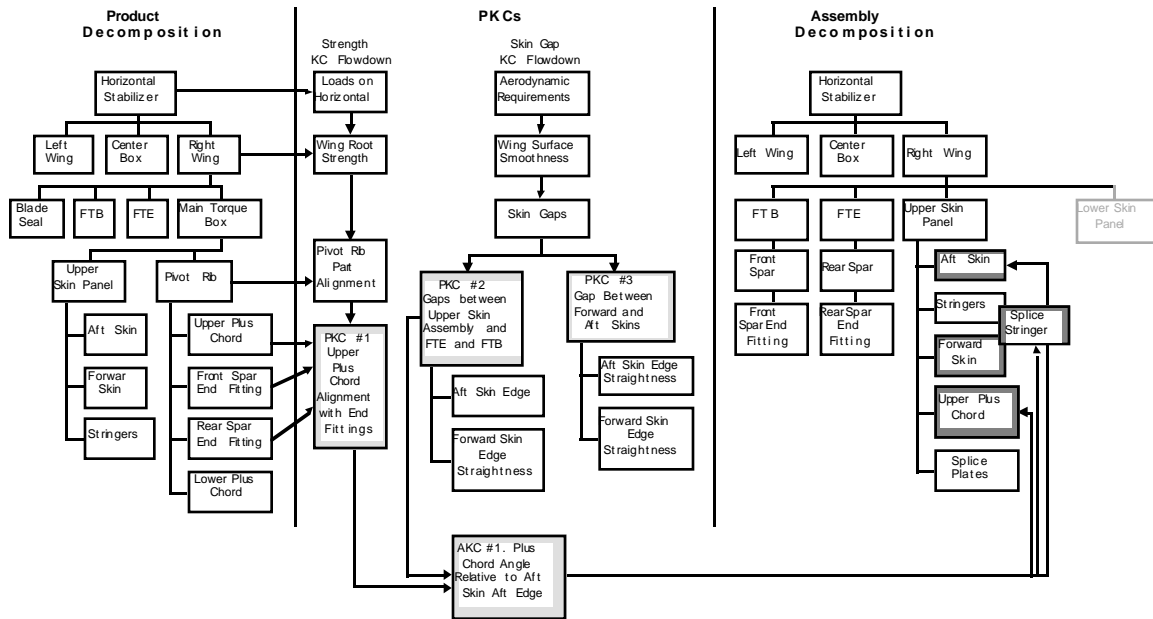


**Figure 19-27. DFC for Existing Process of Final Assembly of the Skin Subassembly (right, in green) to FTB-Ribs-FTE Subassembly (left, in yellow).** This process step appears at the top of Figure 19-13. Like all the subassembly steps, this is a Type-2. Four contacts must be made when the skin subassembly is joined to the FTB-ribs-FTE subassembly, and two PKCs (plus chord alignment and skin gap) are involved. These KCs are coupled. The assembly is performed manually by two assemblers who maneuver the skin subassembly to best achieve the coupled PKCs.

To summarize the results of studying the existing process, Figure 19-28 shows a fairly complete KC flowdown for the horizontal stabilizer. It includes all the PKCs covered by this study as well as the first AKC, which is common to both of the proposed processes discussed next. On the left in this figure is the product decomposition. It reflects the drawing tree made by Boeing. There are engineering drawings for all the elements shown in this decomposition and, of course, there are many more drawings of details. In the middle is a flowdown of the PKCs and the first AKC. Arrows from the product decomposition call out items that are involved in delivering these KCs. On the right is the assembly decomposition, identifying subassemblies that are actually built at Vought. Note that, as discussed above, some of these subassemblies have no counterparts in the product decomposition and thus are not represented by Boeing drawings. Nevertheless, they must be built, and assembly processes for doing so must be designed, along with any necessary tooling. Supporting fabrication processes for the individual parts



must also be designed, along with necessary tooling and inspection apparatus. Prior to our study, no diagram like Figure 19-28 existed.



**Figure 19-28. Full KC Flowdown for the Horizontal Stabilizer.** All the PKCs studied are shown, along with the AKC that is common to both proposed new assembly processes. Only the right wing and upper skin are decomposed in detail because the others are alike. This is the flowdown that resulted from investigating the existing process. All the parts that appear in the assembly decomposition at the right also appear in the product decomposition at the left, but they are grouped differently. Drawings made by Boeing exist for the groups at the left but do not exist for some of the subassemblies at the right.

#### 4. Proposed Methods for the Skin Subassembly

Two methods for building the skin subassembly were proposed for reducing or eliminating the dependence on fixtures and Type-2 assembly methods. One of these was a pure Type-1 design in which the parts were provided with features that permitted fully constrained subassemblies to be built as well as a fully constrained final assembly. The other was a hybrid that required fewer features to be machined onto the parts and relied more on temporary tools to help place the parts in the correct relationships to each other prior to drilling and fastening. The first of these methods will be described in detail while the second will be summarized.

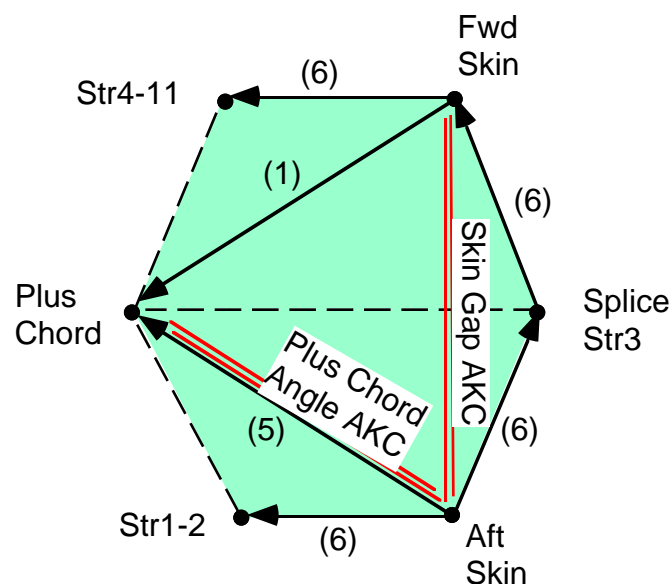
##### a) First Proposed Method: A Pure Type-1

###### (1) Nominal Design

The first proposed process was intended to match Vought's investments and investigations to date. With minimum equipment investment as a goal, the process recommended here attempts to focus on delivering the AKCs, but seeks to utilize existing fabrication equipment at the plant as much as possible, while limiting the investment in new flexible tooling and equipment. It is based on placing some assembly features on the parts while their shapes are being machined.

Converting the existing Type-2 design to a Type-1 requires performing a complete assembly-level design of the skin subassembly. The process begins by performing the nominal design phase. This phase includes defining the KCs, devising a DFC for each KC, attaching features to the DFC, identifying assembly sequences that build properly constrained subassemblies, and choosing one.

To implement a Type-1 solution to this assembly, it is necessary to design a DFC that will deliver the AKCs that the original process delivers. A process flow similar to the current process was adopted, making the aft skin the first part to be loaded into the assembly apparatus, whatever that apparatus should turn out to be. The requirements on the DFC are that it locate the forward skin correctly with respect to the aft skin so as to achieve the skin gap AKC, as well as to locate the plus chord so that it achieves its AKC, its angle with respect to the aft skin. The DFC in Figure 19-29 was proposed to fill these needs. Note that it fulfills all the basic requirements for a DFC: it identifies the root part, it labels each mate with the number of degrees of freedom that it is supposed to constrain on the next part, and there is a chain of mates from one side of each KC to the other. Stringers 1, 2, and 4-11 are shown on the DFC but they are not involved in delivering any of the KCs that are under consideration here, so they will not be mentioned again.

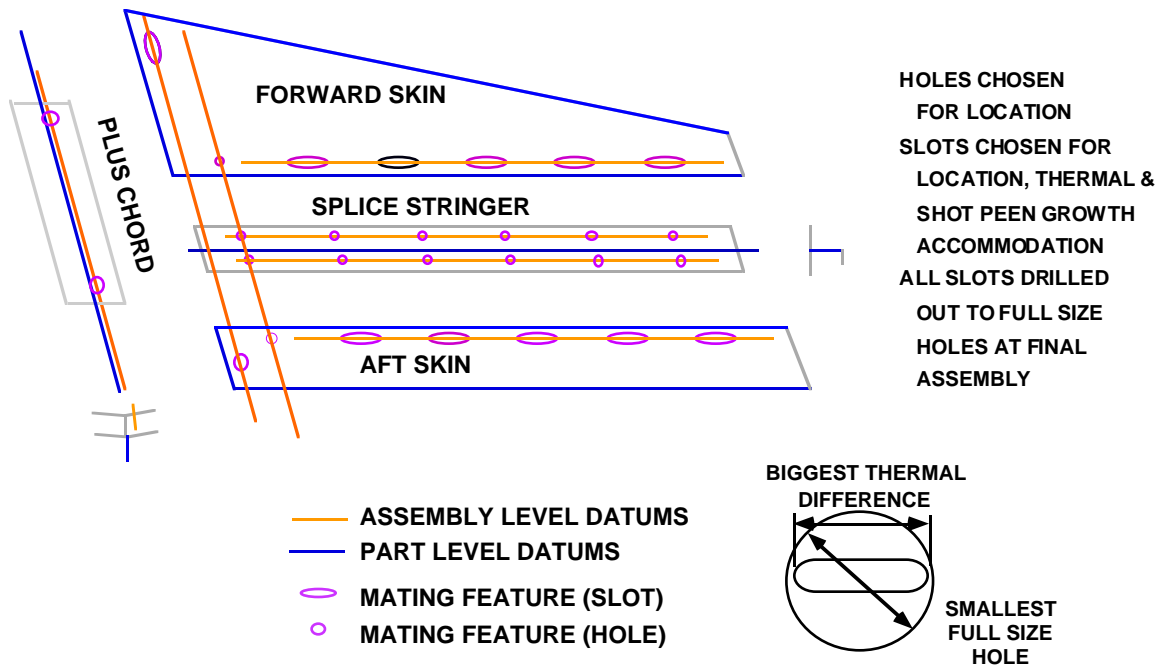


**Figure 19-29. Datum Flow Chain for a Pure Type-1 Assembly Process for the Wing Skin.** In this DFC, the aft skin is the root. It locates the splice stringer which in turn locates the forward skin. Together, forward and aft skin locate the plus chord. This DFC should be compared to the one in Figure 19-25.

The next step is to choose features for each of the mates in the DFC. A proposal for these mates, consistent with the degrees of freedom in Figure 19-29 appears in Figure 19-30. These features are combinations of pin-hole and pin-slot toolkit features from Chapter 4. The fabrication shop puts these features on the parts using the part-level surfaces as datums. The key dimensions to control are the spacing between the two rows of holes in the splice stringer and the placement of the rows of slots on the skins with respect to their bottom edges. It is also important to control the distance from the lower edge to the upper edge of each of these skin pieces. Other important dimensions are the locations of the holes at the ends of the rows of slots on each skin, the inboard hole on the aft skin, the inboard slot on the forward skin, and the hole and slot compound feature on the plus chord.

The assembly process consists of inserting sacrificial aluminum tack fasteners into the mates and then carrying the parts to an automatic drill and rivet machine similar to that shown in Figure 19-2. Details of each assembly step are given below.

Multiple slots are shown along the skin edges in Figure 19-30, and one could conclude from this that the design is over-constrained. However, the splice stringer is extremely flexible in the plane of the figure and can accommodate small misalignments or mis-locations of the slots. Any concern about over-constraint can be alleviated by making all the slots except the most outboard one a little wider, or one can count on the fact that the tack fasteners may be a bit loose in the slots. If such looseness exists, it must be included in any variation analysis that is performed on this process. Any resulting variation will show up as uncertainty in the width of the gap between forward and aft skin as well as the width of other gaps.



