THE USE OF WOOD FOR AIRCRAFT IN THE UNITED KINGDOM

Report of the Forest Products Mission

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UNITED STATES DEPARTMENT OF AGRICULTURE
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INTRODUCTION

On July 2, 1943, the British Air Commission in Washington, D. C., on behalf of the Ministry of Aircraft Production extended to the Secretary of the U. S. Department of Agriculture an invitation for representatives of the Forest Products Laboratory to visit England for the purpose of "strengthening the present collaboration between our two countries on researches into the uses of timber in aircraft construction." The Secretary of Agriculture accepted this invitation.

At the same time, similar invitations were extended by the British Air Commission to the U. S. Army Air Forces, the U. S. Navy Bureau of Aeronautics, the U. S. Civil Aeronautics Administration, and to the Canadian Forest Products Laboratories. Due to pressure of work and limitation of technical personnel, the Army and Navy were unable to accept the invitation.

As finally constituted, the participants in the group, hereinafter referred to as the Forest Products Mission, were as follows:

United States

Carlile P. Winslow, Director, Forest Products Laboratory, Madison, Wisconsin, Chairman of the Mission.

L. J. Markwardt, Assistant Director, Forest Products Laboratory, Madison, Wisconsin.

Thomas R. Truax, Principal Wood Technologist, Forest Products Laboratory, Madison, Wisconsin.

Charles B. Norris, Principal Engineer, Forest Products Laboratory, Madison, Wisconsin.

Horace K. Burr, Chemist, Forest Products Laboratory, Madison, Wisconsin.

Paul C. Spiess, Senior Aeronautical Engineer, Civil Aeronautics Administration, Washington, D. C.

Canada

Thomas A. McElhanney, Superintendent, Forest Products Laboratories of Canada, Ottawa, Ontario, Canada.

W. E. Wakefield, Engineer, Forest Products Laboratories of Canada, Ottawa, Ontario, Canada.

Congestion of air transportation prevented the entire group from leaving at the same time. All but the first three left Montreal about August 15; the others left Montreal on August 30, and arrived in London on September 2.

Mr. J. L. Giles of the British Air Commission left Washington in time to expedite their visit and the activities of the Mission.

Members of the group, including Mr. Giles, returned as their participation objectives were completed. Messrs. Winslow and Markwardt were the last to leave England on October 29.

Ministry of Aircraft production officials most effectively arranged for interviews, conferences, travel, and visits to and with practically all of the United Kingdom governmental, industrial, and scientific operators and personnel concerned with wood aircraft and wood propellers. All in all, approximately 25 industrial operations were visited, and 73 industrial representatives, both technical and managerial, were interviewed. Of the United Kingdom government, 10 technical and research organizations were visited and 47 technical and scientific personnel interviewed.

This report presents the findings of the members of the Mission, and the recommendations of the Forest Products Laboratory members.

ACKNOWLEDGMENTS

On behalf of the Mission, sincere thanks and appreciation are extended to the British Air Commission and Ministry of Aircraft Production for the opportunity accorded to make the study and for their efficient assistance in expediting the purposes of the Mission; and again to the Ministry of Aircraft Production and to the other governmental and industrial operations visited for their cordial, wholehearted, and open-handed assistance in providing information, expressing viewpoints, and interchanging ideas, and for their courteous and friendly hospitality.

Acknowledgment and thanks are particularly extended to Sir Stafford Cripps, Minister of Aircraft Production, and to Air Marshal Sorley, in charge of the Ministry of Aircraft Production Research and Technical Investigations, for their interest in and support of the Mission's work; and, for their guidance and helpful assistance, to Mr. N. E. Rowe, Director of Technical Development, and Mr. H. Grinsted, Deputy Director of Research and Development (Technical Investigations), of the Ministry of Aircraft

Production; to Dr. W. D. Douglas, Assistant Superintendent, and Messrs. Gurney, Pryor, and Garner of the Royal Aircraft Establishment; to Air Commodore H. E. Forrow, Wing Commanders Lawrence and Davies of the Flying Training Command; to Dr. S. L. Smith, and Messrs. Smith, Cox, and Barwell of the National Physical Laboratory; to Dr. Pepper and Mr. Topp of the Chemical Research Laboratory; and to Director Robertson and Messrs. Campbell, Chaplin, Latham, Turner, Barkas, Stillwell, and Knight of the Forest Products Research Laboratory.

