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Wood to Metal: The Structural Origins of the Modern Airplane

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The transition from the wood-and-fabric airplane to the all-metal airplane was essentially complete by World War II. The late 1920s and early 1930s are said to have witnessed a structural revolution in aeronautics with the appearance of streamlined metal aircraft with such features as tightly cowled multiple engines, variable-pitch propellers, retracting landing gear, and stressed-skin aluminum construction. A prevalent assumption regarding this transition is that the building material acted as a primary driver of change, that engineering advance was guided by an inevitable move toward metal structures. Metal did indeed allow engineers to extend performance parameters afforded by innovative structural designs, but, interestingly, many of these key innovations were not developed to take advantage of metal. They emerged independent of the construction material, and often were first used in wooden airplanes. The cluster of original ideas that coalesced in the 1930s constituted one of the major watershed periods in aerospace technology. Metal carried this basic design revolution to the limits of its engineering and technical feasibility, but only after a new foundation was in place. Metal did not spawn the structural revolution. An exploration of the roots of the structural revolution in aeronautics and the complexity of technological progress is presented.

Introduction

APART from jet propulsion, arguably the most influential advance in aeronautical development since the Wright brothers successfully flew their first flyer, was the transition from wood-and-fabric airplanes to all-metal aircraft. The essentials of the story suggest that the fragile, slow, wood-frame, fabric-covered, wire-braced biplanes of the 1920s and early 1930s were supplanted by sturdy, sleek, all-metal monoplanes in the mid-to-late 1930s because of improved powerplants and because manufacturers were able to take advantage of lightweight metals as the primary building material. In short, there was a structural revolution in aeronautics during the decade preceding World War II, emphasizing metal construction.

Like many oversimplified summaries, the preceding statement is basically true. The wood-and-fabric airplane did cease to predominate after 1935. The streamlined metal aircraft that emerged in the mid-1930s, with tightly cowled multiple engines, retracting landing gear, variable-pitch propellers, and stressed-skin aluminum construction did represent a watershed in aircraft design. The overall look and performance of airplanes was fundamentally different by World War II. How did this really happen? Precisely what were the revolutions? Was the shift to metal a simple and straightforward advance, obvious in nature?

A prevalent assumption regarding the transition to all-metal aircraft is that the building material acted as the primary driver of structural design change, that engineering advance was guided by an inevitable move toward metal structures. This may seem a reasonable conclusion given that metal construction has enabled aircraft to endure the greater stresses incurred at high speeds and when carrying large payloads. Indeed, it would, of course, not be possible to achieve the same performance of a Boeing 747 passenger airliner or an F-15 fighter aircraft if they were constructed of wood. Moreover, even during the heyday of the wooden airplane during the 1920s and early 1930s, a large segment of the aeronautical engineering community expressed a strong bias against wood. Even though no clear advantage of metal over wood from a technical point of view yet existed in this period, engineers enthusiastically supported the metal airplane as superior and progressive [Refs. 1 (especially chapters 1 and 3) and 2]. On the surface, it would appear self-evident that materials were the critical factor underlying the structural revolution in aeronautics.

The problem with this deduction is that it in part masks the true pattern of the development of aircraft engineering and design. Yes, metal did allow engineers to extend performance parameters afforded by innovative structural designs. However, and this is the significant point, many of those key innovations were not developed necessarily to take advantage of metal. They emerged independent of the construction material and often were first used in wooden airplanes.

During the two decades prior to the so-called structural revolution of the mid-1930s, a number of pivotal advances in structural design emerged that would become standard practice by World War II. These improvements were first manifest mostly in wooden aircraft construction. Once this set of revolutionary design practices was in place, metal airplanes became dominant because of other advantages that this material had to offer; but the cluster of original ideas that coalesced in the 1930s, constituting one of the major watershed periods in aerospace technology, were developed largely independent of the material.