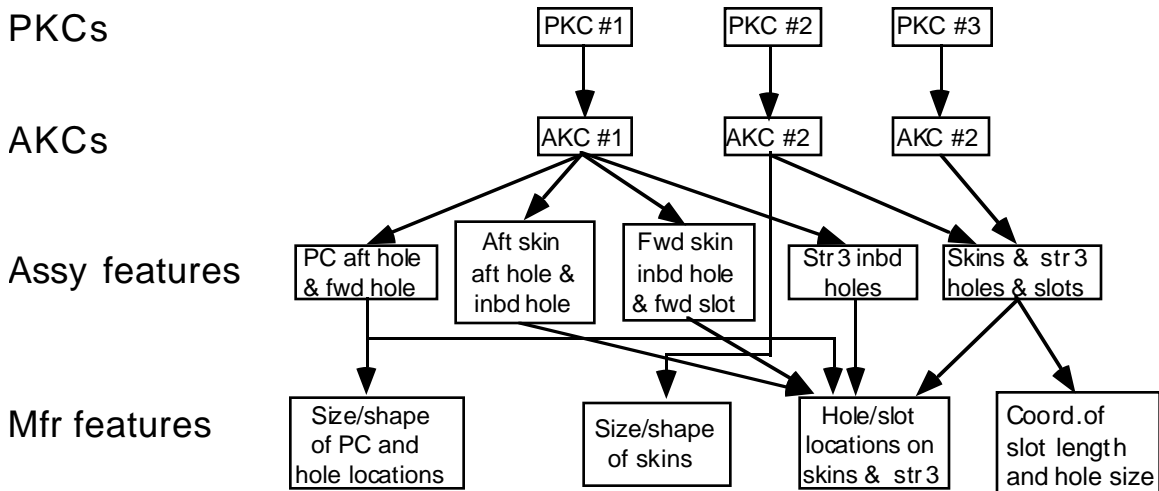
**Figure 19-30. Part and Assembly Level Features for Implementing a Type-1 Solution to the Wing Skin Assembly Problem.**

An interesting aspect of the pin-slot features on the skins is that the slot lengths are constrained not to be too big and not to be too small. If they are too big, they will exceed the size of the final fasteners that will be installed in them. These fasteners get smaller as their location trends outboard, due to lower shear stresses. All final holes drilled by the machine must be completely round and not retain any trace of the elongation from the slot, or else the fasteners will rock in the holes and not be able to support shear stress in the direction of the slot. On the other hand, we must allow for possible differences in temperature between the times that the various parts are being machined. These differences effectively place the slots and holes at different in-out locations along the skins and stringers. Naturally, assembly requires the slots to completely enclose the holes or else the DFC will not satisfy the robustness requirement that it be unique and permanent regardless of all anticipated variations. All these considerations were combined and fortunately a satisfactory length for the slots was found.<sup>10</sup> The ability of the manufacturing processes to deliver this combination of slot length and thermal control is a manufacturing KC as much as is the ability to locate the holes and slots accurately.<sup>11</sup>

<sup>10</sup> An alternate solution could be to put the pin-hole feature at the outboard end. This would permit the thermal expansion comparison to be made against inboard slots, which can be longer because inboard fasteners are larger. You should consider whether there is a disadvantage to this strategy and explain why it was not adopted. Hint: It involves final assembly tolerances.

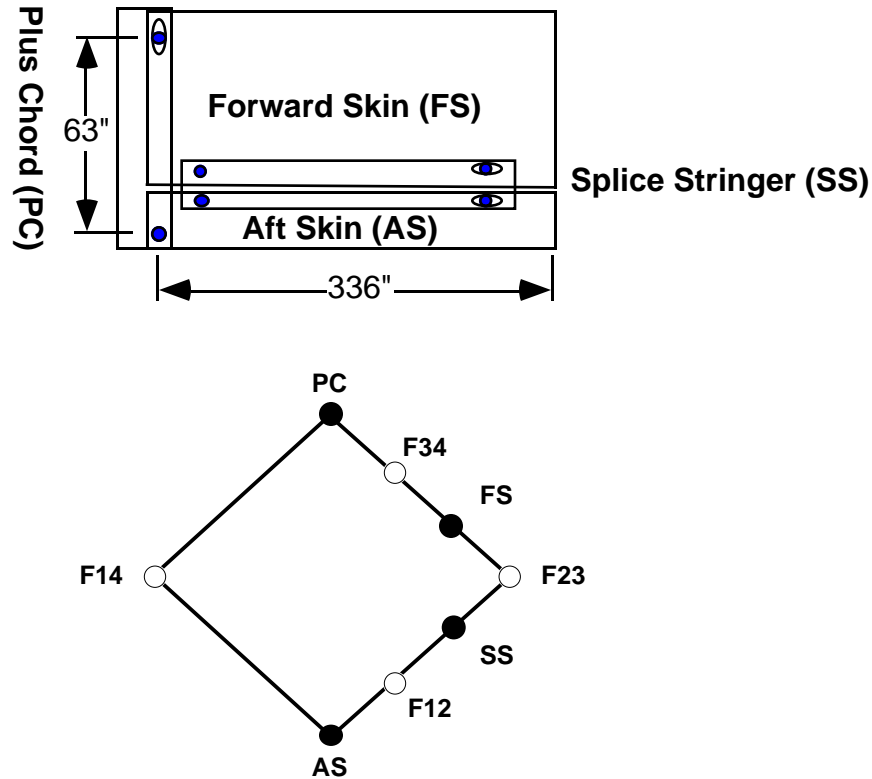
<sup>11</sup> Thanks to David Sharman for pointing this out.

Figure 19-31 diagrams the KC flowdown for the process whose features are given in Figure 19-30. It includes all levels of KCs and features.



**Figure 19-31. Key Characteristics Flowdown for the First Proposed Process.**  
This figure corresponds to Figure 2-3.

Figure 19-32 shows the paths needed for a path-based analysis of the constraints offered by the features shown in Figure 19-30. It shows that the plus chord is properly constrained with respect to the aft skin. The details of the analysis are in Table 19-9 in Section 19.F.

**Left path:**

Find union of all twists along the path from PC to AS, that describe motion of the PC, using some common point for all twists, such as F12. These twists are: F14, a pin-hole joint.

**Right path:**

Find union of all twists along the path from PC to AS, that describe motion of the PC, using the same common point as was used for the left path. These twists are: F34, a pin-slot joint, F23, a combination pin-hole and pin-slot, and F12, another combination pin-hole and pin-slot.

Find the intersection of the twists obtained from the left path and the right path.

**Figure 19-32. Outline of the Constraint Analysis of the Plus Chord.** At the top is a simplified sketch of the parts, showing the mates. Below it is the path diagram for finding the twist matrices. At the bottom is an outline of the procedure. The analysis shows that the plus chord is properly constrained with respect to the aft skin. A similar analysis can be done for the aft skin and the forward skin, although these analyses are trivial. If the parts are assembled in the sequence aft skin to splice stringer, then splice stringer to forward skin, then plus chord to aft skin, and finally plus chord to forward

skin, then each subassembly in turn will be properly constrained. All the detailed steps are in Section 19.F, Table 19-9.

For the DFC that has been adopted, there is for practical purposes only one assembly sequence that builds fully constrained subassemblies and makes all the incoming mates for each part before any of the contacts are made. This sequence is:

- Place aft skin in assembly support
- Place splice stringer on aft skin, aligning the forward inboard hole on the aft skin with the aft inboard hole on the splice stringer.
- Insert a temporary fastener through this hole.
- Align the aft holes on the splice stringer with the slots on the aft skin, and insert temporary fasteners through them.
- Place the forward skin on the support, aligning its aft inboard hole with exposed the hole on the splice stringer.
- Insert a temporary fastener through this hole.
- Align the slots on the forward skin with the exposed holes on the splice stringer, and insert temporary fasteners through them.
- Place the plus chord on the assembly support and align its aft hole with the aft inboard hole on the aft skin.
- Insert a temporary fastener through this hole.
- Align the forward hole in the plus chord with the forward inboard slot on the forward skin, and insert a temporary fastener through this hole.
- Transport this tacked subassembly to the drill-rivet machine and insert permanent fasteners.

Now that we have a plan for delivering each KC and a DFC for each KC, are assured that the constraint structure of the DFC is satisfactory, and have a feasible assembly sequence that obeys the constraints of the DFC, we are finished with the nominal design phase and ready to enter the variation design phase.

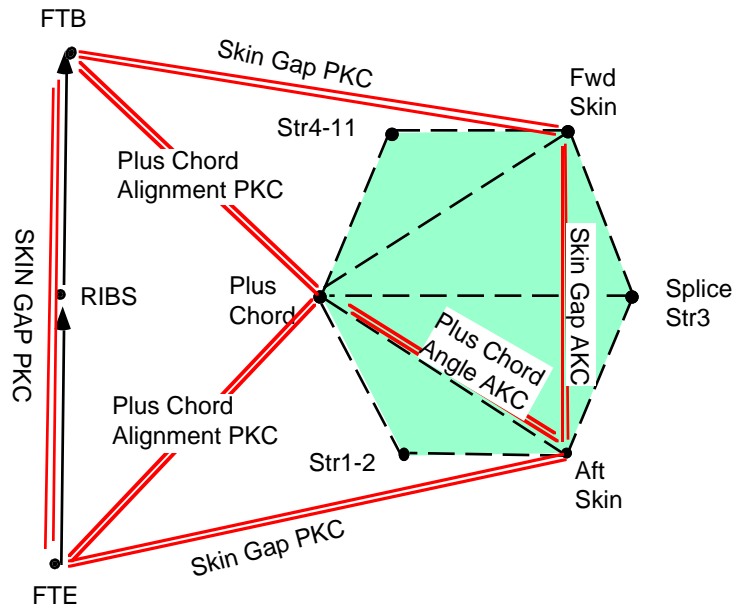
## (2) Variation Design



The robustness of the DFC depends on avoidance of interferences that could arise if the mates are not properly located or sized. We have already discussed the possibility that a pin might end up at the extreme end of a slot due to thermal expansion. Another possibility is that the gap between the skins might close to zero if the mating holes or slots are badly mis-positioned. Since the gap will be at least 0.030" wide and the machine tools are capable of placing a feature within about  $\pm 0.004$ ", this gap will remain open under all circumstances. All other joints are contacts in the form of lap joints, so no interferences can arise there.

The next step is to see if there is conflict between the various AKCs. Although a Screw Theory analysis could be performed to check this, we can see by inspection that no conflict will occur. The reason is that the assembly sequence listed above will first achieve AKC #2 and fully constrain all the parts involved in its achievement. Then it will achieve AKC #1 and fully constrain the last part that is involved in its achievement, while the others involved were fully constrained by previous assembly steps. At each point in the process where an AKC is to be achieved, there are 6 degrees of freedom available that read on that AKC and that AKC alone.

