Wood in aircraft construction

Baccalaureate Thesis

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Abstract

The development of the aircraft at the beginning of the 20th century was a major step in human development. After a long period of research and experiments the brothers Wright have developed the first engine driven aircraft and wood had a great importance to this development. As the pionier material for the totally new sector of aircraft production, new capacities, chances and possibilities for the use of wood have been opened. For a successful use of wood in aircraft constructions an applicable adhesive has to be available. Therefore a big development in the field of gluing was triggered. After a few decades new materials have been developed and tested for the application in aircraft construction and the substitution of wood began.

These main developments in the short history of wood used in aircraft construcion were analysed in this thesis. To show the new capacities and possibilities for the use of wood the development of the production of wooden aircrafts has also been worked out as the development of materials, which were used. The most common American and European wood species and the glues used for airplanes are described.

Keywords

aircraft glue, aircraft material, casein glue, development of aircrafts, historical usage of wood, wooden aircraft

Zusammenfassung

Die Entwicklung des Flugzeuges Anfang des 20. Jahrhunderts war ein großer Schritt in der menschlichen Entwicklung. Nach einer langen Zeit mit Forschung und Experimenten haben die Gebrüder Wright das erste motorbetriebene Flugzeug entwickelt und Holz spielte dabei eine wichtige Rolle. Als Pioniermaterial in dieser total neuen Branche der Flugzeugproduktion öffneten sich neue Kapazitäten, Chancen und Möglichkeiten für die Verwendung von Holz. Für die erfolgreiche Verwendung von Holz im Flugzeugbau müsste auch ein passender Kleber verfügbar sein. Aus diesem Grund wurde auch eine große Entwicklung im ganzen Klebstoffsektor ausgelöst. Nach wenigen Jahrzehnten wurden jedoch bereits neue Materialien für den Einsatz im Flugzeugbau entwickelt und für die Verwendung im Flugzeugbau getestet. Somit begann der Ersatz von Holz durch andere Materialien und Werkstoffe.

Diese wichtigsten Entwicklungen in der kurzen Geschichte der Verwendung von Holz im Flugzeugbau wurden in dieser Studie analysiert. Um die neuen Kapazitäten und Möglichkeiten für die Verwendung von Holz zu zeigen, wurde die Entwicklung der Produktion von Holzflugzeugen ebenfalls ausgearbeitet, sowie die Entwicklung der Materialien welche verwendet wurden. Ein Schwerpunkt wurde auf amerikanische und europäische Holzarten und Kleber gelegt, welche am häufigsten in Flugzeugen eingesetzt wurden.

Schlagwörter

Entwicklung der Flugzeuge, Flugzeuge aus Holz, Flugzeugklebstoffe, Flugzeugmaterialien, historische Verwendung von Holz, Kaseinkleber

CONTENTS

1. Introduction

The use of wood has always been connected with the development of transport and the man's step towards civilization. Man undoubtedly used floating logs as the first means of transportation (Courtland 1962). With the invention of carriages at about 400 B.C. (Judge 1921) wood as construction material for transportation became more and more important. Even the invention of the aircraft at the beginning of the 20th century (Williamson 1996) would not have been able without the use of wood.

At the beginning of the aircraft industry wood was the main material for aircraft construction (Trayer 1930). It was a totally new usage of wood. The requirements were very different to previous applications and so a big development in the whole sector began (Hill 1934).

For the first time in the use of wood the weigth was very important and so it was not possible to over dimension the structual parts. To characterise the properties of the different wood species a lot of research was done. The dimensioning of the whole airplane and the selection of the wood species for the different parts of a plain were based on these results (Judge 1921). In England the main wood species have been defined until the beginning of the First World War (Jenkin 1920) and some of these results are still exact (Mayrhofer 2008).

At the beginning of the aircraft industrie the engineers had big problems with adhesives, especially with the water resistancy (Truax 1930). But these problems could be cleared with the further development of different adhesives. Caused by this development the use of veneer and plywood began (Boulton 1920) and the amount of wood used in aircraft construction increased again.

However, the use of metal as a material for aircraft construction could not be detained. Already 1915 the first aircraft only made of steel has been built (Williamson 1996). Later on synthetics where used for aircraft construction too, and after about 50 years of great importance wood has been nearly substituted and subjected to a niche product in aircraft construction (Sun 1998).

Nevertheless, the use of wood for aicraft construction was a major step in the usage of wood. The further development of wood and wood products caused by the increased research and development programs opend new fields of applications.

The aim of this theses was to show the development, the advantages and disadvantages and the importance of wood as a material for aircraft construction.

2. Methods

This work is manly based on literature research and no information was achieved by practical work. No questionnaire was used for the interviews.

Figure 1 and 2 are created on the information gained from the analyses of about 200 different types of the most common wooden aircrafts. The aircrafts have been chosen from the availability and amount of the information. The whole information is attached at appendix 1.

3. Historical review

3.1 First flying developments

Flying has always fascinated the human nature. Already 1505 Leonardo da Vinci did the first detailed analyses of flying mechanics and developed first drafts of flying vehicles. As so often in history humankind tried to learn form nature and so the first trying was to create big wings to imitate a bird.

At 1782 the first flying balloon was developed. Later on it was equipped by an engine and a propeller and so it was not exposed to the wind. 1900 the first zeppelin was created. The first flight with a glider was realized by Otto Lilienthal in the year 1891 (Courtlandt 1962).

3.2 Development of wooden aircrafts

On the 17th December 1903 the first flight with an engine driven airplane was accomplished by Orville Wright. (Williamson 1996) It was the beginning of a big development.

As you can see in Figure 1 there was a steady rise of aircrafts from 1903. At 1914 the demand on aircrafts jumped up because of the beginning of the First World War, which was the first war where aircrafts were used. The second big increase was caused by the increasing use of aircrafts for the means of transport. At the same time the production of metal airplanes grew. Around 1935 the production of wooden airplanes was reduced.