Without question metal did allow the new design concepts to be pushed further in terms of handling greater flight loads because of increased size, speed, and maneuverability of aircraft. Metal also played an important role in simplifying manufacturing techniques, especially for mass-produced aircraft such as large transports and military airplanes; but, again, it was not the primary driver of fundamental change. Rather, metal carried the basic design revolution to the limits of its engineering and technical feasibility after this new foundation was in place. There were parallel and overlapping aspects to the use of metal and wood as basic construction materials as the modern airplane evolved. It was not a simple case of one material replacing the other. A brief overview of several of the key engineering innovations leading up to the structural revolution of the 1930s makes this clear.

Wood and Fabric

The airplane was the first major technology where weight was an overriding concern. Although it is a factor in the design of ships, locomotives, automobiles, and other transportation machinery, weight considerations are not pivotal to the basic functioning of those technologies as is the case with the airplane. Because of the unique nature of an aerial craft, namely, that it must operate against the force of gravity entirely, weight, or more specifically power-to-weight and strength-to-weight ratios, are among the chief design parameters.

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At the very beginning of the airplane's history, because of this unalterable technical condition, wood was the only viable material from which to build a flying machine. (Some early pioneers, such as Samuel P. Langley and Hiram Maxim, experimented with aircraft employing metal structures, but these efforts saw little success.) When the Wright brothers and their contemporaries made their first tentative leaps into the air, lightweight structures were especially critical. The most successful of the pioneer experimenters, including the Wrights, tested their aerodynamic research and flight control systems using unpowered gliders. Because of the low airspeeds and limited lift-generating capacity of these craft, lightness was essential. Wood was the only feasible substance from which to construct supporting surfaces light enough to fly and also strong enough to withstand flight loads. Other factors that made wood the material of choice were the ease with which it could be fashioned and repaired and its low cost. Bear in mind that at the turn of the century it was still a decade or more before aluminum became readily available at reasonable prices.

Within a few short years after Wilbur and Orville Wright broke the final barriers to human flight over the beach at Kitty Hawk on December 17, 1903, the basic structural design of the first generation of powered, heavier-than-air flying machines was in place: the spar-and-rib wing (Fig. 1), the wire-braced, box-girder fuselage, the wire-trussed, strut-supported biplane wing cell, sealed fabric skin over the airframe, two-wheel fixed landing gear, and so on. Variations existed of course, but these features were standard by the outbreak of World War I. The classic wire-braced, wood-and-fabric biplane was born (Fig. 2).

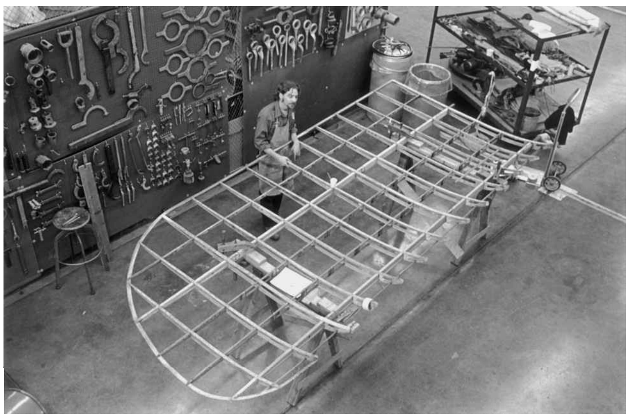

Fig. 1 Standard spar-and-rib wing structure of the first generation of wooden airplanes; this wing is from a 1914 Blériot XI [Smithsonian Institution (SI) negative number 78-17308-20A].