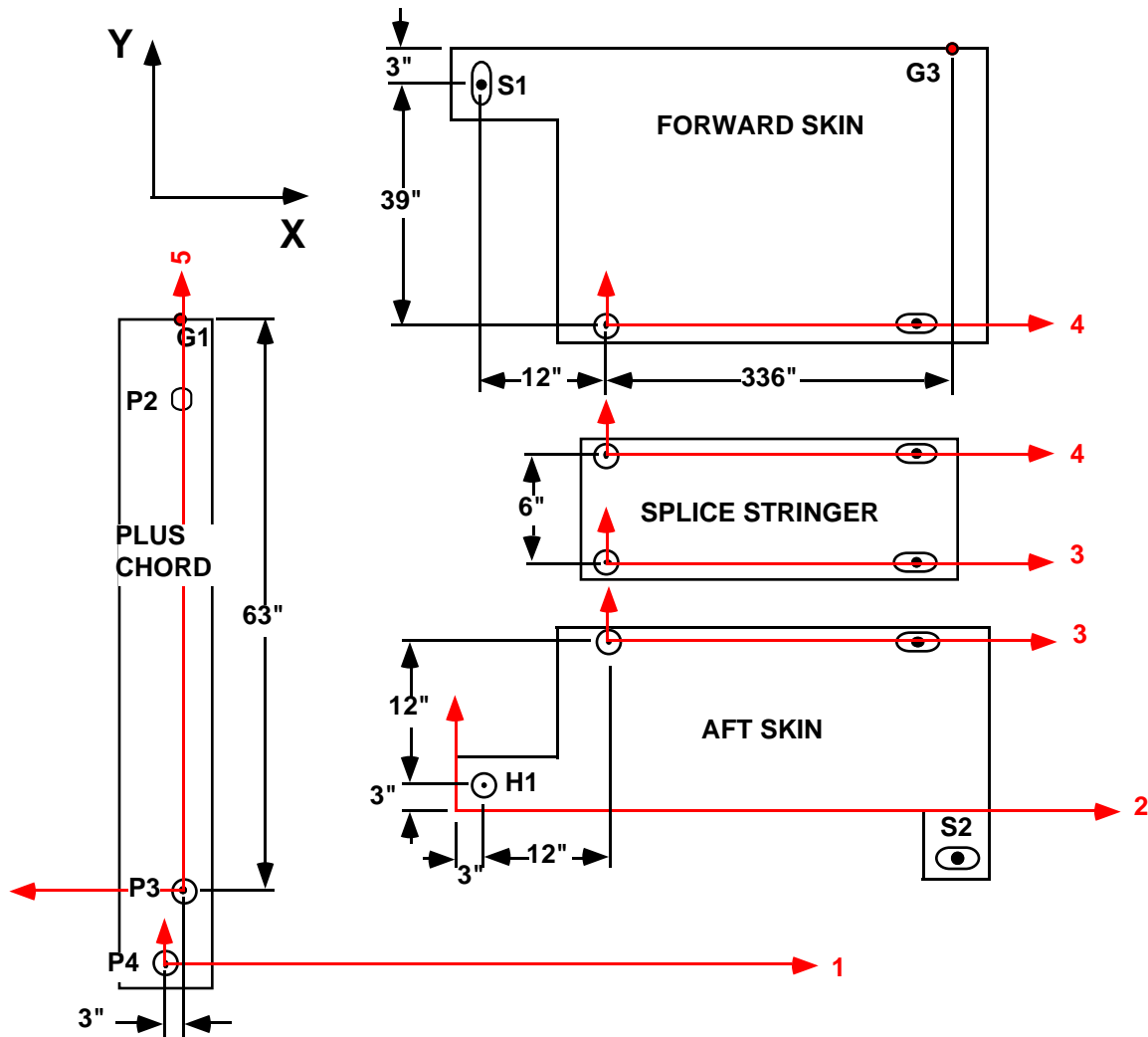
However, when we look at the final assembly, we see that there is conflict among the PKCs. This may be seen from Figure 19-33. This figure shows the assembly of the skin subassembly to the subassembly comprising the ribs, the FTB, and the FTE. The latter subassembly is shown as if it, too, has been assembled as a Type-1, although the method and features for doing so have not been described yet. (See Section 19.C.) We can see that just because we constructed these subassemblies as Type-1s rather than Type-2s we did not change the number of degrees of freedom available during final assembly. For this reason, the KC conflict observed in Figure 19-27 is still present. This fact will deeply affect the tolerance analysis on achievement of the PKCs, which should not be surprising.



**Figure 19-33. DFC for Final Assembly of Horizontal Stabilizer.** As in the current process, the PKCs aiming at outer skin gaps and plus cord alignment to the spars are coupled.

The last step, then, is to perform a variation analysis to see if the PKCs are achieved with high enough probability. For this purpose, we are going to assume that the processes for fabricating the parts and their features are in control and capable at the tolerances that will be given below. This means that the mean of each dimension is on or near the desired nominal value and that  $C_{pk} = 1$  for all dimensions. We are also going to assume that the subassembly of FTB-ribs-FTE has been made exactly right. To implement this assumption, we will simply absorb any errors that might appear in this subassembly into the wing skin subassembly since all the errors we are interested in comprise gaps between features on the wing skin and features on the FTB-ribs-FTE subassembly.

In order to carry out the variation analysis, we need to build the nominal model of the assembly by assigning coordinate frames to the features and joining those frames to create the assembly. Figure 19-34 defines the frames for the wing skin subassembly, which has been simplified to eliminate the tapered shape of the wing skins. Figure 19-35 defines the frames for the final assembly. Here the FTB-ribs-FTE subassembly is shown fully assembled with no internal frames of its own, corresponding to the assumption that it has been made perfectly and that all its errors have been added to errors in the skin subassembly. The two PKCs are also shown in this figure.

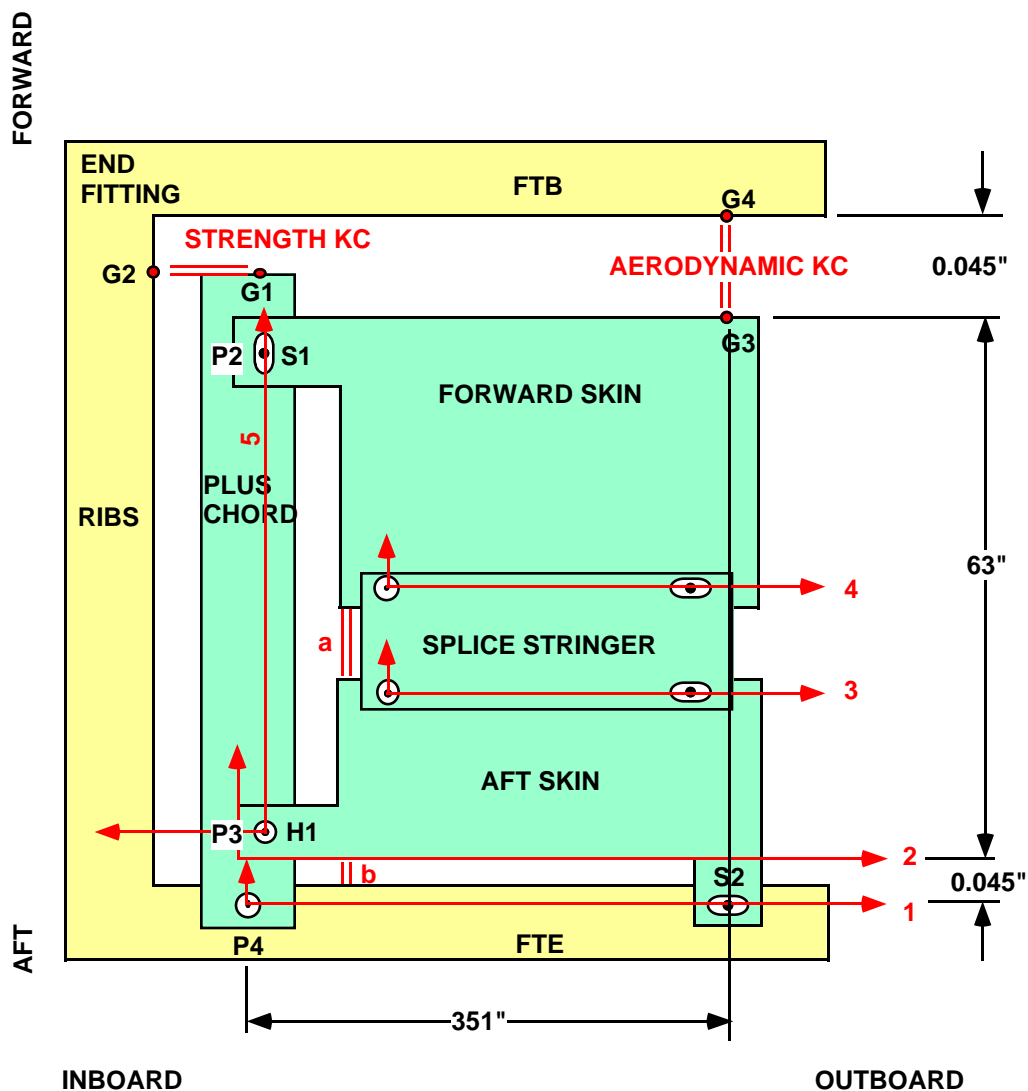


**Figure 19-34. Definitions of Frames and Nominal Dimensions for Parts of the Wing Skin Subassembly.** This drawing is not to scale. Each major frame has its own number, ranging from 1 to 5, written at the end of its X axis. Where the same frame appears on two parts, the implication is that the frames will coincide when the parts are assembled. Point G1 is a feature on the plus chord that must align with a point on the forward spar, which is part of the FTB. Point G3 is a feature on the forward skin that represents the skin side of the gap that must be achieved between the skin and the FTB.

Figure 19-35 is drawn to emulate the assembly sequence used in the current process, which does its best to deal with the coupling of the PKCs. This process is as follows:

- Place the skin subassembly in the assembly support and align the surface of the aft end of the plus chord in the X direction to the end fitting of the inboard end of the aft spar. The tolerance here is  $\pm 0.005''$  but the assemblers seek to align it exactly.

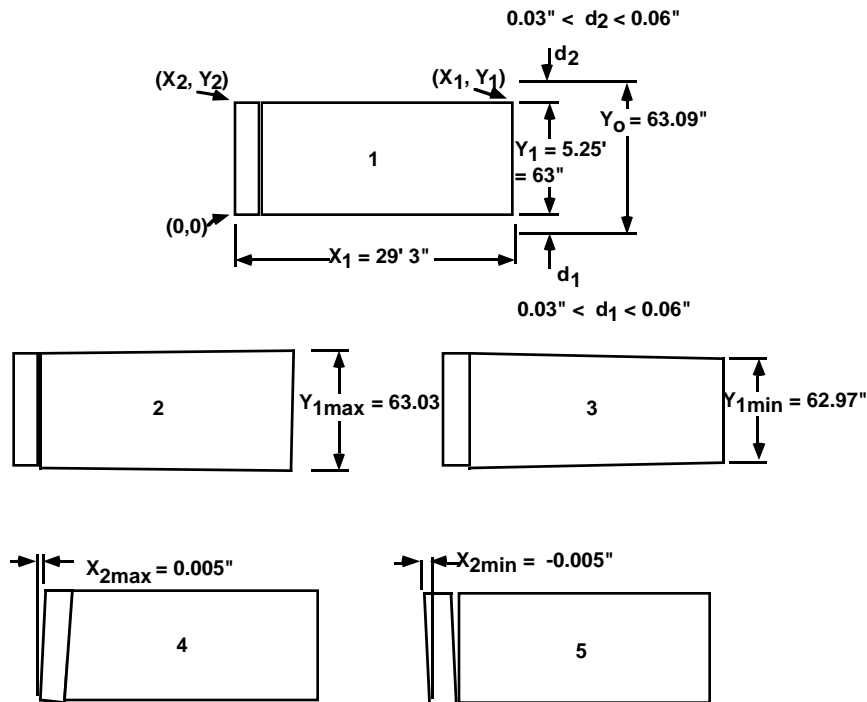
- Set the skin in alignment with the FTE so that the gap in the Y direction is within tolerances. The dimension and tolerance on the gap are  $0.045'' \pm 0.015''$ .
- Maneuver the skin in an attempt to align the forward end of the plus chord with the end fitting of the inboard end of the forward spar without shifting the alignment at the aft end.
- Check the skin gaps at the forward and aft edges of the skin subassembly and try to rotate the skin around the inboard aft corner to get a best fit, giving priority to the plus chord alignments.



**Figure 19-35. Definition of Frames and Nominal Dimensions for Final Assembly of the Horizontal Stabilizer.** This drawing is not to scale.

Figure 19-35 is drawn to show the case where the inboard aft end of the plus chord aligns perfectly with the end fitting on the aft spar and the aft skin gap (marked "b") is in the exact middle of its allowed range. Thus all errors are concentrated at the forward edge of the skin, either at the X-direction alignment between points G1 and G2 (representing PKC #1) or at the Y-direction gap between points G3 and G4 (representing PKC #2). The internal skin gap between forward and aft skin is marked "a". The possibility of error in this gap is included in the analysis that follows.