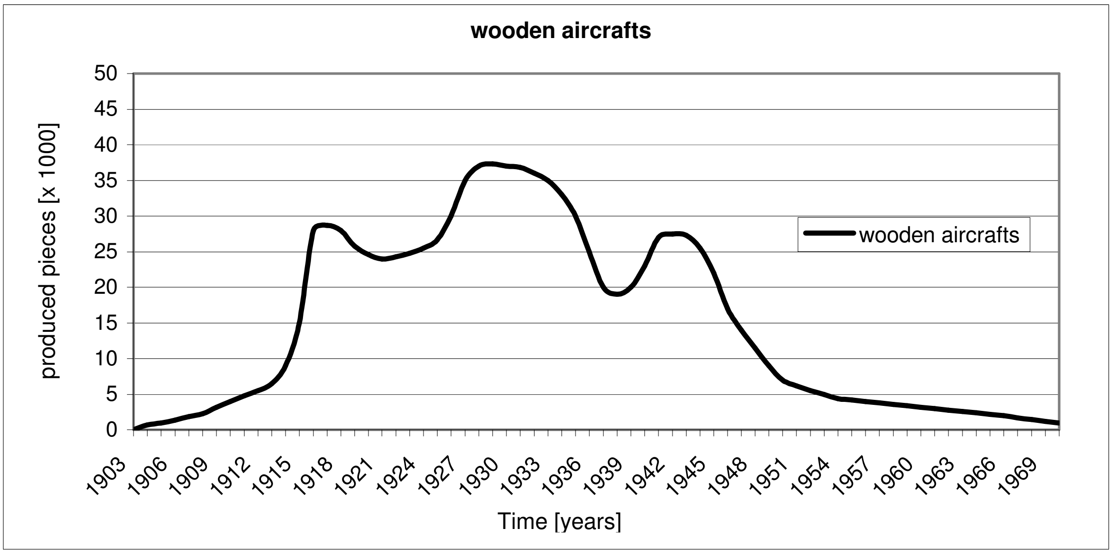

Figure 1: Development of wooden aircrafts

The last increase of wooden airplanes was caused by the Second World War. Metal was needed for weapons and so the demand for wooden airplane rose and also because the big amount of unemployed carpenters and cabinet makers could be used for the production. After the Second World War only small airplanes and gliders were built out of wood and with a steady decrease until 1970 also these sectors were substituted (Müller 2008). Since then wood was only for niche products as for interior fitting at business jets but not for structural parts (Huemer 2008).

3.3 Development of aircraft materials

In Figure 2 the material development of wooden aircrafts is shown. In this figure only the main three materials wood, plywood, and metal are considered. Other materials like cotton or linen were neglected.

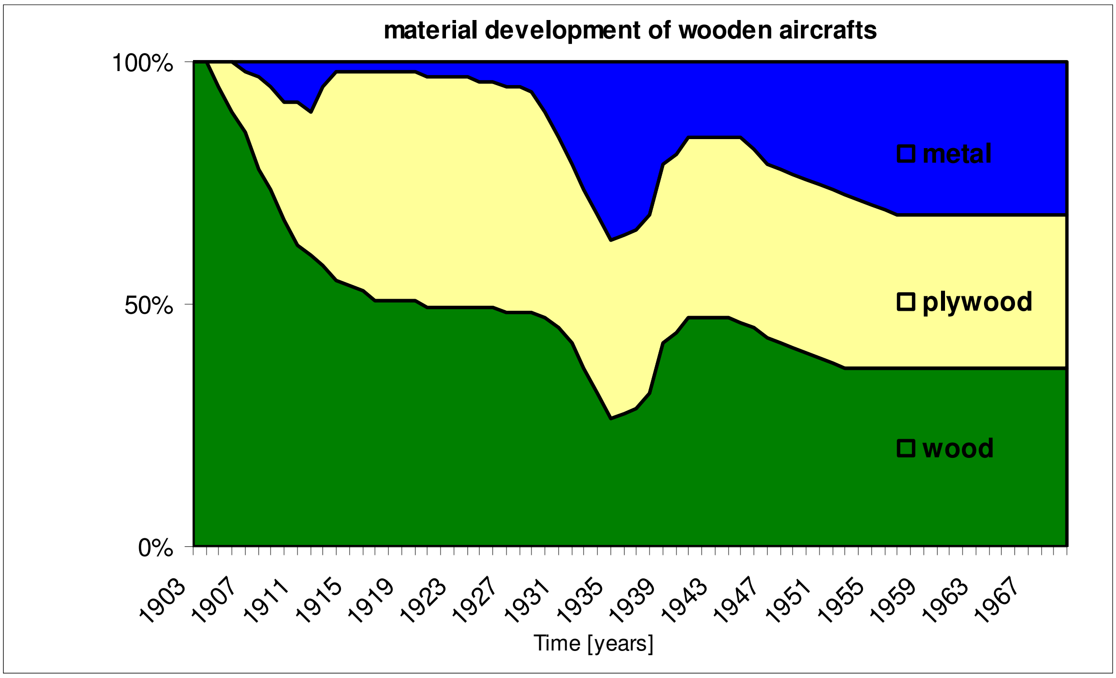

Figure 2: Development of aircraft materials

At the beginning of the 20th century aircrafts were manly built of wood. Very early also plywood was used and had a big increase. Already 1910 the use of metal for the production of airplanes started and increased. In 1915 the first aircraft only made of steel was developed but it was just a try. Maybe because of the First World War, which caused a big reduction of metal in the aircraft sector. At about 1930 increase of metal was enormous and would have probably been continued if not the second World War began. So, a lack of metal caused by the use for weapons increased the amount of wood used for aircrafts. Finally the amount of wood, plywood, and metal used in aircrafts was nearly the same after the war. But as in Figure 1 explained because of the strong reduction of wooden airplanes this amount is not crucial. The amount of wood used in aircrafts at the moment is approximately 100 m^2 to 200 m^2 of high quality veneer and 0,2 m^3 to 0,3 m^3 of lumber for the interior fitting of a business jet (Schatzer 2009).

3.4 Substitutes

The traditional metals used in the aircraft structures are aluminium, titanium and steel alloys which substituted wood as one of the most important material for aircrafts. These alloys have been continiously improved, but in the past three decades, applications of advanced fibre composites have rapidly gained momentum. These days, some modern military jet fighters already contain composite materials up to 50 percent of their structural weight (Sun 1998).

4. Wood species used in aircraft construction

One of the most important problem airplane designer are confronted with is the choice of materials for the structural parts of the ship (Trayer 1930). The factors which have to be considered in choosing a material are the ratio of strength to weight, facility of manufacture, uniformity of product, ability to obtain supplies, reliability of available supplies, and suitability of the material for close designing and suitability of the material for the service. The high requirement on the material because of alternating forces and differences in air pressure and temperature is another challenge.

4.1 Why wood was used?

Wood has been used because of the availability of the resource, because of the mechanical properties especially the ratio of strength to weight. Also the ease with which wood structures may be built and repaired is a factor why wood has been used in aircraft construction. Aside from these aspects wooden aircrafts are also about three times cheaper than aircrafts made of metal.