The Mission is deeply indebted to Mr. W. Hardy, Assistant Director of Research and Development--Non-metallic Materials, Ministry of Aircraft Production, and to his associates, Messrs. Angel, Waterfield, and Phillippe. They not only planned and arranged for all of the visits and interviews, but accompanied the members on many of them. Their friendly courtesies and cordial hospitality, technical knowledge, and untiring assistance added greatly to the success of the trip and will long be remembered.

To Mr. J. L. Giles of the British Air Commission, thanks are particularly due for his valuable assistance in both official and personal ways to the Mission members, for his effective efforts in arranging for current interchange of technical information between the United States and the United Kingdom, and for his helpful participation at the meetings of the ANC Technical Subcommittee on Wood Aircraft Structures at the U. S. Forest Products Laboratory.

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SUMMARY

This summary presents a brief resume of the more significant findings, observations, and information obtained in the United Kingdom by the Forest Products Mission during the late summer and fall of 1943. The report and summary deal principally with the use of wood, veneer, plywood, improved wood, paper, and wood-base laminates, and glues for aircraft and propellers, and are limited particularly to aircraft under war service conditions.

Wood Aircraft

It is significant and impressive that of the entire aircraft production in the United Kingdom, approximately 17 percent is wood, 83 percent metal; for other than trainers, approximately 10 percent is wood. All trainers (with the exception of the Anson and Tiger Moth fuselages) and gliders are of all-wood construction.

The principal wood airplanes in production or use are the Mosquito, Oxford, Anson, Master, Magister, Martinet, Albermarle, and Tiger Moth; and one of the principal gliders is the Horsa.

This extensive use of wood is a logical outgrowth of the urgent need for increased airplane production in the war emergency, which requires maximum effective use of all materials and facilities. In the early days of the war, metal, metalworkers, and metal factories were insufficient but wood, woodworkers, and wood industries were available. Some wood airplanes were already in production in pre-war days.

One of the most outstanding airplanes of the war is the <u>all-wood</u> Mosquito. It is a 23,000-pound, twin-engine, high-speed combat airplane that was designed in a remarkably short time by an experienced firm largely on the basis of the building of the "Comet" racer and the "Albatross" transport. It serves as a day and night reconnaissance bomber, bomber destroyer, and night intruder-fighter.

Even predominately metal planes often use for certain parts considerable amounts of wood and plywood. For example, it is reported that the Lancaster bomber uses 40 percent as much aero lumber per airplane as the Mosquito. On this basis the total aero lumber requirements for the Lancaster production could easily approach those of the Mosquito, if it were produced in greater numbers than the latter.

Adaptability of wood to quick fabrication is illustrated by the fact that one aircraft was designed, built, and flown in 9 weeks, while heavy bombing of England was still prevalent.

In performance, wood airplanes and gliders are reported to have been satisfactory; notably outstanding has been the Mosquito.

Production costs at present are reported to be 10 to 20 percent higher for the wood airplanes than for the metal ones of comparable weight and performance. This difference in cost is said to be largely accounted for by the fact that wood airplanes are primarily produced in small plants operating under dispersal conditions. For the wood Mosquito and metal Beaufighter the costs are about the same. Generally, unless production is large enough to justify the manufacturing equipment required for low-cost production of metal airplanes, the cost of wood airplanes will be the lower.

General opinion of the United Kingdom is that maintenance costs are higher for the wood airplanes than for the metal, but repair costs are lower with wood because repairs can be made more easily and speedily, with less equipment, and workmen can be more easily trained.

Wood airplanes and gliders are extensively used under dispersal conditions, often with little or no protection for long periods, sometimes for years. In general, it is regarded by officers of the Flying Training Command as amazing what wood aircraft have stood up to under adverse conditions. Some wood airplanes have given over 2,000 hours and as much as 7 years flying service in the Flying Training Command. This is regarded as excellent performance.

There were many conflicting opinions regarding the place of wood in future United Kingdom aircraft production. Leading technical authorities of the Ministry of Aircraft Production felt, in general, that for war purposes, because of wood shortage and increasing metal supplies, the present trend is towards stabilization of the present wood plane production, except possibly for the Mosquito; that, while for the foregoing reasons, the war trend is not now for wood planes of new designs, changing war exigencies may require it; that improvements of existing designs and manufacturing methods of wood planes are to be expected; that metal gliders are unlikely during the war; and that, for post-war purposes, the opportunities for wood are greatest in the small-sized airplane that can be quickly produced in quantities that would not justify the extensive equipment required for metal airplanes.