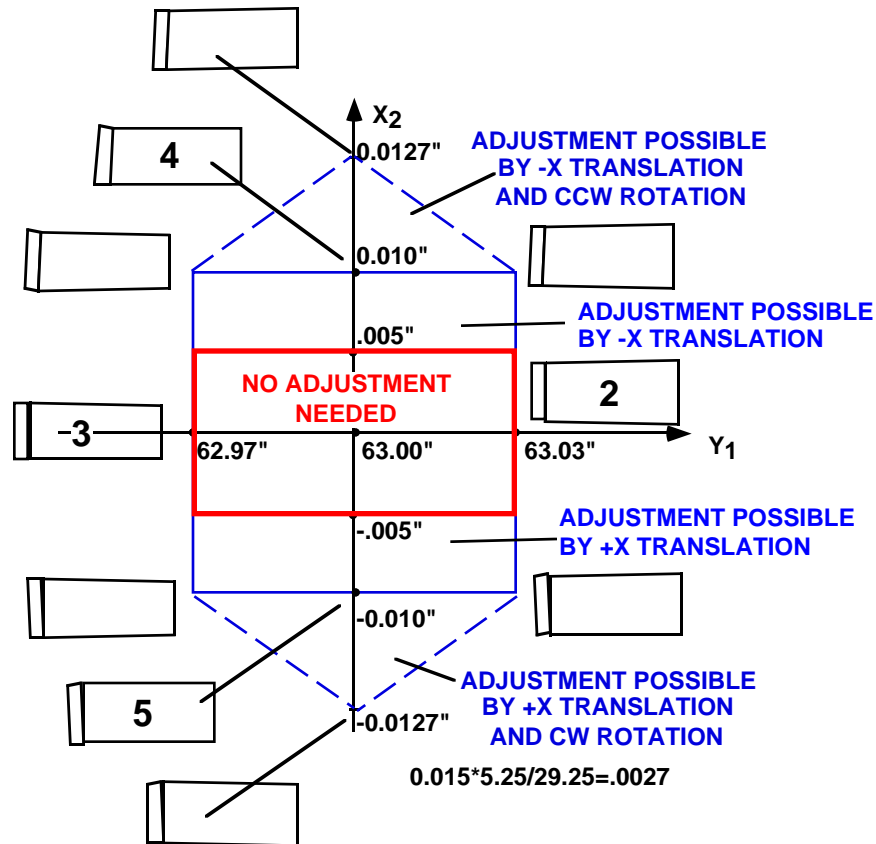
Figure 19-36 shows some of the ways that the skin subassembly might turn out. Four limit possibilities are shown along with the nominal. If the skin is bigger or smaller than the limits shown, and/or if the plus chord is rotated farther either way than the limits shown, then with the aft inboard end of the plus chord properly aligned and the aft gap set in the middle of its allowed range, the assembly would fail both PKCs #1 and #2. Or so it would seem.



**Figure 19-36. Some of the Possible Combinations of Assembly Errors in the Skin Subassembly.** Configuration 1 is the nominal. On it are marked an origin (0,0) indicating the inboard aft corner where the assemblers initially align the skin with respect to the other subassembly. Coordinates (X1, Y1) give the location of point G3 while coordinates (X2, Y2) give the location of point G1. In configuration 2, the plus chord has been aligned properly with respect to the aft skin but the sizes of the skins and their relative positions are such that the distance between the aft and forward edges is at the upper allowed limit. In configuration 3 the skin is at the lower allowed limit. In configuration 4 the skin size is at nominal but the plus chord is misaligned

clockwise to the maximum, while configuration 5 shows the plus chord maximally misaligned counterclockwise. Other combinations are possible.

Actually, the assemblers have a little wiggle room if luck is with them. If the skin is a little small and the plus chord is rotated clockwise from nominal, then the entire skin subassembly can be rotated counterclockwise, improving both PKCs at once. Other fortuitous combinations like this exist, and it is easier to plot them all on a single graph to see what is possible. Figure 19-37 is that graph. It shows that there are three regions in error space, one where the skin subassembly can be left in its initial nominal position, one where up to 0.005" of error in X can be removed from the forward plus chord misalignment by accepting up to 0.005" of aft plus chord misalignment, and the third in which an additional 0.0027" of error in X can be removed from the forward plus chord misalignment by rotating the skin clockwise or counter-clockwise while shifting the skin in the X direction and correspondingly increasing the plus chord misalignment at the aft end.



**Figure 19-37. Combinations of Errors in Skin Size and Plus Chord Rotation That Permit Achievement of the PKCs for the Horizontal Stabilizer.** The horizontal axis gives the value of the Y coordinate giving the position of point G3, while the vertical axis gives the error in the X coordinate of point G1. These are the values we are interested in for determining if the PKCs have been achieved. Four of the five cases marked in Figure 19-36 are

indicated by number in this figure. Note that some combinations need no adjustment at all once the inboard aft corner and the aft skin gap have been set in the middle of their allowed ranges. These combinations occupy the region outlined in heavy lines in the figure. Other combinations of error, occupying the regions outlined in thin lines, permit the PKCs to be achieved by translating the skin in the X direction and/or rotating the skin a little about a pivot point at the inboard aft corner. If the skin is bigger in Y than 63.03 or smaller than 62.97, then no adjustment of its size is possible and PKC #2 cannot be achieved.

A computer variation analysis was performed on this method of assembling the skin to see if the PKCs could be delivered. The chains of frames shown in Figure 19-34 and Figure 19-35 were defined in MATLAB, and random errors were inserted to represent manufacturing errors in locations of holes and slots. (All MATLAB code for this example is on the CD-ROM packaged with this book.) Sources of error include milling machine errors, uncertainty in skin size based on shot peen hardening,<sup>12</sup> and forming errors in the plus chord itself. The MATLAB code appears in Table 19-1, Table 19-2, Table 19-3, and Table 19-4. *Program767.m* in Table 19-1 sets up the operation. It calls program *skins* in Table 19-2, which calculates the nominal locations of all the parts and key locations on them. It then repeatedly calls program *skinerrs* in Table 19-3, which inserts random errors. These errors are accumulated in vectors  $l(i)$ ,  $m(i)$ , and  $n(i)$ . Program *plot\_PC\_gap* in Table 19-4 plots the results.

```
% Program to calculate 767 Horizontal Errors
% what-if tolerance values, one sigma each
D1=.004/3; % hole and slot positions near inboard end
D2=.02/3; % shotpeen-induced error
D3=.012/3; % slot position error on skins far from inboard end
D4=.01; % uniformly distributed plus chord fab error
% calculate nominal positions
skins;
lmax=0;
mmax=0;
nmax=0;
k=10000;
% monte carlo loop to calculate propagated variations
for i=1:k
    l(i)=0;
    m(i)=0;
    n(i)=0;
    d(i)=0;
end
```

<sup>12</sup> Shot peening is a process of hardening a metal part by firing small metal bits, typically the size of poppy seeds, at it. This compresses the outer layers and imposes a compressive stress in them that impedes crack growth. This stress also tends to enlarge the part by an amount that can be hard to predict but can be substantial.



```

for i=1:k
    skinerrs;
    l(i)=63.03-T2G3P(2,4);
    m(i)=T2S1P(1,4)-3;
    n(i)=T1G2(1,4)-T1G1P(1,4);
% various checks
    d(i)=DY;

    if n(i)>nmax
        nmax=n(i);
        J=i;
    end
    if l(i)>lmax
        lmax=l(i);
        K=i;
    end
    if m(i)>mmax
        mmax=m(i);
    end
end
% summary histograms
hist(n,200)
hist(l,200)
gapmax=lmax
slotmax=mmax
PCmax=nmax
plot_PC_gap

```

**Table 19-1. Main Program *Program767.m* for Calculating Errors in Wing Skin Assembly**

```

%skins.m
% nominal locations for aft skin, splice stringer, fwd skin, plus chord
% and key points on them
T12=trans(0,.045,0);
T2H1=trans(3,3,0);
TH13=trans(12,12,0);
T34=trans(0,6,0);
T4G3=trans(28*12,(63-21),0);
T4S1=trans(-12,39,0);
T2G3=T2H1*TH13*T34*T4G3;
TH1S1=TH13*T34*T4S1;
T2S1=T2H1*TH1S1;
TH15=eye(4)*rotz(dtr(90));
T25=T2H1*TH15;
T5G1=trans(63,0,0);
T2G1=T25*T5G1;
T1G4=trans(29.25*12,63.09,0);
T1G3=T12*T2G3;
T1G1=T12*T2G1;
T1G2=trans(3,66.09,0)*rotz(dtr(90));

```

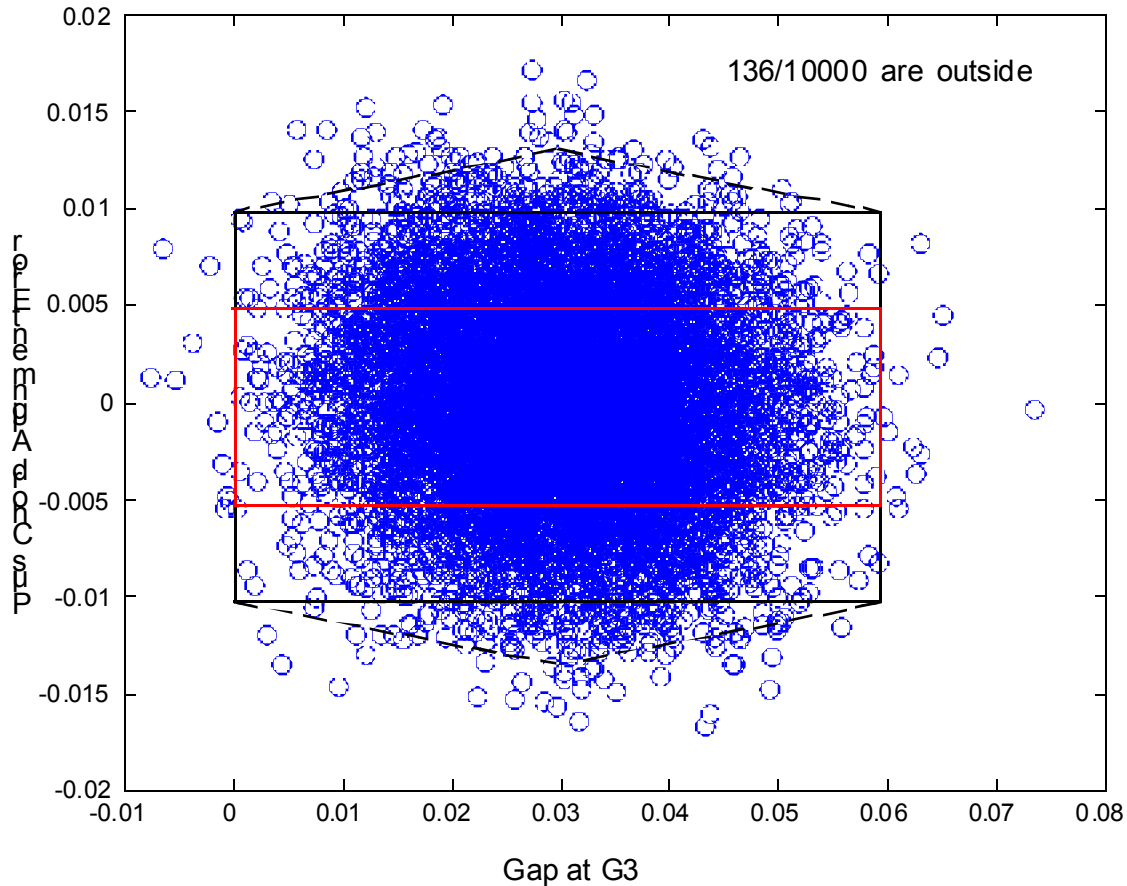
**Table 19-2. Subroutine *skins.m* for Calculating Skin Assembly Errors.** This routine establishes the relationships between the frames defining the main parts and fixtures.

```
%skins.m
% skin errors
% drilling errors on hole and slot locations
DX=D1*randn;
DY=D1*randn;
DT2H1=trans(D1*randn,D1*randn,0);
DX=D1*randn;
DY=D1*randn;
DTH=D3*randn/336;
DTH13=trans(DX,DY,0)*rotz(DTH);
DX=D1*randn;
DY=D1*randn;
DTH=D3*randn/336;
DT34=trans(DX,DY,0)*rotz(DTH);
DX=D1*randn;
DY=D1*randn;
DTH=D3*randn/336;
DT4G3=trans(DX,DY,0)*rotz(DTH);
DX=D1*randn;
DY=D1*randn;
DTH=D3*randn/336;
DT4S1=trans(DX,DY,0);
T2G3P=T2H1*DT2H1*TH13*DTH13*T34*DT34*T4G3*DT4G3;
TH1S1P=TH13*DTH13*T34*DT34*T4S1*DT4S1;
% shot peen error
DX=D2*randn;
DY=D2*randn;
DT4G3=DT4G3*trans(DX,DY,0);
T2G3P=T2G3P*DT4G3;
% plus chord fab error
DTH15=trans(D4*(rand-.5),D4*(rand-.5),0)*rotz((-
TH1S1P(1,4))/TH1S1P(2,4));
T25P=T2H1*DT2H1*TH15*DTH15;
% key points on skin
T2G1P=T25P*T5G1;
T1G1P=T12*T2G1P;
T2S1P=T2H1*DT2H1*TH1S1P;
T1G3P=T12*T2G3P;
```

**Table 19-3. Subroutine *skinerrs.m* for calculating changes to wing skin shape if random errors are included in the transforms relating the parts.**

```
%plot results
plot(l,n,'xb')
xlabel('gap')
ylabel('plus chord error')
```

**Table 19-4. Subroutine *plot\_PC\_gap.m* for Plotting the Results.**



**Figure 19-38. Example Output from MATLAB Simulation of Errors in Wing Assembly.** The acceptance/adjustment zone from Figure 19-37 is drawn to scale on this plot. The plot indicates that nearly all the skin subassemblies will deliver the PKCs. However, it must be remembered that this plot assumes that the parts that the skin assembles to are made and assembled perfectly. In fact, errors of similar size are to be expected in them. Thus far fewer assemblies will deliver the PKCs successfully.