Cantilevers and Monocoques

As with any new technology, be it a potential weapon or lifesaving tool, war always seems to accelerate development. The airplane was no exception. As the armies of Europe devoured each other on the battlefield in World War I, military strategists experimented with the new technology and explored its potential. Industrial entrepreneurs raced to design faster, stronger, and more effective aircraft to better exploit newly emerging aerial tactics. Whatever your perspective on the military success of the airplane in World War I and the influence of that experience on the subsequent course of airpower, there is little arguing with the dramatic advances in aircraft performance during World War I, from a purely technical point of view.[3–5]

With regard to aircraft structures, the two most significant developments to come out of World War I were the fully cantilevered wing and the monocoque fuselage. The cantilevered wing continued to use the basic rib-and-spar arrangement, but this form of construction was designed such that the main spar was a self-supporting beam. In other words, the strength and stiffness of the spar alone could support the flight loads on the wing. No additional external wire bracing or struts were required to keep the wings from collapsing in flight. This was achieved by adding a shear web to the spar by facing it with wooden flanges with the grain oriented at different angles to the main member of the spar. The effect could also be accomplished with a box spar. A box spar, as the name implies, is made by simply constructing the main supporting member of the wing as a long, narrow box to provide the necessary rigidity. Initially, cantilevered wings were covered with fabric in the same manner as conventional wing structures, but soon they began to be skinned with thin wooden veneer, resulting in added strength. These wooden-skinned wings became known as stressed-skin wings because the veneer actually was a load-bearing component of the structure, unlike a fabric covering.

The well-known Dutch aircraft manufacturer, Anthony Fokker, who built airplanes for the Germans during World War I, was among the earliest designers to put the cantilevered wing to good advantage. His famous Dr. I Triplane (Fig. 3) and highly successful D.VII biplane (Fig. 4) featured fabric-covered cantilevered wings with box spars, and his sleek D.VIII monoplane (Fig. 5) foreshadowed a coming standard with its thick-sectioned, plywood-sheeted, cantilevered single wing. Although the D.VIII came too late to have any impact on the war's outcome, Fokker evolved the design into a series of very successful single- and multiengine transport aircraft that played a significant role in the burgeoning air passenger industry during the 1920s.[6–8]

The other key design innovation of the period was the monocoque fuselage. French for single shell, the monocoque fuselage did away with the familiar fabric-covered box-girder approach by making

Fig. 2 Classic wire-braced, wood-and-fabric biplane that remained the standard structural design through the 1920s; this biplane is a World War I Bristol Scout (SI negative number 78-18721).

Fig. 3 Fokker Dr. I Triplane featured fabric-covered cantilevered wings with box spars; note the absence of wire bracing between the wings (SI negative number A9851-A).

Fig. 4 Fokker D.VII had structural features similar to the Dr. I (SI negative number 94-7729).

Fig. 5 Sleek 1918 Fokker D.VIII monoplane foreshadowed a coming standard with its thick-sectioned, plywood-sheeted, cantilevered single wing; Anthony Fokker, in front in necktie, humorously demonstrates the strength of the D.VIII wing design (SI negative number A2185).

Fig. 6 Albatros fighter with fabric covering removed, showing its plywood monocoque fuselage (SI negative number 78-18979).

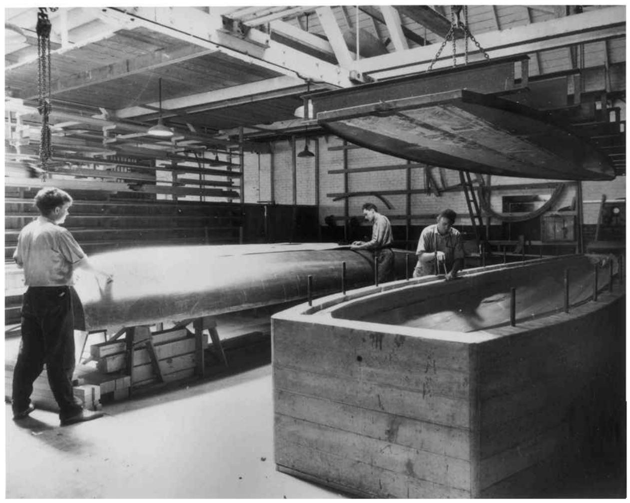

Fig. 7 Forming Lockheed monocoque fuselage shells in concrete molds (SI negative number 91-3446).

the fuselage out of a thin wooden shell, supported internally by bulkheads and longitudinal stringers. The result was an incredibly strong, streamlined, tubelike structure.