4.2 Wood species

An airplane can be made from practically any species of wood which will furnish material in the required sizes, and even the size of the pieces required may be greatly reduced by laminating and splicing those available into larger members. However, by choosing the most suitable woods, it is possible to reduce the weight appreciably and increase the efficiency (Trayer 1930).

Table 1 shows the the most common types of American and Table 2 the most common types of European wood species used in parts of aircraft construction. The numbers are factors to compare the properties of the different species with baseline of Sitka spruce *(Picea sitchensis Bong.)* which has the most useful properties for the use in airplane construction. Afterwards there is a short description of every wood species.

Table 1: Comparison of American wood species used in aircraft construction. (Trayer 1930), (Bauvorschriften für Flugzeuge 1928)

Common and botanical name of species	**specific gravity**	**bending and comp-ression strength**	**hard-ness**	**shock resis-tance**	**stiffness**
American species					
Sitka Spruce *(Picea sitchensis Bong.)*	100	100	100	100	100
substitutes for spruce					
Alaska Cedar (*Chamaecyparis nootkatensis Raf.)*	114	115	126	131	100
Douglas Fir *(Pseudotsuga macrocarpa Mayr.)*	116	123	138	106	125
Western Hemlock *(Tsuga heterophylla Raf.)*	103	108	119	103	106
Western White Pine *(Pinus monticola Dougl..)*	103	93	98	82	85
Cottonwood *(Populus deltiodes Marsh.)*	100	88	86	103	90
Evergreen Magnolia *(Magnolia grandiflora L.)*	124	108	190	199	100
special usage					
Port Ordford Cedar (*Chamaecyparis lawsoniana Var.)*	108	118	114	111	124
Southern Cypress *(Taxodium distichum Rich.)*	114	118	124	107	100
White Ash *(Fraxinus americana L.)*	149	153	255	215	124
Balsa *(Ochroma pyramidale Urb..)*	65	95	93	112	83
Hickorie (*Hicoria glabra Sweet)*	178	192	280	434	146
Cork Elm *(Ulmus racemosa L.)*	154	142	248	266	109
propellers					
Baywood *(Swietenia macrophylla King)*	137	125	140	135	120
Black cherry (*Prunus serotina Erh.)*	127	133	171	158	110
Sugar Maple *(Acer saccharum L.)*	154	154	274	194	131
White oak *(Quercus alba L.)*	151	128	252	163	123
Black Walnut *(Juglans nigra L.)*	138	156	210	175	123
plywood					
Beech *(Fagus grandifolia Erh.)*	151	138	229	190	124
Sweet Birch *(Betula lenta L.)*	162	156	248	224	152
Yellow Birch *(Betula lutea Michx. f.)*	149	143	205	241	128
Chestnut *(Castanea dentata Gaertn.)*	108	96	119	97	82
Black Gum *(Nyssa Sylvatica Var.)*	124	112	186	113	87
Yellow Poplar *(Liriodendron tulupiferia L.)*	103	97	95	82	99

4.2.1 American softwoods

Sitka Spruce *(Picea sitchensis Bong.)* Red, white, and Sitka spruce have about the same properties. They combine lightness and high strength and stiffness per unit weight. They also have considerable toughness. Sitka spruce is far more abundant than the red and the white and the trees reach a large size. Spruce dries well, works well, is easy to glue, and does not present any particularly difficult selection problem. Therefore it was the most important aircraft wood (Trayer 1930).

Alaska cedar (*Chamaecyparis nootkatensis Raf.)* Alaska cedar is a possible alternate for spruce. It is heavier than spruce, equal in stiffness and higher in the strength properties. Available data indicate that it is easy to dry, moderately easy to glue, easy to work, and stays in place fairly well (Hill 1934). With its limited supply Alaska cedar is not likely to be considered for use as an alternate for spruce from the standpoint of special design. It should rather be expected to serve as a supplementary, for substitution in spruce size (Trayer1930).

Port ordford cedar (*Chamaecyparis lawsoniana Var.)* Port ordford cedar could be substituted for spruce in all structural parts. It equals or exceeds spruce in all strength properties and is only slightly heavier (Judge 1921). It is more durable than spruce but it is believed that more of the trees will run spiral grained than will the spruce. It is suitable for plywood construction. Its gluing characteristics are satisfactory (Trayer 1930).

Southern cypress *(Taxodium distichum Rich.)* This species is slightly heavier than spruce and although its properties, excepting stiffness, are somewhat superior to spruce. It would yield a lower strength weight ratio when used in the same sizes. A factor militating against the substitution of cypress for spruce is its variability. It is harder to dry and somewhat harder to glue than spruce (Trayer 1930).

Douglas fir *(Pseudotsuga macrocarpa Mayr.)* Douglas fir is heavier than spruce and its properties are either equal to or grater than those of spruce. On a strength-weight basis, it is slightly inferior to spruce. Clear material can be obtained in the largest sizes required in aircraft construction. Broadly speaking, Douglas fir lumber is either yellow or red. The yellow variety is from the outer parts of mature trees and aircraft stock would have to be selected from it. Care should be taken in eliminating exceptionally high and exceptionally low-weight material (Hill 1934). It is quite probable that wing beam stock would come largely from second-cut logs and such stock would run lower in weight and strength than the average for the species. Douglas fir is harder to dry than spruce and, as a rule, is more inclined to develop seasoning defects. The yellow Douglas fir will usually not develop these defects in service if properly coated (Trayer 1930).

Western hemlock *(Tsuga heterophylla Raf.)* It is only slightly heavier than spruce and all its properties compare favourably with its weight. Recent studies show that it can be kiln dried and glued satisfactorily (Judge 1921). Western hemlock is an abundant species but the trees will yield a smaller percentage of clear material than spruce, and hence the percentage of the lumber that will meet aircraft requirements is smaller (judge 1921). All things considered it should be regarded as a possible alternate for spruce in spruce sizes.

Western white pine *(Pinus monticola Dougl..)* Western white pine is slightly lighter than spruce and is less desirable in its properties, particularly hardness and shock-resisting ability. Its strength-weight ratio, however, compares quite favourably with that of spruce. It has uniform strength properties, dries easily, works well and stays in place well. It is recommended as a substitute for spruce (Trayer 1930).

4.2.2 American hardwoods

White ash *(Fraxinus americana L.)* Their properties such as to make them highly desirable for longerons, landing-gear struts, and other members which require great strength and stiffness (Hill 1934). They are especially suitable for parts which require strength and have to be steam bent. Aircraft manufacturers use northern-grown ash almost exclusively. This is because the ash cut in the North is generally second growth. So the better stock has to be segregated in the grading at the sawmill (Judge 1921).