One such plot appears in Figure 19-38. It is based on assuming the error amounts shown in the first few lines of Program767. Errors D1, D2, and D3, are the one-sigma values of presumed Normal distributions, while D4 is one sigma of a uniform distribution. All these distributions are assumed to have zero mean. The construction of the rest of the assembly comprising FTB, FTE, and ribs is assumed to have zero error, so any errors in the construction or assembly of these parts would have to be added to the results in Figure 19-38. This figure shows that nearly all of the skin assemblies will deliver the PKCs. If we assume that comparable errors to D1 – D4 exist in the other parts, then it is likely that a substantial fraction of the skins will not deliver the PKCs.

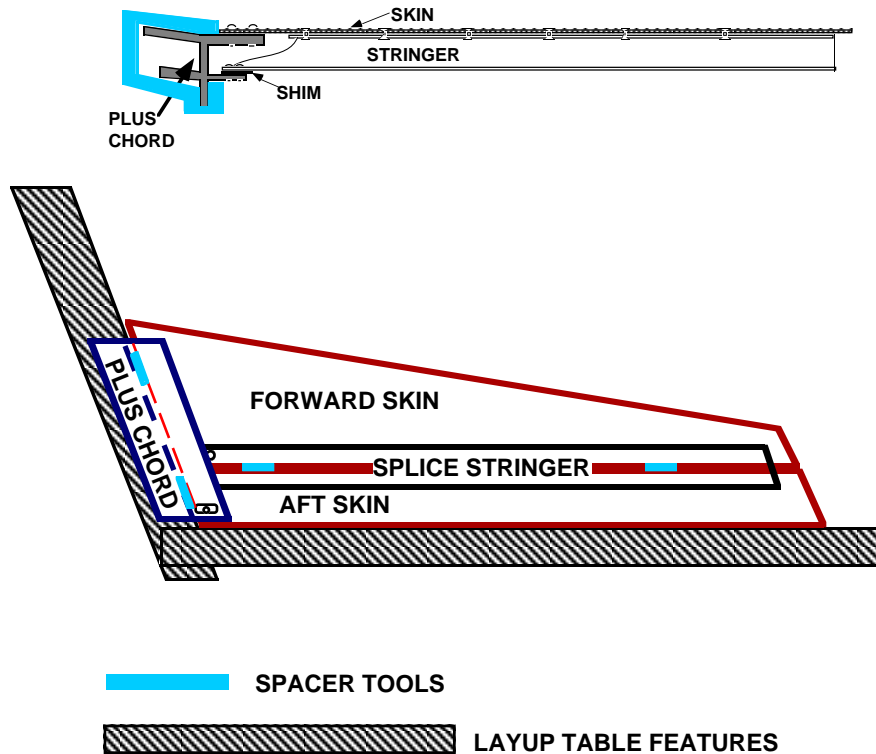
There are several possible responses to such a finding. One is to buy better machine tools. Another is to seek to understand the shot peening

process to better predict the growth in skin size that it creates. Yet another is to think up another process that has a better chance of being successful. A brief look at such an alternative is discussed next.

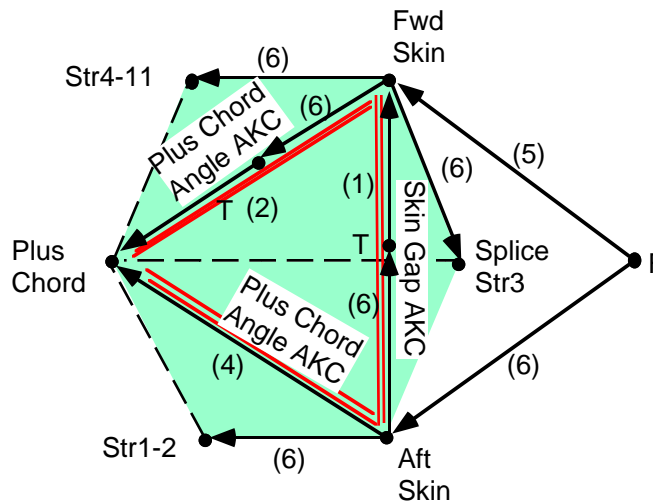
#### **b) Second Proposed Method: A Hybrid**

Proposed process #2 is an assembly approach that defines some new equipment intended to deliver the AKCs repeatably. It is described only briefly here. See Figure 19-39 through Figure 19-42. The concept uses a horizontal flexible contour bed to hold and align the skins. The aft and inboard edges of the skins are the important features. These features contain the angle that generates AKC #1. The two skins are placed on the contour bed and slid inboard and aft until they mate with the edge features on the bed. The forward skin is separated in the fore-aft direction from the aft skin via a hand tool that sets the skin gap and delivers AKC #2. The splice stringer is mated to the forward skin via one hole at the stringer's inboard end and is match-drilled to the two skins, after which temporary fasteners are installed to hold these three parts together. The plus chord is then attached to the aft skin via a hole-slot joint that fixes the plus chord in the fore-aft direction with respect to the skins. Another hand tool is placed between the two inboard skin edges and the web surface of the plus chord so that this surface is at the correct position and angle with respect to the aft edge of the aft skin for the purpose of delivering PKC #1. The plus chord is clamped to the skins and match-drilled so that it can be tack-fastened to both skins. The fully tacked assembly is then taken to a drill and rivet station where final fasteners are installed. The assembly sequence is essentially the same as the one for process #1.

This concept is fundamentally different from proposed process #1 because very few assembly features are created on the parts during fabrication. Instead, proposed process #2 represents an automated, flexible method of accomplishing match drilling and tacking during assembly. Parts are located accurately with a limited amount of small, dedicated fixtures and hand tools so the interfaces that deliver the KCs are tightly controlled. Figure 19-41 shows the only features required to be created on the parts during part fabrication.



**Figure 19-39. Sketch of Process #2 for Wing Skin Subassembly.** This process relies less on assembly features machined into the parts than does process #1. Instead, most of the alignment of the skins and splice stringer at the time of assembly is done using hand tools that mate to part edges rather than aligning holes on parts. The splice stringer is drilled in place after the other parts are located.



**Figure 19-40. DFC for Process #2.** This process uses a mixture of features on parts, a fixture (F), and tools (T) to create proper constraint for all the parts in the wing skin subassembly.

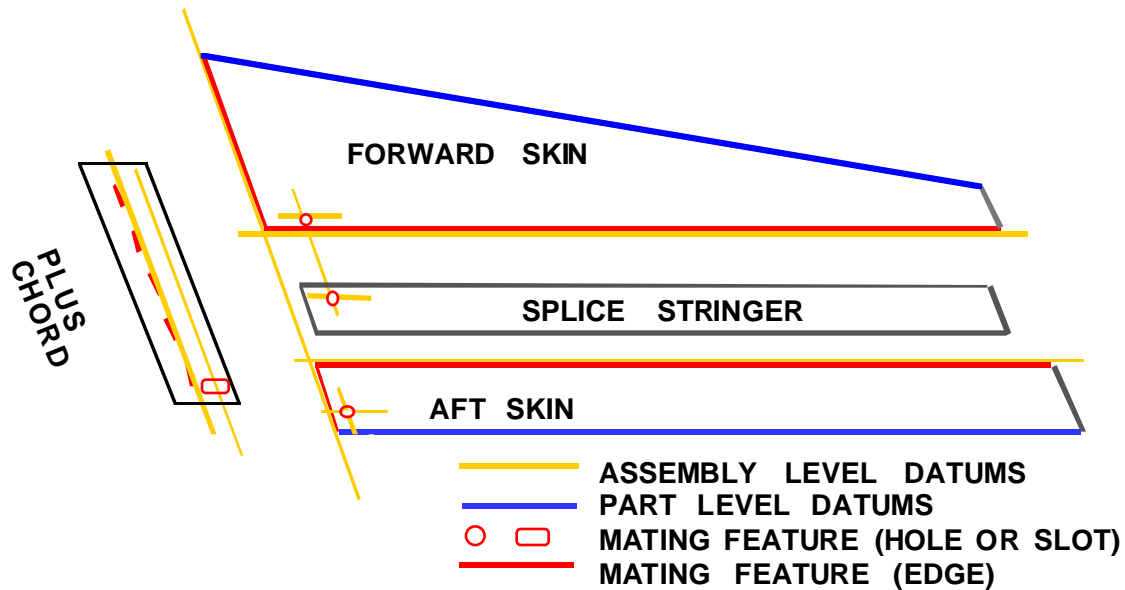


Figure 19-41. Assembly Features for Process #2.

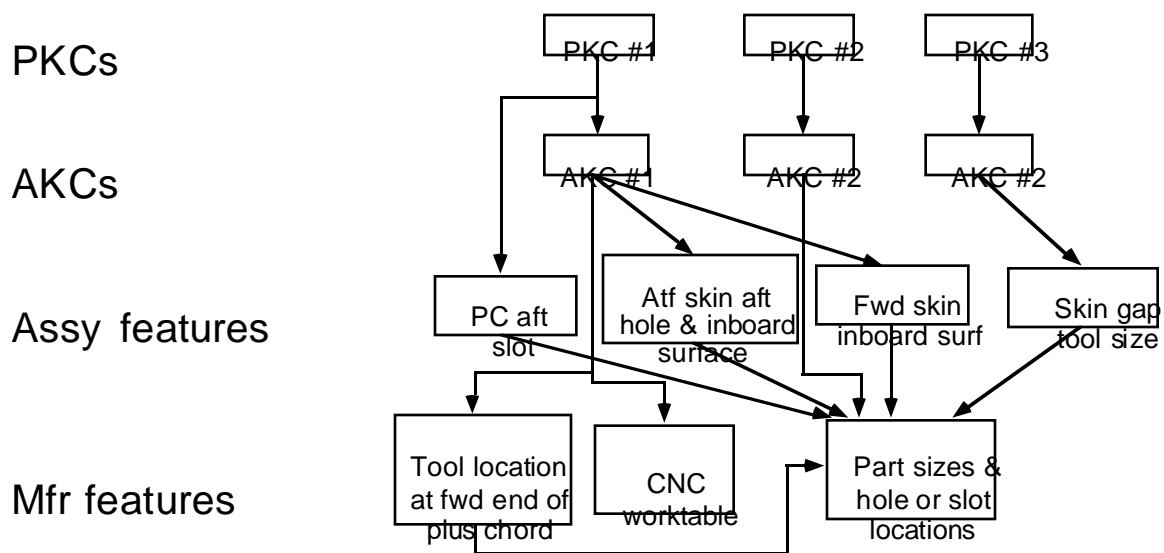


Figure 19-42. KC Flowdown for Process #2.