Some experienced manufacturers and designers felt that wood was especially suitable for airplanes up to 10,000 pounds, and in combination with metal for larger airplanes; others felt that there is no limit to the size of wood airplanes if advanced design techniques are employed.

Design Data and Methods

The same load factors are used in the design of wood aircraft as for metal. An improved method of specifying design load factors for new types, based on a study of structural failures resulting from overloads, was investigated. Analysis showed that design load factors for successful types could be divided graphically into two classes representing airplanes whose tactical use required high maneuverability in the vertical plane, and those not requiring such maneuverability.

As in the United States, the basic formulas for structural design with wood, plywood, and sandwich construction are far behind those used for metal. Forward British designers, however, are keenly aware that the best type of wood aircraft structure is necessarily very different from the best type for metal.

While the best available engineering methods are fairly satisfactory for the design of simple structures, (structures that readily lend themselves to accepted methods of analysis) the development of the more efficient and more mathematically complicated airplane structures requires a large amount of testing and empirical work. One of the British gliders and the Mosquito are examples of these two extremes. Thus, the glider, because of the simplicity of the structure, was designed, built, and flown without being statically tested; contributing to the design were considerable data issued by the U. S. Forest Products Laboratory.

Singularly, the structures that are the more complex from the standpoint of design are usually the most simple of fabrication.

The Mosquito design was based on empirical methods. Designed for a gross weight and load of 17,000 pounds, this was increased to 23,000 pounds after successful flight, with but little structural alteration to accommodate added armament.

A study of the advantages of laminar flow around airfoil sections has led to a great interest in maintaining the proper section to very close tolerances. This leads directly to a keen interest in the relatively stiff sandwich types of construction. The sandwich construction so effectively used in the Mosquito fuselage consists of birch plywood faces and a balsa core, affording a relatively thick section of high strength and rigidity, and good sound and thermal insulating qualities. Because of the importance and possibilities of sandwich types of construction, there is urgent need for more adequate and precise methods and formulas for their design.

Intense interest was found in the aircraft design data being developed at the U. S. Forest Products Laboratory, and urgent need was expressed for additional data that would permit more adequate and precise mathematical treatment of the plywood problem and of the mechanics of sandwich construction.

The marked influence on strength of the rate at which loads are applied to wood aircraft structures has also been recognized by the British. A theory is being considered that may involve substantial increases in design stresses for airplane parts that become highly stressed under the rapid loading conditions of maneuvers. Little experimental work has been done in this important field, however, to rationalize the relation between the effect of rate of loading and the duration of stress in relation to the design and testing of airplane structures. Further studies are under way at the U. S. Forest Products Laboratory and are considered of vital importance.

Wood Properties, Test Methods

Tests at the Royal Aircraft Establishment on plywood glued with casein to stringers to simulate structural airplane attachments have shown greater failing loads in tension perpendicular to the glued surface when the glue is damp than when it is dry, and the Royal Aircraft Establishment has concluded that a high relative humidity is not so harmful to strength as is frequently assumed. Further tests on full-size tail planes have shown much less difference in strength between wet and dry structures than has ordinarily been expected. If these implications are confirmed by further moisture-strength tests, the results will have far-reaching import in connection with the interpretation of static tests of airplane structures and the degree of moisture protection necessary.

Tests at the Forest Products Research Laboratory on plywood panels have shown that veneer defects are not so critical from the standpoint of shear as they are with other types of stress, and that where shear strength is the controlling factor, as in many airplane uses, the specifications can be materially liberalized. British Standards Institution Specification 6V3 for aircraft plywood reflects such liberalization.

Extensive studies at the Forest Products Research Laboratory on Sitka spruce and Western hemlock have shown that, aside from actual tests, density is the best criterion of strength, which is in conformity with similar findings in the United States. The studies have shown also that the Izod test results do not correlate well with strength properties. This recently resulted in the omission of an Izod test requirement in the revision of Specification D. T. D. 36B (Material Specification; Sitka Spruce and Approved Substitutes).

In the Mosquito wing, screws are used extensively in gluing the upper skin to the stringers. Tests by DeHavilland indicate that for such double skin construction there exists a component of stress normal to the glued surface, and that the screws are effective in increasing the over-all strength of the structure, presumably by adding to the tensile strength normal to the glued surface. In shear, the mechanical fastenings, when used in conjunction with glue, are not regarded as effective after the glue has set.