The monocoque design actually first appeared just prior to World War I. The earliest attempts built up several layers of extremely thin plywood on a circular wooden frame. It was a very laborious process with mixed results, and few aircraft were built this way. The Deperdussin Racers of 1912 and 1913 are the most famous examples of this early method. Among the first designs to use the monocoque technique extensively were the famed German Albatros fighters of World War I (Fig. 6). These aircraft had fuselages that were produced by gluing and nailing plywood panels onto the framework of bulkheads and stringers. This method is sometimes referred to as semimonocoque because the plywood skin is not molded into a one-piece shell before being attached to the frame.

The real breakthrough in monocoque construction came in 1918 with a process developed by the Loughead Aircraft Manufacturing Company. (The Loughead brothers were forced to suspend operations in 1921, but with new financing formed another firm in 1926 called the Lockheed Aircraft Company with the more familiar spelling of their name.) Working with their engineer, a young Jack Northrop, and factory superintendent Tony Stadlman, Allan and Malcolm Loughead patented a method of forming fuselage half-shells out of spruce veneer in large concrete molds fitted with a rubber bladder (Fig. 7). The veneers were set in place, casein glue was applied, and the bladder was inflated to force the wood into the mold. After the glue cured, the shells were removed from the mold, and two beautifully formed fuselage halves were then joined over a light skeletal framework. The advantage of the monocoque fuselage was that, because of the comparatively lesser amount of internal structure needed due to the intrinsic strength of the molded shell, the same interior height and breadth could be achieved with a significantly smaller overall cross-sectional area. This of course reduced drag and cut down on weight, the ever-present goal of all aircraft designers.[9]

The Loughead process for wooden monocoque construction was employed in a highly successful series of elegant monoplanes produced by the re-established Lockheed company in the late 1920s and early 1930s. Amelia Earhart brought worldwide fame to the Lockheed design when, in 1932, she became the first woman to make a solo transatlantic flight in her bright red Lockheed Vega. The Lindberghs, Charles, along with his wife Anne Morrow as navigator, pioneered transoceanic routes for Pan American Airways in the early 1930s using a low-wing version of the Lockheed monoplane called the Sirius. These aircraft also were fitted with plywood covered, stressed-skin, cantilevered wings virtually identical to those of the Fokker transports, placing Lockheed aircraft among the most advanced of their day.[9]

The cantilevered wing and the monocoque fuselage were just two of many design innovations that emerged during World War I and were refined the following decade. As these structural advances were developed, countless aircraft of a more traditional design continued to be produced. The reliable wire-braced, fabric-covered biplane remained a ubiquitous creature on airfields for some time. However, practitioners of aircraft design clearly were moving in new directions. The modern airplane definitely was in gestation. If we jump ahead and take a look at a few examples of aircraft that are considered to mark the so-called structural revolution of the 1930s, some interesting points regarding materials and airframe design become evident.

Metal and the Structural Revolution

The two aircraft most often cited as the embodiment of the structural revolution are the Boeing 247D (Fig. 8), introduced in 1933, and the Douglas DC-3 (Fig. 9), appearing two years later. (The famous Ford Trimotor transport, produced in the late 1920s, was an all-metal aircraft that did incorporate the structural elements discussed here. However, it did not mark the watershed in aircraft design represented by the Boeing 247D and the Douglas DC-3. The 247 and the DC-3 were decidedly modern in appearance and design, and thus provide a more telling comparison to the earlier wooden designs for this paper's analysis of the structural revolution in aeronautics.) Aside from their piston engines rather than jets, these airplanes do not look all that different from a typical passenger airliner of today. They have cowled multiple engines, a single, low-wing configuration, retractable landing gear, and all-metal construction. They seem nothing like the Albatros biplane or Fokker D.VIII monoplane discussed earlier. Surely the 247 and the DC-3 signaled the beginning of a radically new era in aircraft design, or did they?