Balsa *(Ochroma pyramidale Urb..)* Balsa is one of the lightest, if not the lightest woods known. From structural standpoint it has no place in aircraft construction but it is used for streamlining, filler material, and for core stock where insulation is desired, as in cabins. It also is used extensively in the manufacture of life preservers, fenders for lifeboats, and for insulating as in refrigerating compartments. Little known about its strength properties. Broadly speaking, its weight is about one-third that of spruce and it is about one-fourth as strong. It is practically possible to split the wood by driving nails into it (Hill 1934).

Baywood *(Swietenia macrophylla King)* Baywood is heavier than spruce. It has good working properties, dries well and is easy to glue. Its strength-weight ratio is not that good, so it is mainly used for propellers (Trayer 1930).

Beech *(Fagus grandifolia Erh.)* Beech is quite heavy and has about the strength properties of sweet and yellow birch. It might be used to some extent for propellers and other parts for which birch is commonly used (Trayer 1930).

Sweet Birch *(Betula lenta L.),* Yellow Birch *(Betula lutea Michx. f.)* These species are heavy and possess hardness and stiffness in a pronounced degree. They have a uniform texture and take a fine finish. These birches are among the most desirable species for propeller construction. On account of their hardness and resistance to wear they are used to face other woods to protect them from abrasion. Birch is the best wood for the faces of plywood when a high density of wood is desired (Judge 1921).

Black cherry (*Prunus serotina Erh.)* Black cherry is a moderately heavy wood, somewhat lighter than black walnut and lower in its strength properties. Like black walnut, it is diffuse porous and is an excellent cabinet wood. It is used for propellers and should, in general, be suitable for other parts where walnut is used (Trayer 1930).

Chestnut *(Castanea dentata Gaertn.)* Chestnut is somewhat heavier than spruce and exceeds it in hardness, but is lacking in stiffness. It can be glued satisfactorily and it would serve for certain plywood requirements very well (Trayer 1930).

Cottonwood *(Populus deltiodes Marsh.)* This species has about the same weight as spruce and is inferior in all its strength properties. It is a tough wood, however, receives nails without splitting, and bends well. Therefore it can be substituted for spruce (Trayer 1930).

Cork Elm *(Ulmus racemosa L.)* Cork elm is somewhat heavier than ash. It is low in stiffness though very resistant to shock. Like white elm it must be held during drying or it will warp. If properly dried it can be used for longerons and other parts as a substitute for ash (Hill 1934).

Black gum *(Nyssa Sylvatica Var.)* Black gum has interlocked grain and tends to warp in drying. It is considerably heavier than spruce and is low in stiffness. Its common use in aircraft construction is for plywood (Trayer 1930).

Hickorie (*Hicoria glabra Sweet)* The Hickorie is very tough and strong. It is especially suitable for tail skids and is great shock-resisting ability is required. On a strength-weight basis it is inferior to ash for such parts as longerons (Trayer 1930).

Evergreen magnolia *(Magnolia grandiflora L.)* Mountain magnolia *(Magnolia fraseri)*: These species are heavier than spruce but have desirable strength properties. Only a few hardwoods give any promise of being suitable substitutes for spruce and they are one of them (Hill 1934).

Sugar maple *(Acer saccharum L.)* Sugar maple is a heavy wood and is hard and stiff. It has a uniform texture and takes a fine finish. Like birch it is often used to face other woods to protect them from abrasion. It is a suitable propeller wood (Trayer 1930).

White oak *(Quercus alba L.)* Oak is heavy and hard and variable in its strength properties even within a single species. The white oaks shrink and swell more slowly with changes in the weather than all the other oaks. The radial shrinkage of the oaks is about one half of the tangential shrinkage. For this reason, quarter sawed oak is superior for propellers (Judge 1921). Oak propellers, because of their resistance to the abrasive action of water, are extensively used by the Navy (Hill 1934).

Black walnut *(Juglans nigra L.)* Black walnut is an excellent propeller wood. It is somewhat difficult to dry but when handled properly is seasoned very satisfactorily. It retains its shape well and is hard enough to resist the wear encountered in service (Trayer 1930).

Yellow poplar *(Liriodendron tulupiferia L.)* Yellow poplar is only slightly heavier than spruce and has about the same properties except for shock resisting ability in which it is rather low. It has excellent working qualities, stays to place well, and is comparatively free from checks and shakes. It is a prominent core species for plywood and would be a fairly satisfactory substitute for spruce in beams and struts (Trayer 1930).

Table 2: Comparison of European wood species used in aircraft construction. (Trayer 1930), (Bauvorschriften für Flugzeuge 1928)

Common and botanical name of species	**specific gravity**		**bending and comp-ression strength**		**hard-ness**		**shock resis-tance**	**stiffness**	
European species									
Pine *(Pinus silvestris L.)*	100	490 kg/m^3	100	88 N/mm^2	100	40 N/mm^2	100	100	12000 N/mm^2
substitutes for pine									
European spruce (Picea abies Karst.)	98	430 kg/m^3	95	80 N/mm^2	93	30 N/mm^2	109	97	11000 N/mm^2
Lime (Tilia platyphylla Scop.)	100	490 kg/m^3	103	90 N/mm^2	102	38 N/mm^2	115	95	7400 N/mm^2
plywood									
Beech (Fagus silfatica L.)	**164**	680 kg/m^3	132	94 N/mm^2	218	72 N/mm^2	198	123	16000 N/mm^2
Birch (Betula verrucosa Ehrh.)	**154**	610 kg/m^3	**161**	**99** N/mm^2	**253**	59 N/mm^2	233	**163**	15000 N/mm^2
propeller									
Walnut (Juglans regia L.)	136	640 kg/m^3	152	110 N/mm^2	214	70 N/mm^2	168	118	13000 N/mm^2
Ash (Fraxinus excelsior L.)	145	650 kg/m^3	**157**	65 N/mm^2	232	65 N/mm^2	195	133	13400 N/mm^2

4.2.3 European softwoods

Pine *(Pinus silvestris L.)* Pine was the most important wood species for aircraft construction in Europe. It has great strength and stiffness per unit weight. It works and dries well and is easy to glue. The sapwood is very durable. Therefore it was used for nearly every part of an airplane and it was available in the requested amounts (Küch 1939).