Glues and Gluing Technique

The types of glues and the purposes for which they are used in aircraft are essentially the same as in the United States. Nearly all aircraft plywood is made with hot-pressed phenol-formaldehyde glues, mainly in the form of film; laminating and assembly gluing is done chiefly with cold-setting urea-formaldehyde glues although some casein glue is still used and the gluing of most propeller blocks and nearly all repair work is done with casein glues.

While at the time of the Mission's visit, low-temperature setting phenol-formaldehyde glues were used in aircraft construction only to a minor extent and melamine and resorcinol glues had not received much attention, it has recently been reported that a large user of wood in aircraft has adopted low-temperature setting phenolic glue.

The three types of glues used in aircraft are, in general, similar in quality to corresponding types in the United States insofar as existing standards and requirements permit comparison.

Casein glues containing suitable toxics are apparently not available, although the need for increasing the mold resistance of this class of glues is recognized.

Much of the research on glues now in progress in the United Kingdom relates to the durability of urea-formaldehyde glue bonds in wood, means of increasing their durability, test methods, specification requirements, the nature of adhesion between glue and wood, and to methods of modifying the glue to improve adhesion. Investigations of gluing techniques now in progress relate in large part to specific problems, such as improving the gluing properties of plywood surfaces, rate of setting of glues in joints and its acceleration with heat, application of the hardener of a cold-setting urea-formaldehyde glue separately to the wood or in combination with the resin, and gluing normal wood in combinations with resin-impregnated compressed wood and paper.

Some airplane applications involving the bonding of metal to wood are already in use. However, there are still many problems in the gluing of sandwich types of construction and metal-wood composites. It is recognized in the United Kingdom, as in the United States, that the synthetic-resin glues and special adhesives should be more thoroughly studied.

Emphasis has been placed in England on cold-setting urea-formaldehyde glues that do not craze in thick glue lines, and a gap-filling test has been made the principal requirement for such glues for aircraft use. It has also been shown that highly acid urea-formaldehyde glue joints decrease in strength on aging, but as yet no limit has been placed on the acidity of urea-formaldehyde glues in existing specifications. It is recognized, however, that such a limitation on urea-formaldehyde glues or joints may be desirable.

The development and standardization of short-term tests, on cold-setting urea-formaldehyde glues, that will assure the maximum durability under service conditions, and the correlation and interpretation of the test and requirements in terms of crazing, allowable glue line thickness, time of setting, and other use characteristics, are of great importance.

Glued laminated construction is resorted to as a general procedure in the manufacture of spars, stringers, and other structural elements. Efficient utilization is obtained through the extensive use of scarf joints, and through the use of lower grade material for less critical structures, such as spars for jettison tanks. There is little waste of material.

Fabrication Technique and Methods

Aircraft plywood is produced with less waste of veneer, but doubtless with a larger expenditure of man-hours, and more effort is made to adjust the quality of plywood to the requirements of specific parts of aircraft than in the United States. All plywood surfaces that are to be glued in assembly operations are sanded or sand-blasted to improve adhesion. The water resistance and other properties of the glue bond in United Kingdom aircraft plywood are considered comparable to American-made plywood.

Fabrication methods, practices, and techniques are not always conventional or similar to those used in the United States. Much less use is made of bag-molding processes, of hot presses, of hose press technique, of electric resistance and electrostatic methods of accelerating the setting of glues, and of multiple-assembly jigs for the production of aircraft parts. The methods used in the fabrication of the Mosquito plane are, for the most part, unique and have no parallel in American production.

The more significant differences of the United Kingdom fabrication practices, as compared with United States practices are: Higher moisture contents of wood, lower temperatures within the plants during much of the year, more hand-surfacing of parts to be joined, more extensive hand-spreading of glue, separate application of glue hardener to the wood, and application of lower pressures in some gluing operations. In general, the gluing practices used in scarfing, laminating, and assembling operations are believed to tend toward the production of thick glue lines and to be responsible for the rather general feeling that gap-filling glues are a necessity.

Some unique and efficient methods were observed in the use of electric resistance heating and pressing devices, in scarfing and laminating specific parts, that might be used advantageously in United States practices. Likewise, some jigs, pressure and heating devices, and other fabrication methods and techniques in use in the United States, could perhaps be used or adapted to improve United Kingdom practices. A free interchange of detailed information on all such methods and devices should help materially in improving production in both countries.

Air conditioning of fabricating plants in the United Kingdom is rare. Although desirable for many operations, it is not regarded as essential with the prevailing climatic conditions and the freedom of plants from overheating.