If we are looking expressly at the structural design of the airframes, the 247 and the DC-3, in fact, exhibit a number of features strikingly reminiscent of those developed years earlier. Take the wing, for example. On the Boeing 247, the design was essentially the same as the cantilevered monoplane wing developed by Fokker during World War I, except that it was constructed of metal. The 247 had a thick-sectioned monoplane wing with a heavy main spar as the primary load-bearing member. (A common memory of anyone who flew on a 247 was the need to step over the huge wing spar that ran through the cabin when moving to the rear of the aircraft.) Thin sheet metal covered the entire structure to provide the stressed-skin effect for added rigidity. Apart from its being made of metal, the 247 wing was remarkably similar to the plywood-skinned, wooden cantilevered wings that Fokker, Lockheed, and several other manufacturers built during the 1920s.[10]

Similarly, the first thing historians always point to when speaking of the revolutionary character of the DC-3 is its wing structure. Known as the multicellular wing, it was developed by Northrop. While working at Lockheed, Northrop had already built a reputation for himself in the industry for his important contributions to the refinement of the monocoque fuselage. The multicellular wing of the DC-3 was also a cantilevered monoplane wing, but rather than using flanges to create a web along a main spar, it featured many spars narrowly spaced along the intersecting ribs. This in effect created small rectangular cells over which the sheet metal was riveted (Fig. 10). Although clearly a significant innovation, especially from a manufacturing perspective, the multicellular wing was still just another means of producing a cantilevered, stressed-skinned monoplane wing structure. Its roots clearly can be seen in the earlier developments of wooden cantilevered wings.[11]

We can draw a similar parallel between the so-called revolutionary metal aircraft and previous structural innovations in wooden aircraft with regard to monocoque fuselage construction. Both the 247 and the DC-3 had fuselages constructed of light metal frameworks with sheet metal panels riveted in place (Fig. 11). Except for the material

Fig. 8 Boeing 247D, introduced in 1933 (SI negative number A42344-E).

Fig. 9 Revolutionary all-metal Douglas DC-3 passenger airliner, introduced in 1935 (SI negative number A45861).

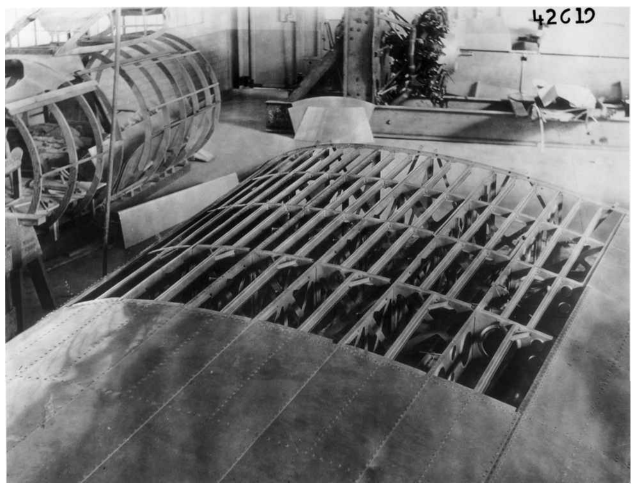

Fig. 10 Multicellular wing structure of the DC-3 developed by Northrop (SI negative number 94-7728).