European spruce (Picea abies Karst.) European spruce is slightly lighter than pine and its properties compare favourably with those of pine and it stays to place very well. It is an excellent substitute for pine (Küch 1939).

4.2.4 European hardwoods

Ash (Fraxinus excelsior L.) Their properties such as to make them highly desirable for longerons, landing-gear struts, and other members which require great strength and stiffness. They are especially suitable for parts which require strength and have to be steam bent (Jenkin 1930).

Beech (Fagus silfatica L.) Beech is quite heavy and has about the strength properties of birch. It might be used to some extent for propellers and other parts for which birch is commonly used (Jenkin 1930).

Birch (Betula verrucosa Ehrh.) This species is heavy and possess hardness and stiffness in a pronounced degree. It has a uniform texture and takes a fine finish. On account of their hardness and resistance to wear they are used to face other woods to protect them from abrasion. Birch is the best wood for the faces of plywood when a high density of wood is desired (Trayer 1930).

Lime (Tilia platyphylla Scop.) Lime is a possible alternate for pine. It compares favourably with pine in its weight and in all its strength properties except from stiffness. Though it is very shock resistant (Jenkin 1930).

Walnut (Juglans regia L.) Walnut is among the most desirable species for propeller construction. It is somewhat difficult and slowly to dry but when handled properly is seasoned very satisfactorily (Jenkin 1930).

4.3 Requirements on the lumber

The conditions in which timber has been used in airplanes are very different from those in any other engineering structure. Timber is rarely used in machines and experience of its properties is mainly confined to its use in buildings, ships, docks, scaffolding, etc. where it is used in large sizes and where its exact strength is not important. Its use in airplanes has been more analogous to its use in furniture, but there again no calculations of strength are needed. In airplanes it has been used in relatively small sections in the form of columns and beams, the strength of which must be subject to accurate calculation. Most of the data on the strength of timber before it was required for airplanes have related to its strength and other properties in large baulks, often in the green unseasoned condition, and are based on practical experience so different from airplane construction that they are quite useless for this purpose (Jenkin 1920).
Accurate information on the strength and elasticity in all directions of the grain was needed. On which the complex calculation, such as those on the strength and stiffness of continuous beams or on propellers, may safely be based. Extensive investigations have been made on these lines into the strength of many different timbers in laboratories all over the world at the beginning of the 20th century.

4.3.1 Mechanical properties

Table 3 shows the mechanical requirements on American and table 4 the mechanical requirements on European wood species. An important fact is, that the European aircraft designer prefers the tensile strength instead of the shearing strength in America to characterise the wood. Although the stresses which appears on the material used in an aircraft are mainly compression, bending, and shearing strength which cause tensile strength (Marshall 1942).

The requirements in both areas are really high which infers the high quality of the construction.

Table 3: Mechanical requirements on American wood species (Information of inspectors of airplane wood 1919)

Common and botanical name of species	**specific gravity [kg/m³]**	**bending strength [N/mm²]**	**shearing strength [N/mm²]**	**compr-ession [N/mm²]**	**modulus of elasticity [N/mm²]**
Sitka Spruce *(Picea sitchensis Bong.)*	360	37	6,4	30	9.100
American Softwoods					
Alaska Cedar (*Chamaecyparis nootkatensis Raf.)*	440	43	6,9	36	11.550
Port Ordford Cedar (*Chamaecyparis lawsoniana Var.)*	420	43	8,1	37	11.900
Southern Cypress *(Taxodium distichum Rich.)*	420	43	6,4	38	9.100
Douglas Fir *(Pseudotsuga macrocarpa Mayr.)*	470	48	7,1	42	12.460
Western Hemlock *(Tsuga heterophylla Raf.)*	420	43	7,6	36	10.500
Western White Pine *(Pinus monticola Dougl..)*	420	36	4,7	34	9.800
American Hardwoods					
White Ash *(Fraxinus americana L.)*	560	54	12,3	42	10.500
Beech *(Fagus grandifolia Erh.)*	660	52	11,9	41	10.500
Sweet Birch *(Betula lenta L.)*	610	59	11,3	46	12.600
Black cherry (*Prunus serotina Erh.)*	480	51	10,5	41	9.800
Cottonwood *(Populus deltiodes Marsh.)*	390	32	5,6	27	8.400
Cork Elm *(Ulmus racemosa L.)*	600	47	11,6	41	9.800
Black Gum *(Nyssa Sylvatica Var.)*	480	47	10,5	34	9.800
Hickorie (*Hicoria glabra Sweet)*	730	62	12,6	51	13.300
Sugar Maple *(Acer saccharum L.)*	600	57	13,9	46	11.200
White oak *(Quercus alba L.)*	650	47	12,3	41	9.800
Black Walnut *(Juglans nigra L.)*	520	55	9,1	43	10.500
Yellow Poplar *(Liriodendron tulupiferia L.)*	380	34	6,3	29	9.100

Table 4: Mechanical requirements on European wood species (Bauvorschriften für Flugzeuge 1928), (Bauvorschriften für Segelflugzeuge 1950)

Common and botanical name of species	**specific gravity [kg/m³]**	**bending strength [N/mm²]**	**tensile [N/mm²]**	**compr-ession [N/mm²]**	**modulus of elasticity [N/mm²]**
European softwoods					
Pine class I *(Pinus silvestris L.)*	620	75	80	40	10.000
Pine class II *(Pinus silvestris L.)*	570	65	70	40	10.000
European spruce (Picea abies Karst.)	480	60	70	35	10.000
European hardwoods					
Ash (Fraxinus excelsior L.)	700	100	100	45	11.000
Beech (Fagus silfatica L.)	700	100	100	55	15.000
Birch (Betula verrucosa Ehrh.)	640	110	110	45	14.000
Lime (Tilia platyphylla Scop.)	510	80	80	45	7.400
Walnut (Juglans regia L.)	660	110	110	60	11.000

5. Glues used in aircraft construction

The term “glue” is widely applied to adhesives which possess the property of joining two surfaces together, and the adhesive may either be a vegetable, mineral, or animal origin (Judge 1921).

A typical airplane with a span width of 10 to 15 metres requires from about 250 to 2.000 board feet or more of lumber and considerable quantities of veneer and plywood in its construction. The wings, fuselage, ribs, struts, propellers, tank compartments, bow ends, coverings,… nearly every single part was built with glue (Turax 1930). But glue is not only in laminating and building up large irregular wooden parts and in the making of plywood but it also affords the principal means of fastening the various wooden parts together into the finished structure. Joints, together with fastenings, are, however generally regarded as the weakest part of the built up construction.