Wood and Paper-Base Laminates and Other Material Developments

The laminated compressed wood used in the United Kingdom differs from that developed at the U. S. Forest Products Laboratory mainly in that it is not so dimensionally stable under moisture changes, but it is less notch sensitive. Virtually the only direct uses for laminated compressed wood in United Kingdom military aircraft are, aside from propellers, for bearing blocks and plates. Other and extensive uses for laminated compressed wood have been developed, however, including such products as molded fan blades for airplane motors, dies for forming sheet metal, and jigs for the assembly and production of aircraft and other parts.

Experiments have demonstrated that the present types of paper-base laminates could not be substituted directly for aluminum in the skins of aircraft because of their dimensional instability with changes in moisture content. Efforts are under way to obtain dimensional stability, but so far have not resulted in a fully satisfactory material for this application. Consideration is being given the possible use of such a laminate for a skin in sandwich construction.

Faced with the relative brittleness and dimensional instability of paper-base phenolic laminates, the British are attempting to develop an improved material by first stabilizing the base paper with a very small quantity of suitable resin and then using another resin capable of providing toughness as the massive impregnant. While this seems a hopeful approach to the problem, recent results in the United States indicate that another method may be more promising to provide intrafiber stability.

It has been shown possible to mercerize paper after it has been stabilized and thus gain added strength and absorbency.

While two veneer-paper plastic composite materials have been developed that appear to have possibilities for use in aircraft, they have not been put to use except experimentally. If the supply of suitable aircraft-grade birch veneer becomes more critical, these composites can be produced as substitutes.

A number of United Kingdom aircraft parts (including the Mosquito fuselage) are now made of sandwich construction. Three types of sandwich core materials are in use in the United Kingdom: Low-density woods, artificial foams, and built-up cellular constructions (mechanical equivalents of foams).

Balsa is regarded as a highly satisfactory core material for sandwich construction. Exigencies of supply have necessitated the consideration of other woods, however, (Quipo is now accepted by the Ministry of Aircraft Production, but is not yet in use), and of other substitutes in connection particularly with Mosquito production.

Certain artificial foams and mechanical equivalents appear to approach balsa wood in efficiency at a specific gravity of 0.10. Artificial materials of much greater density than this are considered inefficient, and it is thought by United Kingdom technicians that core materials in the specific gravity range of 0.05 to 0.10 are most promising.

Maintenance and Repairs

The maintenance and repair of aircraft in service is a major activity in the United Kingdom. The system in effect includes the inspection of airplanes after regular periods of service and the making of minor repairs by the service crews and repairmen at the air bases and a rather extensive system of civilian repair units, in which airplanes damaged up to 80 percent of their value are repaired or rebuilt. Most civilian repair stations are former garages, small woodworking or other manufacturing plants in the neighborhood of the flying fields. A few aircraft manufacturers also maintain a repair department. The system is considered efficient in keeping airplanes in service and maintaining a satisfactory standard of quality.

Under active flying conditions, the amount of damage due to normal deterioration is less than that from accidents. Moisture accumulation is responsible for much of the normal deterioration. Consequently, much care is taken in the repair of airplanes to provide adequate drain holes, properly located and spaced, and to keep the drain holes open in service.

Separate maintenance and repair manuals that describe and illustrate methods of repair of different parts of the airplane have been issued for each type of aircraft in service.

It is considered by the Royal Air Force and the Ministry of Aircraft Production representatives that wood airplanes require more maintenance than metal airplanes, but are more easily repaired after crashes; that damage and deterioration in wood airplanes are more easily detected than in metal airplanes; and that skilled woodworkers are more readily available than skilled metalworkers.

Practically all repair of wood airplanes is done by hand methods and tools. Facility of repair is illustrated by a standardized major job on the Mosquito, in which the entire wing tip is amputated at a fixed place. A standard repair kit provides the necessary parts and material to splice on a new tip with a minimum of time and labor.

Serviceability in Relation to Moisture

Drainage and Finish

Provision for proper drainage in wood aircraft is one of the most important features affecting durability. In fact, it is so important that British practice now requires that the location of drain holes be checked by an actual drainage test. In this test water is poured into a wing with the upper surface removed, and the drain holes are located to insure the escape of all free water.

Because of the importance of drainage, the daily inspection of drain holes to remove dirt, grit, or other obstructions is required by the Flying Training Command, and the stenciling of instructions to this effect on the airplane itself is recommended to further promote compliance.