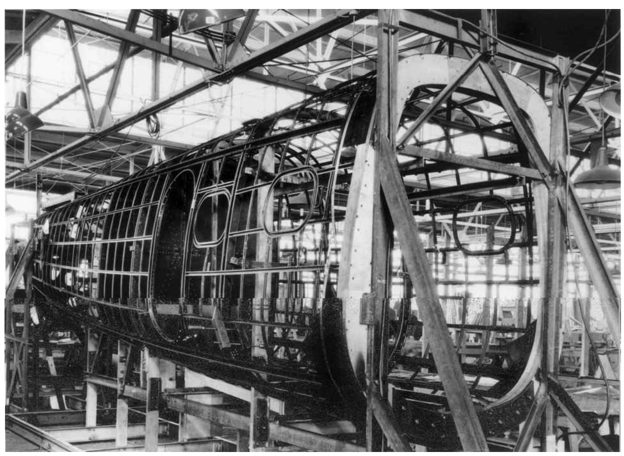

Fig. 11 Metal monocoque fuselage structure of the Boeing 247D before the application of sheet aluminum panels (SI negative number 94-7727).

Fig. 12 Modern-looking, all-metal Junkers J-1 of 1915 (SI negative number A2493).

being metal, the design was virtually identical to that used on the World War I Albatros fighter, which had thin plywood panels glued and nailed over a wooden skeleton.

This is in no way to suggest that the many innovations represented in the 247 and DC-3 were not pivotal. They certainly were in many respects. However, at least in terms of structures, these innovations were not driven by specific technical requirements necessitated by metal aircraft. The continued use of wood was not an inhibiting factor in aeronautical engineering. As we have seen, two of the most important structural features of the gleaming, modern-looking, metal airplanes emerging on the eve of World War II were developed, at least in their initial form, on wooden aircraft. There is no doubt that the transition to metal as the primary construction material, along with dramatic advances in propulsion technology, enabled designers to carry the structural innovations discussed here to limits far exceeding those that could have been met with wood. However, it is also true that the structural revolution of the 1930s was far more complex than a simple transition from wood to metal aircraft. On the conceptual design level, a good bit of the revolution was achieved independent of the material.

To further illustrate the less-than-straightforward path of aircraft structures development, it is instructive to look back briefly and note a few examples of the early use of metal. Two should make the point. If we return to Anthony Fokker, we see that he was using steel tubing to build box-girder fuselages and tail surfaces during World War I. All of the Fokker airplanes that featured cantilevered wings, the Triplane, the D.VII, and the D.VIII monoplane, also had welded steel-tube fuselages and tailplanes.[8] Although Fokker was merely replacing the wooden members of the standard box-girder fuselage with metal, and not building metal monocoques, this still provides a telling example of how conceptual design and materials are not always interdependent in aircraft engineering.

An even more striking example of how the line between the antiquated and the modern can become blurred is the Junkers J-1. The J-1, built in 1915, was the world's first successful all-metal airplane (Fig. 12). Only one was made to research the potential for a line of all-metal, cantilevered-wing fighters in World War I. It was one of the earliest aircraft to employ the stressed-skin technique, in either wood or metal. Built entirely from steel tubing and iron sheet, its weight made it sluggish and unmaneuverable in flight, and its welded construction presented numerous maintenance problems. Nevertheless, it clearly was an inspired creation. Designed only a dozen years after the Wrights first flew, the J-1 certainly undercuts the notion of the streamlined all-metal monoplane as a purely modern artifact.[12]

Conclusions

What does this brief bit of aerospace history tell us? Beyond illustrating a few of the salient technical elements of the origins of metal aircraft construction, the story also suggests an interesting cultural insight regarding materials and engineering design. Namely, ostensible notions of what is modern and what is outdated sometimes can be masked and confused if we only consider the material, and not the design concept independent of the material. In assessing technology during the twentieth century, wood typically has been seen as old and regressive and metal as new and progressive. In the case of aeronautics, however, these concepts often mixed and merged in interesting and complex ways. A seemingly antiquated wooden airplane, from a structural design perspective, in some respects may have been just as modern and revolutionary as a newer-looking metal one. This teaches us that we must sometimes look beyond acquired prejudices regarding materials when making assessments of what is new and innovative.

Acknowledgment

All photographs are from the Archives Division of the National Air and Space Museum, Smithsonian Institution.

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