A satisfying glue must fulfil very exact requirements. It must be strong and resist moisture and dry heat, also fungus and bacterial attacks, and must not deteriorate with time (Hill 1934).

5.1 Historical development

The use of Casein as an adhesive for wood goes back to the earliest recorded use of veneer and glue. Even the Egyptian, Greek and Roman eras makes frequent mentions of the use of the curd of milk for the gluing of wood and inlays of ivory, precious stones and rare veneers (The casein manufacturing company 1928). In the early days of wooden aircraft construction the only glue that was accepted for the better grade of joint-work was hide glue. It did not possess any material waterproofing qualities, despite various attempts to make it water resistant by the addition of certain chemicals, and had to be carefully protected from excessive moisture by several coats or varnish of shellac (Hill 1930). In 1917 driven by the war, the forests products laboratory at Madison, Wisconsin took up a study of airplane glues for the government. Casein and blood albumin glues were both in the experimental stage, and were neither dependable nor of sufficient strength. After six month of extensive development work with various manufacturers a big improvement has been made. Both glues, when properly manufactured and applied, are equal in strength to all but the finest hide glues, are, for all practical purposes waterproof, and are uniform and reliable (Boulton 1920). From that point of time on casein glue was the most important factor in airplane construction, but also in all high grad joint work.

5.2 Water resistant glues

The development of a water resistant gluem, which meets the necessary requirements and is thoroughly reliable has been the most important and difficult problem in the whole airplane evolution (Boulton 1920).

The word “water resistant” is subject to wide interpretation. It is a commonly used word, but its use in the context of glues and glued materials needs precise definition. It is not desired that a water resistant glue is absolutely water resistant under every conditions. The degree of waterproofness varies with the degree of glue used, and also varies according to the construction of the glued material.

The requirement of the United States Army for a glue to become waterproof is: After soaking in cold water for 48 hours, it has to reach at least half of the strength it reaches with dry conditions (Markward 1931).

5.2.1 Casein glue

This glue consists of casein, soda, silica and other minerals. Casein is a constituent of fresh milk, in which it exists in a state of suspension. It can be obtained by filtration and is probably a compound of lime and casein with a weak acid. Casein glues are supplied in the powdered form and are rubbed up or mixed with water for use (Judge 1921). The glue is mixed with cold water in a ratio of one part of dry glue to two parts of water by weight and does not require a heated room or heated wood for successful use. Because of this easy application and the average to very good properties, casein glue has been the best all-round glue for aircraft construction (Trayer 1930).

5.2.2 Albumin glues

These glues are principally derived from egg and blood sources. Eggs contain only 12 percent of albumen and so 100 to 125 eggs are required for every pound of dry albumen. Blood albumen is made from the fresh blood of cattle and it is stated that the blood from one cow will produce less than 1 pound of glue. The blood albumen glues are preferred to those derived from eggs.

Albumen glues are applied hot and the same precautions taken as with other glues as regards the room temperature, application, and thinness of layer and pressure required. Albumen glues come under the category of cements, in the true sense of the word, as their hardening is due to chemical action and not to evaporation, as in the case of ordinary glues (Judge 1921).

They are highly water resistant, surpassing even the best casein cements in this respect. They are therefore often used for plywood which needs to be specially waterproof in use, or of that which is intended for soaking or steaming preparatory to being moulded into shape (Hill 1934).

5.2.3 Vegetable – protein glue

Soybean and peanut meal serve as bases for adhesives which in general properties resemble casein glues. Some of them have a good degree of water resistance and are relatively cheap, but they do not show so high dry strength as the better quality casein glues. Therefore it has not really been used for aircrafts (Truax 1930).

5.2.4 Phenol – aldehyde condensation products

By heating a phenol with an aldehyde it is possible to produce hard, strong adhesive substances, which when set by hot pressing appear to be unaffected by moisture in any form. No aqueous solutions of these materials have been prepared that can be applied to wood. Tests of plywood glued with these products indicate very satisfactory joint strengths under all moister conditions tried. Apparently phenol-aldehyde adhesives are more durable under extremely unfavourable conditions than the glues that have been used for woodworking, but their high costs have thus far practically prohibited their use. The necessity for hot pressing also restricts their application (Truax 1930).

5.2.5 Marine glue

Marine Glue is not a glue in the true sense of the word. It is used as a water-excluding filler in aircraft construction and is confined chiefly to float and hull constructions (Trayer 1930).

5.3 Not water resistant glues

5.3.1 Animal glues

The so called animal glues- which include hide, bone and sinew glues are made of scraps from hide, green bones and sinews and other parts of cattle. The material is cooked in water, the extract concentrated through evaporation, and dried. Two or more runs are made from the same stock. The kind of material used and the number of runs cause large variations in the quality of glue produced, but only a high grade is used in aircraft work. Animal glue can be obtained from the manufacturer in large flakes, ground in small pieces, or in a powdered. The advantage of the ground and powdered is that they require less time to soak prior to being heated. Animal glue has the particular advantage of high strength but it is lacking in water resistance (Trayer 1930). It is mainly used for propellers in aircraft construction because they are coated anyway (Truax 1930).

5.3.2 Miscellaneous materials

Other materials, including cellulose cements, asphalts, resins, gums and rubber have been tried as adhesives for wood. Cellulose cements have set very slowly in wood joints and are otherwise difficult to use to obtain satisfactory adhesion. Likewise asphalts, resins and gums have been tried out alone or in combination with other materials, but the results have not been entirely satisfactory. In this forms these materials have been not suitable as glues for aircraft joints, although there have been possibilities of development.

Plywood, for example, has been glued by the hot-press process with an adhesive having rubber as its basic material. Joint tests of such plywood in both wet and dry condition indicated satisfactory strength. The high costs have been the practical limitation affecting its use (Truax 1930).

5.4 Properties of aircraft glues

Chemical analysis has been found practically useless as a means of testing glues because of the lack of knowledge of their exact chemical composition at the early 20th century. Physical test must therefore be relied upon. A considerable number of physical test have been devised. For judging the suitability of glue for high-grade joint work the tests considered most important are strength (adhesiveness), viscosity, jelly strength, keeping qualities, grease, foam and reaction to litmus (Teesdale 1922). It was rather difficult to compare the results of tests made by one laboratory with those of another, as strength of solution, temperature and manipulation have been often different at the beginning. For this reasons the most satisfactory method of purchasing glues as to specify that they must be equal to a standard sample (Information of inspectors of airplane wood 1919).