Experience has convinced the United Kingdom authorities that flush grommets are undesirable as reinforcement at the edges of drain holes, and that protruding grommets also are not satisfactory. Drain holes in plywood must be carefully bored to avoid splinters on the inner surface and special tools have been developed for the purpose.

The weathering characteristics of wood aircraft are improved through the use of a fabric covering (madapollam) applied with dope as a part of the standard finish of the wings. The experience with this covering has been so satisfactory that it is a standard requirement. This United Kingdom conclusion is based on an extensive service test, in which observations were made over a 6-months' period during which no fabric was used on planes under production, as a result of which the Ministry of Aircraft Production authorities, as well as manufacturers, agreed that fabric was essential and should be used.

The application of finish to interior surfaces, such as a wing, has always been difficult to handle properly. The interior surfaces are generally inaccessible after assembly, and it is difficult to block out the areas that must be left unfinished to permit satisfactory gluing in the subsequent assembly operations. Tests and experience in the United Kingdom have indicated that interior finishing can be dispensed with without sacrificing durability or serviceability, and it is no longer required.

Flying Training Command officials emphasize the importance of properly placed and adequate inspection holes in connection with maintenance and repair. This feature is an important one for the designer, as inspection holes should be provided when the airplane is manufactured.

Fire is not regarded as a special hazard with wood airplanes, because if the gasoline burns, the airplane will burn out regardless of the material of construction. Principal causes of fire are electrical faults and spilled gasoline. The Mosquito was tested and found to withstand incendiary bullets satisfactorily.

Conditioning and Moisture Content

Kiln-drying of aircraft wood in England apparently presents no serious problem. Because of the relatively low initial moisture content, the small thicknesses of the stock, and the fact that drying to low moisture contents is avoided, the kilns may be regarded somewhat as conditioning kilns. The drying schedule recommended for Sitka spruce calls for an initial temperature of 110° F., with a relative humidity of 80 percent; the final, 130° F. and 65 percent.

Investigations are under way at the Forest Products Research Laboratory to determine the temperature and moisture contents of wood in wings and other aircraft parts under English climatic conditions, to be augmented with tests by the various Forest Products Laboratories of Australia, Canada, India, and South Africa. The U. S. Forest Products Laboratory is cooperating in this project by making similar investigations under American conditions.

Wood Propellers

About 60 percent of the propellers used in the United Kingdom are now made of wood and wood-base laminates. These include not only fixed pitch propellers, but also variable pitch blades for trainers, fighters, and bombers, comprising the "Weybridge," "Jablo," and "Hydulignum," types which are in quantity production.

Construction Details

The three types of variable pitch blades represent marked differences in construction and manufacturing procedures. While all use some form of compressed wood in the hub, the Weybridge uses natural wood for the blade, the natural wood being scarfed to the compressed wood; the Jablo employs compressed wood, of decreasing density from the root to the tip, and has a phosphor bronze-mesh envelope over the blade. The Hydulignum also uses compressed wood decreasing in density from the root to the tip, but the increased hub density is obtained by compressing the hub portion in both directions. Methods of final coating and finish also vary, but all use the same Rotol metal hub.

It is reported that wood and wood-base blades give satisfactory performance and can be used interchangeably with metal blades of the same size and shape. Generally, the all-wood Mosquito uses metal blades while the all-metal Spitfire often uses wood blades.

It is of passing interest that for the Weybridge blade, experiments are being conducted with compreg made in the United States by the Forest Products Laboratory method.

Improvement Possibilities

The development of new types of wood propellers in the United Kingdom has been directed toward increasing blade stiffness, adapting wood blades to the Hamilton Standard hub, equalizing the shear strengths in both directions in the root, and experimenting with a molded type of hollow blade. In addition, consideration is being given to a redesign to avoid the eccentric loading of the press platens in the manufacture of tapering-density blades, such as Jablo.

It is possible that, with new developments in stabilized wood, combined with United Kingdom practical experience and our own Wright Field's propeller section's knowledge and theories, blades could be made more cheaply, in shorter time, with less labor, and with superior properties. It is recognized, however, that because maximum production is vital, and because present methods are giving satisfactory blades, any developmental work should not be done at the risk of diminishing production.

Cost

According to current figures furnished by the Ministry of Aircraft Production, wood blades are from 10 to 50 percent higher in production cost than metal blades of similar size and shape on a full production basis. It is reported, however, that on a basis of total service costs (including repair), this differential is much less because of the facility of repair and maintenance of the wood blade. Wood accomodates itself much more readily to changes in design than does metal, and probably has the advantage in cost for new types under limited production.