Although a variation analysis was performed, it is not presented here. It shows that this process is quite capable of delivering all the PKCs, basically because there are so few features on the parts that need to be placed accurately. Many of the key dimensions are achieved with small hand tools that can easily be made to the required tolerances and conveniently checked for wear. They directly transfer important dimensions between adjacent parts, such as between the two skins or between the inboard skin edges and the web of the plus chord that must align with the end fittings. There are fewer intermediate parts and features between one end of each KC and the other. In

other words, most of the chains are shorter. All other things being equal, shorter chains usually develop less variation than longer ones.

However, this process requires new equipment in the form of a layup table with a CNC drilling capability to tack fasten the parts to each other. It also requires an assembly mechanic capable of being trained to operate such equipment, something that had not been done at this company before.

### c) Technical Comparison of the Proposed Processes

Table 19-5 compares the existing process and the two proposals from a mostly technical point of view. It shows that proposed process #1 is unable to deliver PKC #1 on a small percent of the assemblies, while proposed process #2 is able to do so but at a higher cost. The size of PKC #1 errors is not large enough to cause the assemblies to be scrapped because a waiver can be requested from Boeing. In weighing whether to adopt proposed process #1, Vought's management would have to decide if it wanted to take on the risk of requesting waivers if that would mean affecting its quality reputation adversely. Proposed process #2 does not present this risk, although it requires a larger up-front investment plus other costs and considerations discussed in Section 19.B.6

|             | Existing Process                                                                                                                   | Proposed Process #1                                                                                                                                                                                                                   | Proposed Process #2                                                                                                                                               |
|-------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Pros</b> | <ul style="list-style-type: none"> <li>Delivers all AKCs and PKCs repeatably</li> </ul>                                            | <ul style="list-style-type: none"> <li>Delivers AKC #2 and PKC #2 &amp; #3 repeatably</li> <li>Completely flexible method that uses existing machines</li> <li>No dedicated fixtures</li> <li>Controls critical interfaces</li> </ul> | <ul style="list-style-type: none"> <li>Delivers all AKCs and PKCs repeatably</li> <li>Completely flexible method</li> <li>Controls critical interfaces</li> </ul> |
| <b>Cons</b> | <ul style="list-style-type: none"> <li>Inflexible fixtures</li> <li>Variation absorbed at stringer-plus chord interface</li> </ul> | <ul style="list-style-type: none"> <li>Fails to deliver AKC #1 and PKC #1 on a small percent of assemblies</li> </ul>                                                                                                                 | <ul style="list-style-type: none"> <li>Requires higher-functionality tack fixture (higher cost)</li> <li>Requires a limited number of small fixtures</li> </ul>   |

**Table 19-5. Summary of Existing Type-2 Process, a Proposed Type-1 Process, and a Proposed Hybrid Process.**

Further analysis of this table, together with the KC flowdowns of the two processes presented in Figure 19-31 and Figure 19-42, shows that, as expected,



the PKCs are the same because they are customer requirements. The AKCs are the same also, though this is not true in every case. The processes differ in the DFCs and the choice of features used to implement the AKCs. Proposed process #1 is a true Type-1 in the sense that all the assembly features are on the parts when they arrive at the assembly station. In proposed process #2, some of the assembly features are on the parts while others are given to the parts by tooling during assembly, a characteristic of Type-2 assembly processes. Comparison of the variation analysis results indicates that, while a pure Type-1 approach may be attractive, the required tolerances may not be economical to achieve. For this reason, proposed process #2 steps back from that ideal and implements some of the DFCs using hand tools and match drilling.

The wingtip process described in [Swanstrom and Hawke] is achieved almost completely as a Type-1. It is considerably smaller than the 767 wing, so the tolerances are easier to achieve. Additionally, there are no skin gap PKCs. Instead, the main tolerance challenges on the winglet involve gaps that are filled by shims. In several cases, improved process control during part fabrication eliminated the need for shims while in others the size of the shim was predictable, avoiding the time-consuming process of peeling shims to suit the gap.

## 5. Economic Analysis<sup>13</sup>

A business case analysis was done to determine a) how one should use economic analysis to determine if an investment in flexible assembly of the skin subassembly is justified and b) to see if it is justified in this case. The basis of the analysis was the following set of assumptions

1. The base case for comparison was the then-existing manual process (called "as-is").
2. Two candidate automated flexible processes, described above, were compared to the base case. Each candidate is a concept comprising process steps, required mating features machined onto the parts, and various pieces of drilling and riveting equipment.
3. Only the 767 skin subassembly was studied in detail. Conclusions from this study were extrapolated to similar products made for other aircraft.

### a) Methodology

The methodology involved assuming several production scenarios: some involve switching current business from manual to automated processing, while others assume that new business would arrive.

---

<sup>13</sup> Material in this section is based on [Anderson].

Process times were estimated for three manufacturing cells: one that tacked the parts together, one CNC autoriveter for installing the final fasteners, and one finishing cell. Process times were estimated for each machine based on performance of similar equipment observed in the industry. A computer simulation was used to determine the overall capacity of all three cells, including transport capacity between them. Based on the different business scenarios, required investment in equipment to meet production requirements was calculated.

Two studies were conducted within the above scenarios. In the first, only four parts were included in what could be called a pilot program. In the second, all parts made for Boeing 747, 757, and 767 horizontals were included. In each case, one and two shift operations were studied. The four parts were the upper and lower skins of horizontal stabilizers, the skin of a vertical stabilizer, and a center box structure. Times for parts other than horizontal skins were extrapolated from detailed time estimates for skins.

## **b) Results**

Based on a variety of simulations, each of the proposed automated cells reduced process flow-through time by around 50% compared to the existing manual process. The savings from this were attributed entirely to labor costs and amount to about \$480,000 per year if four parts are made in new cells, and \$1.9 million per year if all parts are made. No savings were attributed to work in process inventory, which of course would be substantial.

Equipment investment requirements were based on estimated equipment costs as shown in Table 19-6:

| Process Name        | Tack Cell   | Auto-Rivet Cell | Finishing     |
|---------------------|-------------|-----------------|---------------|
| Proposed Process #1 | \$2 million | \$4.8 million   | \$0.5 million |
| Proposed Process #2 | \$3.5       | \$4.8           | \$0.5         |

**Table 19-6 Equipment Investment Required for Precision Assembly.**

The total number of each kind of machine needed, based on simulating the different scenarios, are shown in Table 19-7 and Table 19-8.

| Scenario           | Tack Cell(s) | Auto-Rivet Cell(s) | Finishing Cell(s) |
|--------------------|--------------|--------------------|-------------------|
| 1 shift/all parts  | 3            | 3                  | 2                 |
| 1 shift/4 parts    | 2            | 2                  | 1                 |
| 2 shifts/all parts | 2            | 2                  | 1                 |
| 2 shifts/4 parts   | 1            | 1                  | 1                 |

**Table 19-7 Equipment Requirements for Different Scenarios for Proposed Processes 1 and 2.**

| Cell        | Proposed Process #1 |          | Proposed Process #2 |          |
|-------------|---------------------|----------|---------------------|----------|
|             | 1 shift             | 2 shifts | 1 shift             | 2 shifts |
| Tack        | 3/65%               | 2/49%    | 3/70%               | 2/53%    |
| Auto Rivet  | 3/93%               | 2/70%    | 3/90%               | 2/68%    |
| Finishing   | 2/80%               | 1/82%    | 2/72%               | 1/74%    |
| Total cells | 8                   | 5        | 8                   | 5        |

**Table 19-8. Equipment Requirements for All Parts and their Utilization.** For example, for proposed process #1, 1 shift operation requires three tack cells, each of which operates at 65% utilization.

### c) Summary Findings

The attributed savings do not provide an attractive rate of return for the estimated investment. Several mitigating factors need to be taken into consideration regarding this conclusion. The above analysis is conservative in attributing savings, because it does not credit the automated processes with any savings due to work in process inventory or quality. Second, should new business arrive, a great deal of savings can be anticipated because new fixtures would not have to be designed and built,<sup>14</sup> although three shift operation might be necessary due to the high rates of utilization under the existing business scenario. Third, no provision was made in this analysis for savings possible should there be a change in product demand mix. In the existing manual environment, there is no way to utilize 747 fixtures for 757 parts, for example. The new equipment is assumed able to do any part from any of the aircraft. Fourth, there was no attribution of savings in floor space, whereas the new equipment would replace many existing fixtures spread over a large floor area. Finally, no savings were attributed to the image of advanced manufacturing that the new processes and equipment would provide.

The result is that a management decision is required, involving additional studies to see if the omitted factors make the investment attractive based on pure business terms or based on that plus the marketing appeal of a new method.

<sup>14</sup> [Swanstrom and Hawke] reports substantial savings of this kind.

## 6. Institutional and Cultural Analysis<sup>15</sup>

The existing process is well-understood throughout the aircraft industry. Managers and shop floor mechanics understand how to carry it out successfully. The required tasks include ensuring that parts are solidly seated in fixtures against their reference surfaces and firmly clamped to each other, as well as carefully drilling holes at designated locations. Some of these locations, such as for holes that join the plus chord to the skins, are defined by drill bushing fixtures that the mechanic attaches to the assembly fixture. The majority of the holes, however, are located by dots of paint that result from the mechanic overlaying a mask on the parts and spraying black paint on the mask. These holes must be drilled with care to ensure that their axes are normal to the surface of the skin. Failure to do so can result in the parts becoming warped and scrapped. Discussions with the mechanics at Vought showed that they have a great deal of “wisdom” which has accumulated over years of building these products. Much of this wisdom is undocumented. In most cases, they are unaware of the overall KC flowdown but understand well what is required of their particular subassemblies.

In most cases, the parts in the existing process have slip-joint contact interfaces to each other. In only one case is it required that a part be the correct shape in order that assembly proceed successfully. That part is the plus chord, which must be sufficiently straight. All the AKCs and PKCs are determined by the fixture, as indicated in the DFC diagrams. This means that the fabrication shop’s performance is measured completely by other factors, such as achievement of correct skin thickness. By contrast, great responsibility falls on the mechanics who care for the assembly fixtures.

If a pure or even hybrid Type-1 process is adopted, there will be several institutional and cultural impacts. First, the fabrication shop will take on crucial responsibility for the success of assembly, because it will apply some or all of the assembly features. If there are problems during assembly, it will no longer be sufficient to look at the assembly fixtures or the assembler himself but instead it will be necessary to hold joint discussions between the assembly shop and the fabrication shop. Diagnosis of problems will require inspecting numerous items located far from each other in the factory. Responsibility for problems and their solution will likely be shared. Such discussions are rarely needed under the existing process. This change may sound easy to accomplish, but it may in fact be the most difficult in practice. As noted in [Henderson and Clark], new architectures require new institutional relationships to be created, and existing organizations have difficulty doing so.

---

<sup>15</sup> Material in this section is based on [Shaukat].

Second, the assembly mechanics will need new skills and attitudes. They will be dealing with a new method of assembly, with new failure modes, requiring new diagnostic methods. Past experience will be a weak guide. The new DFCs will create new relationships between new entities on the parts, which in other respects will look deceptively similar to the old ones. In proposed process #1, for example, the splice stringer takes on a crucial role. In the existing process and in proposed process #2, it is mainly a bystander. Furthermore, in proposed process #2, the assembly mechanics must operate an NC drilling machine much like the machines in the fabrication shop. Such equipment contains software and sensors that are completely new to the assembly mechanics. It has to be treated with care, unlike the assembly fixtures, which are comparatively rugged. When something goes wrong, the indicators will be quite different from the indicators associated with the existing process.