The principal adhesives of proved value for making wood joints in aircraft are casein glues, blood-albumin glues and animal glues when properly protected against large moisture changes. In table 5 the general properties and characteristics of these three glues are listed. On the most of the points of comparison there is a lack of definite and specific knowledge and as a result only general terminology can be use in describing them. Further more, there is a wide variation among the glues of the three classes. Only the strongest and most durable glues of each class are described (Truax 1930).

Table 5: Properties and characteristics of different classes of woodworking glues in aircraft (Truax 1930)

property	**glue**		
	casein	**albumin**	**animal**
strength (dry)	very high	medium	very high
strength (after 48 hours soaking in water)	up to 50 % of dry strength	50 to nearly 100 % of dry strength	very low
duarbility in 100% relative humidity	deteriorates eventually rate varies with glue	deteriorates slowly	deteriorates quickly
rate of setting	rapid	very rapid with heat	rapid
working life	few to several hours	several hours to a few days	few hours to several days
temperature requirements	ordinary room temperatures	heat required to set glue	control of wood and room temperature
dulling effect on tools	moderate	slight	moderate

5.4.1 Requirements

The samples have to stay 12 hours under pressure and afterwards have to be stored for six days in an air dried room. For the whole joint a breaking strength of 55 kg/cm² as average of at least five samples is required. Undershooting of ten percent is required if the failure mainly arises from detached early wood out of the joint. To establish water-resistance the samples have stay 12 hours und water with room temperature. Immediately afterwards a breaking strength of 20 kg/cm² and after drying in a standard climate for 48 hours a breaking strength of 50 kg/cm² are required (Bauvorschriften für Flugzeuge 1928).

5.4.2 Effect of water

Apart from joint test there is comparatively little specific information on the properties of glues as materials of aircraft construction. The most important property was the effect of moisture on the glue.

In Figure 4 the tensile strength – moisture content relation for a specific animal glue that meets the specifications for aircraft work is shown. Small specimens of glue at at different moisture content were tested in tension. The strong decrease in strength with increase in moisture is striking.

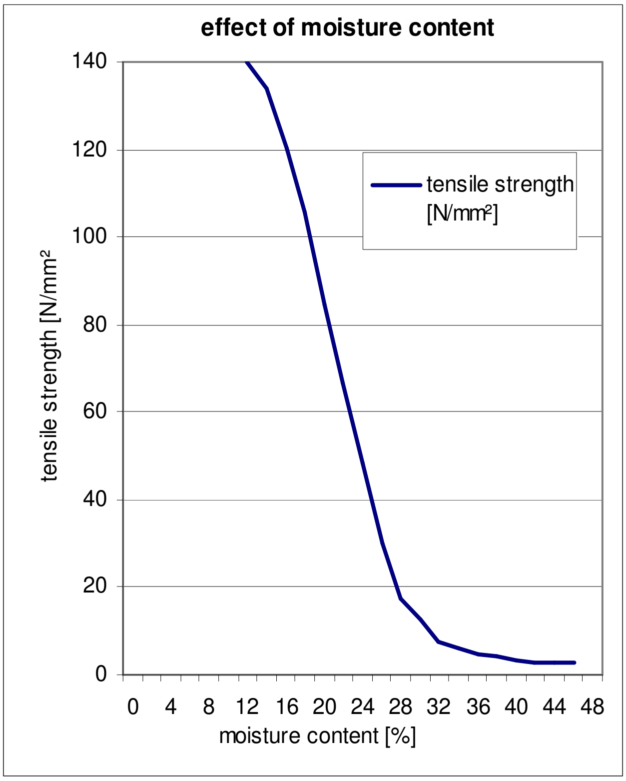

Figure 4 The effect of moisture content on the tensile strength of an animal glue that meets aircraft specification (Truax 1930)

Curves shown in Figure 5 indicate the relation of relative humidity to moisture content of the same animal glue and of one type pf a water-resistant casein glue. The casein glue absorbed an even larger percentage of moisture than the animal glue, but from other tests was found to retain a greater proportion of its dry strength. Because of this, water resistant glues particularly casein and blood-albumin set on wood at almost any moisture content, but animal glue will not set on wood of high moisture content, 15 percent being about the maximum for satisfactory results (Truax 1930).

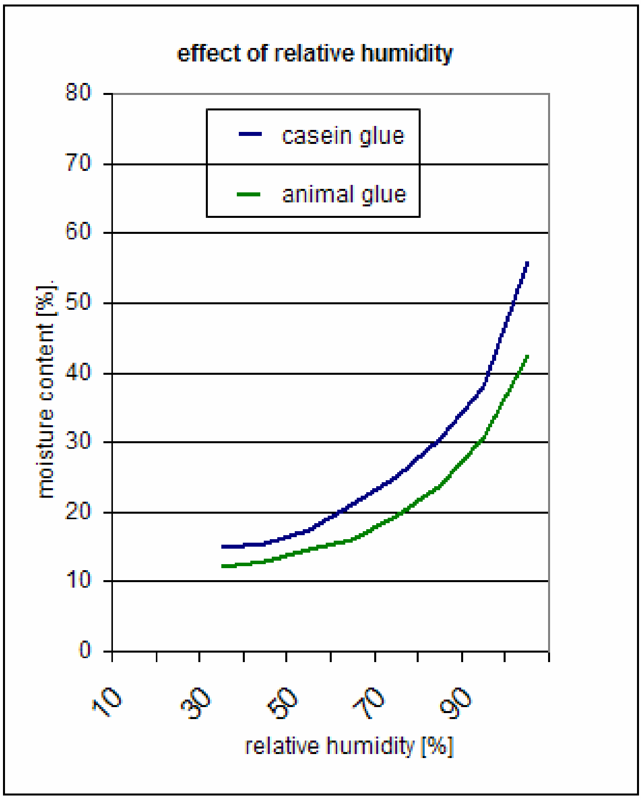

Figure 5: Effect of relative humidity on moisture content of animal and casein glues suitable for aircraft. (Truax 1930)

5.4.3 Durability

None of the glues in practical can be expected to form permanent joints in aircraft parts that are subject to prolong saturation with water, such as seaplane hulls and floats unless the glues or joints are especially treated. Even the most water-resistant blood-albumin or casein glued joints, which show strength when first saturated with water of 25 to nearly 100 percent of their dry strength, fail completely when exposed without protection for a long time to free water or to extremely high atmospheric humidity (Teesdale 1922). Failure in such cases apparently caused by chemical decomposition of the glue or by its deterioration from the action of fungi and bacteria or perhaps both. Further more, unprotected water-resistant joints, which are known to withstand a limited number of soaking periods of several days, fail eventually if subjected to a long series of large moisture changes by alternate wetting and drying. Under such cyclic conditions mechanical failure may be a factor in the breakdown.