Performance

Ministry of Aircraft Production officials indicate that on modern airplanes it is possible to use wood blades without loss in performance over metal types; also that wood blades could meet the requirements of high-power large engines, but for this use the length of service to be expected may be the principal concern. On the up-to-date Spitfire, with Merlin engines, the compressed wood blade was reported to be equal in every respect to the duralumin type.

Repairs

Damaged propeller blades are repaired in large numbers by scarfing on a piece of the proper size and then reshaping, rebalancing, and refinishing. The extent of repair may vary from a small insert to a replacement to half the radius, as in the Jablo, and to a replacement of as much as three-fourths of the blade, as in the Weybridge propeller. Such repaired blades are reported to give good service.

Wood blades are generally regarded as easy, rapid, and cheap to repair. They cause a minimum of damage to the shaft and the engine in crash landings, because the blades break rather than bend, and likewise are advantageous for use with contrarotating propellers in reducing damage to the drive mechanism and engine in accidents.

The Flying Training Command points out at the same time that in crash landings the metal blade bends and acts as a skid, thus often saving the lives of the crew.

Future Trends

Manufacturers of wood propellers are of the belief that lighter weights of wood propellers may favor their use on large transport aircraft in the post-war period with substantial economy on a weight-mile basis. For peace purposes the crash landing problem is not so important as it is with war airplanes.

Recommendations

Current Application

It is recommended that mutual and coordinated United States and United Kingdom effort should be directed toward:

(1) Maintaining, through correspondence, reports, and personal contacts, complete and continuous interchange of pertinent information on wood, glues, wood- and paper-base laminates, veneer and plywood; on methods, techniques, and practices involved in their production and fabrication; and on design formulas and methods relating to wood aircraft.

(2) Developing, for wood aircraft, designs based on the special characteristics of the material rather than simulating the structural designs developed for other widely different materials.

(3) Investigating the structural performance and serviceability of wood aircraft and of repair methods and techniques applicable under the diverse operating conditions in the various theaters of use.

(4) Putting into practice improved fabrication methods and techniques, through interchange of detailed information on new and efficient jigs, heating methods, pressure devices, and processes.

(5) Developing, insofar as is practically possible, uniform specifications on woods, veneers, plywood, glues, wood- and paper-base laminates, and finishes used in aircraft.

(6) Interchanging samples of current and new glues for testing and study of their properties.

(7) Extending the use of low-temperature phenol-formaldehyde glues in laminating and assembly of gluing operations.

For United States practices, it is recommended that special consideration be given to:

(8) Liberalizing of United States plywood specifications, with respect to quality of veneer, and coordinating the production of plywood to specific uses and requirements, insofar as possible.

(9) Improving methods of conserving high quality veneer, along lines of United Kingdom practice.

(10) Requiring the use of a light-weight fabric as a part of the protective finish for all exterior surfaces of wood.

(11) Providing adequate and properly located drain holes in wing and control compartments.

(12) The full possibilities of repair and repair methods, as a means of increasing the number of serviceable airplanes, as is done in the United Kingdom.

Research Needs

Marked progress has been made in the United States and the United Kingdom since the outbreak of the war in the solution of certain problems relating to the more efficient use of wood and glues for aircraft. In view of the inherent utility of wood, both for current war applications and for post-war civilian needs, it is particularly recommended that active research be continued and developed on a number of important projects, such as:

(1) Evaluation of various synthetic resin glues for aircraft use, including the development of test methods and requirements; correlation of glue properties, as determined by chemical methods and short-term joint tests, with serviceability in aircraft.

(2) Investigation of gluing conditions for the synthetic resin glues and the development of techniques for the production of joints with wood, wood- and paper-base laminates, metal and wood, and various combinations of sandwich-type materials.

(3) Investigation of methods and techniques suitable for the repair of aircraft under operating conditions and the effect of such repairs on the strength of members; also incorporation of best practices currently in repair manuals.

(4) Study of methods and materials for finishing plywood and fabric surfaces to simplify, improve, and speed present practices.

(5) Continue investigation of the temperature and moisture conditions in wings and other parts of aircraft in service and determine the effect of finishes and drain holes in minimizing or eliminating undesirable conditions.

(6) Development of wood-, modified wood-, and paper-base laminates that combine dimensional stability and freedom from brittleness.

(7) Determination of the effect of moisture on the strength of glued structural units, as related to the interpretation of the results of static tests of wood airplanes or airplane parts.