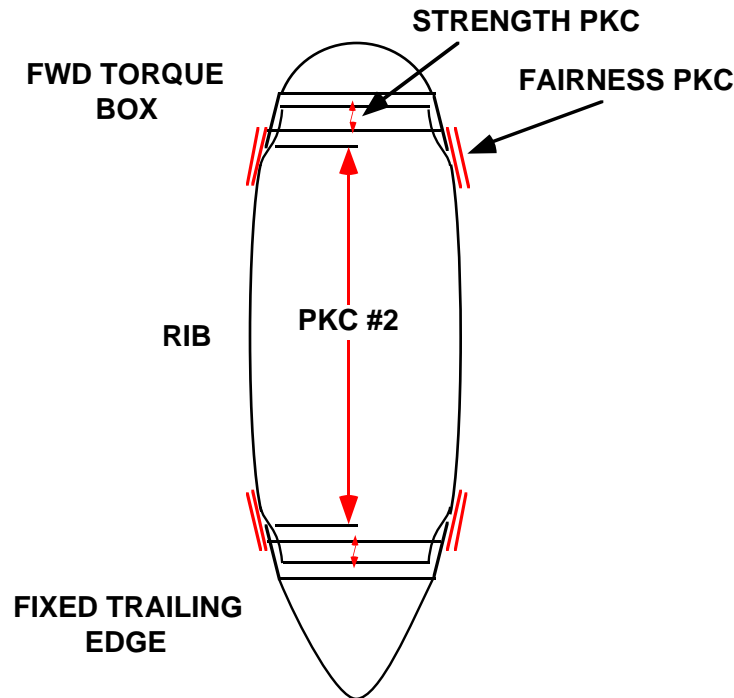
Management's expectations and attitudes will also have to change. They must be prepared to train the mechanics in the necessary skills and processes. They must also be prepared to cooperate among themselves in new ways, because the new processes distribute responsibilities across the shops in new ways. Learning will take place as the new process comes into use. Management must oversee this carefully and ensure that lessons learned are documented and properly incorporated into the procedures and, if necessary, into hardware and software.

### ***C. Type-1 and Type-2 Methods of Final Wing Assembly***

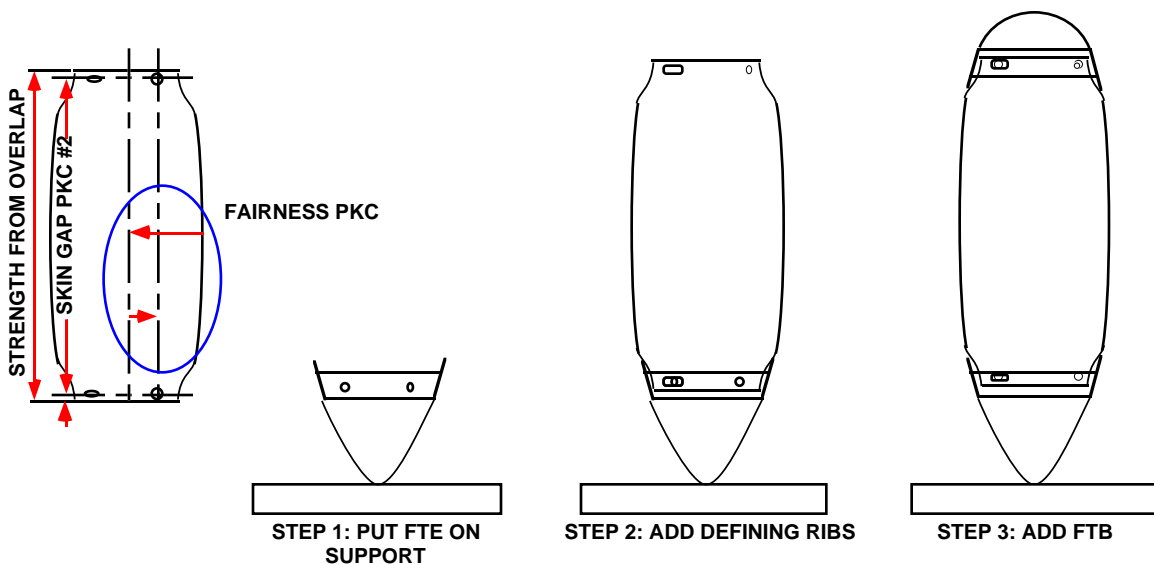
The case study at Vought did not include final assembly but the methods used can be applied to that stage as well. This section briefly analyzes the existing Type-2 process and indicates how it might be converted to Type-1.

As indicated in Figure 19-13, the existing final assembly process is done on a fixture that holds FTB, ribs, and FTE in the correct relative positions. Figure 19-43 shows a cross-section sketch of the subassembly comprising these parts, prior to the skins being installed. This figure shows what the important PKCs are at this stage. The fixture ensures their delivery.

Figure 19-44 shows a set of features on the ribs, FTB, and FTE that will create this subassembly as a Type-1. Essential features have been added to the ribs, FTB, and FTE to transfer the critical dimensions that will locate these parts with respect to each other and deliver the KCs according to the DFC shown in Figure 19-21. This subassembly must be supported against gravity until the skins have been installed. Without the support, it could topple over or could suffer a shear failure in which the FTB falls to the left or right in the plane of the skin while the ribs fold over like dominoes.



**Figure 19-43. Sketch of FTB-Rib-FTE Subassembly with PKCs.** In order to ensure aerodynamic efficiency, the wing skins must blend smoothly into the curvature of the FTB and the FTE. This is called “fairness.” The strength of the wing depends on the previously identified PKC #1, as well as on the ribs overlapping their mating surfaces on the FTB and FTE respectively as shown here. (Remember that PKC #1 depends on a dimension that is perpendicular to the plane of this drawing.) The figure also shows PKC #2 as the distance between the skin edges on the FTB and FTE. In the existing Type-2 process, the final assembly fixture delivers all these PKCs.



**Figure 19-44. Sketch of FTB-Rib-FTE Assembly as a Type-1.** At the left is shown a rib with the key dimensions contributing to the fairness PKC and the skin gap PKC #2. Also shown are a pin-hole and pin-slot compound feature at each end of the rib. Two ribs will have these features (called the defining ribs by Hart-Smith as discussed in Chapter 4) and will be installed first. One of these is the most inboard or pivot rib, which directly creates the fore-aft spacing between the end fittings on the forward and aft spars. The other is at the outboard end. After the two defining ribs have been assembled to the FTE, the FTB will be installed on them. Then, all other ribs will be drilled in place after being tacked to the FTB and FTE via sacrificial tack holes and temporary fasteners that deliver the fairness PKC at each rib. Since the subassembly of FTB, ribs, and FTE is not very stable in the upright orientation, some kind of support must be provided. Unlike a true assembly fixture, this support does not have any mates to the subassembly. Therefore it is relatively inexpensive.

Installation of the skin subassemblies proceeds just as it does in the existing process, due to the difficulty of making all of these parts to sufficient accuracy to permit a pure Type-1 process. An unresolved issue involves final achievement of PKC #1. Since there is no hard fixture holding the FTB-Ribs-FTE subassembly, one could imagine using the plus chord as the reference for aligning the forward and aft end fittings to the plus chord. In this scenario, the skin subassembly would be mounted relative to the aft spar so that the plus chord aligned with the aft end fitting and the aft skin gap was centered in its tolerance range. Then the FTB would be shifted slightly left or right (inboard or outboard), taking advantage of the flexibility of the ribs, until the forward end fitting aligned with the forward end of the plus chord. One could imagine accomplishing this shift with a jack screw on the support that keeps the FTB-ribs-FTE subassembly upright. Assuming that the parts had been made to the required tolerances, the required shift would be no more than a few thousandths of an inch. PKC #1 could essentially be delivered perfectly without the need of any shims. If this method did not deliver the forward skin gap adequately, then the skin could be shifted up or down (forward or aft) until it were, and then the rest of the process could proceed as before. This scenario thus has the potential to reduce or eliminate the coupling between PKC #1 and PKC #2.

#### ***D. Chapter Summary***

Assembly system planning is a critical decision period that will have a lasting effect on product cost and quality. Like any design problem, successful assembly system planning requires recognition of design requirements and a sound up-front approach to trade-offs. This chapter demonstrated a structured method to perform a holistic process for designing complex assemblies and their assembly processes. It employed all of the assembly design methods described in earlier chapters.



The case study produced two proposed approaches to flexible assembly of large aircraft skin structures, with a focus on delivering the critical interfaces while minimizing cost where possible. The two approaches were the input for an important decision, trading off equipment investment versus repeatable delivery of the AKCs. The method allowed us to focus investments toward the most important interfaces and to perform a variation analysis that is an important input to the cost trade-off.

The case study started from an existing product and assembly decomposition. Such a starting point put constraints on the possible decisions. Naturally, the methodology would have a much larger influence and more scope if it were to be applied during design of a new item, as was done by [Swanstrom and Hawke]. Then, assembly system assessments could be made early in the process while product architectures were being debated and the PKC flowdown process was under way. Specifically, assembly system planners would be able to assess different candidate assembly decompositions by identifying AKCs and utilizing the method presented here. AKCs are unique to a particular candidate assembly decomposition. Because the assembly decomposition does not always match the product decomposition, AKCs can be used to assess the effect of assembly decomposition decisions. Therefore, recognition of AKCs can allow candidate assembly systems to be evaluated based on the ability to deliver AKCs, and hence satisfy the requirements stated in the PKCs, in addition to other merits such as cost, capacity, ergonomics, etc. An approach to evaluating KC flowdowns for different assembly decompositions may be found in [Cunningham and Whitney]. It permits different AKCs to be compared early in product design.

Naturally, when suppliers are involved in making portions of a final assembly, they must be involved in the decomposition process so that they can propose AKCs that fit their experience and methods. If these AKCs affect design details that are the responsibility of the final assembler, then this fact must be taken into account.

The economic analysis, while not favorable on the narrowest of criteria in this particular case, nevertheless points to ways that can lead to adoption of such methods in the future, especially if sufficient new business arrives.

### ***E. Problems and Thought Questions***

1. Figure 19-44 and its caption refer to several PKCs. Do they conflict?

2. Section 19.B.5 contains an economic analysis based on replacing the existing fixtures with various Type-1 processes that require new equipment. The analysis concludes that the investment is not easy to justify based on labor replacement alone. If we assume that new business arrives, the analysis would likely be different. If Vought were to continue using Type-2 methods, new fixtures would have to be designed and built for each new horizontal

stabilizer assembly. Assume that such fixtures would cost a total of \$2 million. If the investment in Type-1 processes to support production of four parts had been made, assume that a reprogramming and tool adjustment cost of \$100K would be required instead. Would one new stabilizer design within two years of setting up the Type-1 process be sufficient to make the investment attractive? How about two new stabilizer designs within 4 years?

3. Section 19.F analyzes the features proposed for skins, splice stringer, and plus chord for proposed process #1 and concludes that they are properly constrained. Repeat this analysis for proposed process #2.

4. Draw the DFC for the Type-1 final assembly process for placing the skin subassembly onto the FTB-ribs-FTE subassembly as discussed in Section 19.C. This process suggests exploiting the flexibility of the ribs to help deliver PKC #1. Pay particular attention to what locates what when considering the plus chords and the end fittings on the forward and aft spars. How do you represent the fact that the ribs locate FTB with respect to FTE in the fore-aft direction but not the inboard-outboard direction? Remember that this issue is involved in the DFCs for car doors discussed in Chapter 8.

5. Using the same basic part errors used for proposed process #1, repeat the variation analysis described in Section 19.B.4.a)(2) for proposed process #2. Assume that fixture errors are  $\pm 0.005''$  and hand tool errors are  $\pm 0.002''$ .

6. When a variation analysis is performed, it is important to know what errors within the process contribute the most to the variation at the assembly level. This is often called a sensitivity analysis. Using either the given analysis for proposed process #1 or the analysis developed in the previous problem, determine the sensitivities for each of the features based on increasing or decreasing the individual feature errors by  $0.001''$ .

## ***F. Appendix***

This appendix contains details of the motion and constraint analyses of the wing assembly using features for proposed process #1.