Due to the different climate conditions in the different air layers aircraft constructions are subjected to extreme and fast climate changes. Therefore, results from studies on natural aging effects of engineered timber constructions are only of limited validity to the understanding of long term aging effects of aircraft constructions because of the slow or moderate climate cycles used

(Clad 1965). Tensile test on several parts of a fuselage of 50 year old wooden gliders determined the aging effect of casein glue lines. The casein joints did not meet the aircraft specification after 50 years of aging (Müller et al. 2004).

6. Conclusion

Wood has been the most important material at the beginning of the airplane industries at the early 20th century. Because of the further development of metal and synthetics and the development of new materials especially compounds wood has been totally substituted. At the current state of technology the importance of wood in aircraft construction will also be subjected to niche products in the next decades.

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References

Books

A manual of practical cold gluing methods for all wood workers (1928) The casein manufacturing company, New York, p. 7-9, 26-29, 50

Bauvorschrift für Segelflugzeuge (1950) Heft II, Bundesministerium für Verkehr und verstaatlichte Betriebe – Amt für Zivile Luftfahrt, Deutschland, p.7-15

Bauvorschriften für Flugzeuge (1928) Deutsche Versuchsanstalt für Luftfahrt, Berlin, p. 20-24, 38-40

Boulton BC (1920) The manufacture and use of plywood and glue. Sir Isaac Pitman & Sons, Bath, Melbourne, Toronto, and New York. p. 52-76

Courtland C (1962) Geschichte der Luftfahrt, Rencontre und Erik Nitsche International, Lausanne p. 13-27, 41-64, 114 - 119

Griehl M (1975) German aircraft of World War II. Schiffer Publishing Ltd. Atglen ISBN 0-7643-0911-0

Hill FT (1934) The materials of aircraft construction. Sir Isaac Pitman & Sons, Bath, Melbourne, Toronto, and New York. p. 231-270, 282-304,

Information of inspectors of airplane wood (1919) Bureau of aicraft production The forests products laboratory, forest service, U.S. department of agriculture, Washington, p. 21, 44-48

Jenkin CF (1920) Report on materials of construction used in aircraft and aircraft engines. His Majesty`s Stationary office, London p. 95-140

Judge AW (1921) Aircraft and automobile materials of construction: Non-ferrous and organic materials. Sir Isaac Pitman & Sons, Bath, Melbourne, Toronto, and New York p. 188-255, 391-414

Keimel R (2003) Luftfahrzeugbau in Österreich: Von den Anfängen bis zur Gegenwart, Aviatik Verlag GmbH, Oberhaching ISBN 3-925505-78-4

Marshall GC (1942) Aircraft woodwork, war department, Washington p. 2-9, 103-113

Museum für Verkehr und Technik Berlin (1991) Hunderte Jahre deutsche Luftfahrt, Bertelsmann Lexikon Verlag GmbH, München ISBN 3-570-07060-3

Sun CT (1998) Mechanics of aircraft structures. John Wiley & Sons, Inc. NewYork / Chichester / Weinheim / Brisbane / Singapore / Totonto, ISBN 0-471-17877-2, p. 11-17

Teesdale CH (1922) Modern glues and glue testing. The periodical publishing Grand Rapids, Michingan. p. 16, 27 - 30

Trayer GW (1930) Wood in aircraft construction. The national lumber manufacturers association, Washington, D.C. p. 13, 61-81, 105, 129

Truax TR (1930) Gluing wood in aircraft manufacture. United States Department of Agriculture, Washington, D.C. p. 1-8, 15-17, 22-27,

Wagenführ R, Scheiber C (1985) Holzatlas. VEB Fachbuchverlag Leipzig

Weltbild Verlag (1995) Enzyklopädie der Flugzeuge. Edito-Service S.A. Genf ISBN 3-89350-055-3

Wilkinson SF (1937) The construction of wooden aircraft. Sir Isaac Pitman & Sons, London p. 3, 11-27

Williamson SK (1996) The golden Age of Aviation, TODTRI Book publishers, New York, ISBN 3-7688-1128-X, p. 5, 9-25, 37-52

Papers

Clad W (1965) On the elasticity of curred glue–line in wood bondings. Holz als Roh- und Werkstoff. 23(2): 58-67

Elmendorf A (1920) Data on the design of plywood dor aircraft N.A.C.A (National advisory committee for aeronautics) Report No. 84

Küch W (1939) Untersuchungen an Holz, Sperrholz und Schichthölzern im Hinblick auf ihre Verwendung im Flugzeugbau. Holz als Roh- und Werkstoff. 2(7/8): 257-320

Markwardt L (1931) Aircraft woods: their properties, selection, and charachteristics. N.A.C.A (National advisory committee for aeronautics) Report No. 354

Müller U, Teischinger A, Müller H (2004) Durability of wood adhesives in 50 year old aircraft and glider constructions. Wood research 49(3): 25 - 34

Otto H (1942) Normung von Kiefernholz im Flugzeugbau. Holz als Roh- und Werkstoff. 5(4): 105-144

Truax TR (1928) Gluing practice at aircraft manufacturing plants and repair stations. N.A.C.A. (National advisory committee for aeronautics) Report No. 291

Internet

Junkers H (2003-2009) Mehr als Stoff und Stangen: Junkers Flugzeuge, S+P Media AG, München, http://www.junkers.de/flugzeuge/, last visite 26th of January 2009

Steidle G (2008) Geschichte der Luftfahrt http://www.luftfahrtgeschichte.com/index2.htm, last visite 26th of January 2009

Interviews

Huemer B (2009) FACC AG, Fischer advanced composite components, product controler, interview at the 5th of January 2009, Ried im Innkreis, Upper Austria

Knapp S (2008) Craft Lab GmbH Restaurations, Modell- und Ausstellungsbau employee, interview at the 3rd of December 2008, Vienna

Mayrhofer K (2008) Craft Lab GmbH Restaurations, Modell- und Ausstellungsbau, head of the business, interview at the 10th of December 2008, Vienna

Müller U (2008) Institute of wood science and technology, University of natutral resources and applied live sciences, interview at the 17th November 2008, Vienna

Schatzer J (2009) List components & furniture GmbH project management, interview at the 14th of January 2009, Vienna

Appendix