### **Motion analysis:**

Left path twists:

»TPCAS=[0 0 1 0 0 0] (read: Twist for Plus Chord to Aft Skin)

TPCAS =

0 0 1 0 0 0

Right path twists:

»TPCFS=[0 0 1 63 0 0; 0 0 0 1 0] (Plus Chord to Forward Skin)

TPCFS =

0 0 1 63 0 0

0 0 0 0 1 0

»TFSSS=[0 0 0 0 0] (Forward Skin to Splice Stringer)

TFSSS =

0 0 0 0 0 0

»TSSAS=[0 0 0 0 0] (Splice Stringer to Aft Skin)

TSSAS =

0 0 0 0 0 0

Union of left path twists:

»TLPU=TPCAS

TLPU =

0 0 1 0 0 0

Union of right path twists:

»TRPU=[TPCFS;TFSSS;TSSAS]

TRPU =

0 0 1 63 0 0

0 0 0 0 1 0

0 0 0 0 0 0

0 0 0 0 0 0

Motion analysis:

»WLPU=recip(TLPU)

WLPU =

1 0 0 0 0 0

0 1 0 0 0 0

0 0 1 0 0 0

0 0 0 1 0 0

0 0 0 0 1 0

»WRPU=recip(TRPU)

WRPU =

1.0000 0 0 0 0 -63.0000

0 0 1.0000 0 0 0

0 0 0 1.0000 0 0

0 0 0 0 1.0000 0.0000

»WLRU=[WLPU;WRPU]

WLRU =

1.0000 0 0 0 0 0

0 1.0000 0 0 0 0

0 0 1.0000 0 0 0

0 0 0 1.0000 0 0

0 0 0 0 1.0000 0

1.0000 0 0 0 0 -63.0000

0 0 1.0000 0 0 0

0 0 0 1.0000 0 0

0 0 0 0 1.0000 0.0000

»TLR=recip(WLRU)

empty matrix

TLR =

[]

This shows that the parts are not under constrained.

**Constraint analysis:**

»TLRU=[TLPU;TRPU]

```

TLRU =
  0  0  1  0  0  0
  0  0  1  63  0  0
  0  0  0  0  1  0
  0  0  0  0  0  0
  0  0  0  0  0  0
»WLR=recip(TLRU)
WLR =
  0  0  1  0  0  0
  0  0  0  1  0  0
  0  0  0  0  1  0

```

»This result warns us that there is over-constraint along Z and about X and Y. This arises due to the possible conflict between the pins in the slot and hole joining the plus chord and the skins. In our case, the skins are flexible enough that no undue stress will arise from these over-constraints.

**Table 19-9. Details of Motion and Constraint Analysis of Wing Skin Subassembly Using First Proposed Process**

### ***G. Further Reading***

[Anderson] Anderson, Mary Ann, "Analysis of Flexible Assembly Implementation in the Automotive and Aerospace Industries," MIT Mech Eng Dept SM Thesis, Feb, 1997.

[Cunningham, et al] Cunningham, T. W., Lee, D.J., Mantripragada, R., Thornton, A.C., and Whitney, D.E., "Definition, Analysis, and Planning of a Flexible Assembly System," Proceedings of the Japan/U.S.A. Symposium on Flexible Automation, ASME, Boston, MA, June, 1996.

[Cunningham and Whitney] Cunningham, T. W., and Whitney, D. E., "The Chains Metrics Method and its Role in Identifying Integration Risk in Concept Design," paper DETC98/DTM-5662, ASME Design Theory and Methodology Conf, Sept 13-16, 1998, Atlanta GA.

[Hart-Smith] D. J. Hart-Smith, "Interface Control-The Secret to Making DFMA Succeed," presented at Society of Automotive Engineers, 1997, SAE Paper 972191.

[Henderson and Clark] Henderson, R. M., and Clark, K. B., "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Admin. Sci. Q., vol 35 (1990), pp 9-30.

[Munk and Strand] Munk, C., and D. Strand, "AFPAC-Accurate Fuselage Panel Assembly Cell," SAE Paper 922411, presented at Aerofast 92, Oct 13-15, 1992

[Muske] Muske, S., "Application of Dimensional Management on 747 Fuselage," SAE Paper 975605, 1997.

[NASA CR-4730] D.R Polland, S. R. Finn, K. H. Griess, J. L. Hafenrichter, C. T. Hanson, L. B. Ilcewicz, S. L. Metschan, D. B. Scholz, and P. J. Smith, "Global Cost and Weight Evaluation of fuselage Side Panel Design Concepts," April, 1997.

[NASA CR-4735] K. S. Willden, C. G. Harris, B. W. Flynn, M. G. Gessel, D. B. Scholz, S. Stawski and V. Winston, Advanced Technology Composite Fuselage---Manufacturing, April 1997,

[Niu a] Niu, Michael C. Y., *Airframe Structural Design*, Los Angeles: Technical Book Company, 1988

[Niu b] Niu, Michael C. Y., *Composite Airframe Structures*, Los Angeles: Technical Book Company, 1992.

[Shaukat] Shaukat, T. M., "Aligning Technical and Organizational Aspects of Complex Manufacturing Systems," MIT Technology and Public Policy SM Thesis, January, 1997.

[Swanstrom and Hawke] Swanstrom, F. M., and Hawke, T., "Design for Manufacturing and Assembly (DFMA): A Case Study in Cost Reduction for Composite Wingtip Structures," Proceedings of the 31<sup>st</sup> International SAMPE Technical Conference, Chicago, Oct 26-30, 1999, p 101-113.

**H. Index**

|                                               |                              |
|-----------------------------------------------|------------------------------|
| “                                             |                              |
| “as-built” drawing                            | 29                           |
| “as-designed” drawing                         | 29                           |
| <b>7</b>                                      |                              |
| 767 FTB-Rib-FTE subassembly                   | 20                           |
| 767 horizontal stabilizer                     | 15                           |
| existing manufacturing method                 | 20                           |
| main parts                                    | 18                           |
| 767 upper wing skin subassembly               | 21                           |
| <b>A</b>                                      |                              |
| Airbus                                        | 8                            |
| Aircraft structures                           | 1                            |
| AKCs                                          |                              |
| of 767 horizontal stabilizer                  | 30                           |
| of proposed Type-1 assembly of 767            |                              |
| horizontal stabilizer                         | 36                           |
| aluminum                                      |                              |
| aircraft structure                            | 2                            |
| architecture                                  |                              |
| of 767 horizontal stabilizer                  | 22                           |
| assembly efficiency                           |                              |
| of aircraft assembly                          | 12                           |
| Assembly KCs (AKCs)                           |                              |
| of 767 horizontal stabilizer                  | 15                           |
| assembly sequence                             |                              |
| for proposed Type-1 767 horizontal stabilizer |                              |
| process                                       | 41                           |
| of 767 horizontal stabilizer                  | 25                           |
| asset specificity                             | 6                            |
| <b>B</b>                                      |                              |
| best fit                                      |                              |
| in aircraft assembly                          | 26                           |
| Boeing                                        | 1, 11                        |
| 777                                           | 14                           |
| bolted assemblies                             | 7                            |
| <b>C</b>                                      |                              |
| carbon fiber epoxy composites                 |                              |
| aircraft structure                            | 9                            |
| constraint                                    | 1                            |
| contact                                       |                              |
| in aircraft assembly                          | 12                           |
| cost                                          |                              |
| of carbon fiber epoxy composite aircraft      |                              |
| structure                                     | 9                            |
| <b>D</b>                                      |                              |
| Datum Flow Chain                              | 1                            |
| DFA study                                     |                              |
| of aircraft assembly                          | 12                           |
| DFC                                           |                              |
| existing, for 767 horizontal stabilizer final |                              |
| assembly                                      | 33                           |
| <b>for 767 wing skin subassembly</b>          | 32                           |
| for aircraft assemblies                       | 6                            |
| for proposed Type-1 assembly of 767           |                              |
| horizontal stabilizer                         | 36                           |
| of 767 horizontal stabilizer                  | 28                           |
| <b>E</b>                                      |                              |
| economic analysis                             | 1                            |
| of proposed 767 Type-1 assembly process       | 56                           |
| existing assembly process                     |                              |
| of 767 horizontal stabilizer                  | 26                           |
| <b>F</b>                                      |                              |
| final assembly                                |                              |
| existing, of 767 horizontal stabilizer        | 32                           |
| Type-1, of 767 horizontal stabilizer          | 60                           |
| fixed trailing edge (FTE)                     |                              |
| of 767 horizontal stabilizer                  | 16                           |
| fixture                                       |                              |
| existing, for 767 skin subassembly            | 31                           |
| fixtures                                      |                              |
| for aircraft assembly                         | 5                            |
| forward torque box (FTB)                      |                              |
| of 767 horizontal stabilizer                  | 16                           |
| <b>I</b>                                      |                              |
| integral                                      |                              |
| wing design                                   | 8                            |
| <b>K</b>                                      |                              |
| Kawasaki Heavy Industries                     | 11                           |
| KC flowdown                                   |                              |
| existing, for 767 horizontal stabilizer       | 34                           |
| for proposed Type-1 767 horizontal stabilizer |                              |
| process                                       | 39                           |
| KCs                                           |                              |
| conflict in proposed Type-1 767 horizontal    |                              |
| stabilizer process                            | 42                           |
| conflict, in 767 horizontal stabilizer        | 26                           |
| uncoupled, in 767 horizontal stabilizer       | 23                           |
| key characteristics                           | 1. <i>See also</i> KCs, PKCs |
| <b>L</b>                                      |                              |
| lower skin                                    |                              |
| of 767 horizontal stabilizer                  | 16                           |
| <b>M</b>                                      |                              |
| mate                                          |                              |
| in aircraft assembly                          | 12                           |

|                                                         |        |
|---------------------------------------------------------|--------|
| MATLAB                                                  |        |
| analysis of variation of 767 horizontal stabilizer..... | 48     |
| modular                                                 |        |
| wing design.....                                        | 8      |
| motion analysis                                         |        |
| of proposed 767 horizontal stabilizer assembly .....    | 39     |
| <b>N</b>                                                |        |
| NC drilling machine                                     |        |
| temperature-compensated.....                            | 11     |
| <b>O</b>                                                |        |
| over-constraint                                         |        |
| in 767 horizontal stabilizer.....                       | 37     |
| <b>P</b>                                                |        |
| pin-hole and pin-slot toolkit features                  |        |
| used in 767 horizontal stabilizer.....                  | 37     |
| PKCs                                                    |        |
| of 767 horizontal stabilizer.....                       | 17, 21 |
| plus chord                                              |        |
| of 767 horizontal stabilizer.....                       | 16     |
| Product KCs (PKCs)                                      |        |
| of 767 horizontal stabilizer.....                       | 15     |
| <b>R</b>                                                |        |
| ribs                                                    |        |
| of 767 horizontal stabilizer.....                       | 16     |
| riveting machines                                       |        |
| for aircraft.....                                       | 3      |
| rivets, riveting .....                                  | 2      |
| robustness                                              |        |
| of DFC for 767 horizontal stabilizer .....              | 38     |
| <b>S</b>                                                |        |
| shot peen hardening .....                               | 48     |
| spars                                                   |        |
| of 767 horizontal stabilizer.....                       | 16     |
| stressed skin.....                                      | 8      |
| stressed skin                                           |        |
| wing design.....                                        | 2      |
| stringers                                               |        |
| of 767 horizontal stabilizer.....                       | 16     |
| <b>T</b>                                                |        |
| temperature                                             |        |
| effect on 767 horizontal stabilizer assembly            |        |
| process.....                                            | 38     |
| thermal expansion coefficient.....                      | 8      |
| tolerances.....                                         | 1      |
| Type-1 assemblies                                       |        |
| bridges and buildings.....                              | 8      |
| conversion of aircraft from Type-2.....                 | 11     |
| Type-1 assembly                                         |        |
| for 767 horizontal stabilizer, first proposed.          | 36     |
| for 767 horizontal stabilizer, second proposed          |        |
| process.....                                            | 52     |
| Type-2 assemblies                                       |        |
| aircraft.....                                           | 7      |
| Type-2 assembly process                                 |        |
| for 767 horizontal stabilizer.....                      | 30     |
| <b>U</b>                                                |        |
| upper skin                                              |        |
| of 767 horizontal stabilizer.....                       | 16     |
| <b>V</b>                                                |        |
| variation analysis                                      |        |
| of proposed Type-1 767 horizontal stabilizer            |        |
| process.....                                            | 43     |
| Vought.....                                             | 14     |
| <b>W</b>                                                |        |
| welding .....                                           | 3      |
| wingtip                                                 |        |
| composite, for 767 .....                                | 12, 56 |