(8) Evaluation of the influence of rate of loading and duration of stress on strength, and relate the results to design values and the interpretation of data from static tests of airplanes.

(9) Continuation of the basic research on plywood to develop the necessary design formulas and data for efficient design.

(10) Development of the mathematical formulas covering the fundamental behavior of sandwich construction employing a high-density skin and low-density core or equivalent types.

(11) Investigation of the possibility of producing low-density cores for sandwich structures from various wood- and fiber-base materials with favorable weight-strength ratios.

(12) Development of an improved, simplified propeller blade that lends itself to rapid and cheap production.

Coordinating Committee

It is recommended that arrangements be made for a Mission from the United Kingdom to visit the United States and Canada in the near future, and that during their visit plans be made to establish a joint committee to implement the interchange of data, information, and practices, to coordinate research plans and activities, and to aid in the application of results.

I. WOOD FOR AIRCRAFT

Reasons for the Manufacture of Wood Aircraft in the United Kingdom

The principal wood airplanes in active production or in use in England are the Mosquito, Oxford, Anson, Magister, Master, Martinet, Albermarle, and Tiger Moth; and the Horsa and Hotspur gliders. The general policy in Great Britain is to build of wood all trainers and gliders and some combat airplanes.

The important reasons for manufacturing wood aircraft in the United Kingdom are due to the conditions surrounding the war effort. However, so successful an airplane as the Mosquito would not have been produced if it had not been for the experience gained, particularly at DeHavilland, in the design and manufacture of wood aircraft in the past. The Mosquito is the result of 20 to 25 years of experience in wood design, the use of sandwich construction, and is the result of at least 6 years' experience involving two planes before the Mosquito. The interest in wood during all these years was due to a conviction that light bulky materials are more suitable for aircraft construction than heavy dense materials, since local instability is thus more easily avoided.

The special conditions that led to the use of wood were the shortage of suitable metals, metalworkers, and metal factories, and the availability of wood, woodworking plants, and skilled woodworkers. The metalworking plants were filled to capacity with war work of all kinds. Still an insufficient quantity of war materials was being produced. Meanwhile furniture and other woodworking plants had much less to do and skilled artisans were available. It was evident that the manufacture of wood aircraft would greatly increase the total war effort.

This condition, together with the urgent need for aircraft, led to the quick decision to manufacture aircraft of wood. One wood aircraft was designed, built and flown in 9 weeks while heavy bombing of England was still prevalent.

Wood aircraft were designed and manufactured in England before the war (especially by DeHavilland), but war conditions greatly increased the number of types. At the present time, wood in England is more scarce than metal.

Some experienced manufacturers and designers felt that wood was especially suitable for airplanes up to about 10,000 pounds, and in combination with metal for larger airplanes; others felt there is no limit to the size of well-designed wood airplanes, such as the Mosquito, which also achieves marked economy in fabrication. Production costs at present are reported to be 10 to 20 percent higher for wood airplanes than the metal ones of comparable weight and performance. This difference in cost is said to be largely accounted for by the fact that wood airplanes are primarily produced in small plants under dispersal conditions.

For the wood Mosquito and the metal Beaufighter the costs are about the same; generally, unless production is large enough to justify the manufacturing equipment required for low-cost production of metal airplanes, the cost of wood airplanes will be the lower.

There is no question but that wood aircraft and wood propellers have been highly valuable in the British war effort. Serving under adverse conditions of exposure--mostly without hangar facilities of any kind or with only limited protection, it is amazing what well constructed and properly finished airplanes have stood up to, reports the Flying Training Command. Particularly good results are reported with the Anson trainer (metal fuselage, wood wings), some of which have been in training service for 7 years, service in which a single airplane may make from 40 to 60 landings per day. Many airplanes, such as Tiger Moths, are giving upwards of 2,000 hours flying service in the Flying Training Command before checking to see if they should be withdrawn from use. This amount of time is regarded as excellent service, particularly when aerobatics are employed. During such a period numerous repairs are, of course, required because of crash landings and other accidents. Oxfords also stand up well. Without much protedtion, they frequently show no deterioration until about 1,000 flying hours, which means about 2 years' service. Contributing to the weathering ability of wood airplanes in the United Kingdom is the general use of fabric covering (madapollam) over the wood and plywood surfaces, in conjunction with the use of suitable dopes and finishes.

One of the most publicized and outstanding airplanes of the war is the all-wood DeHavilland Mosquito previously referred to. This is a 23,000-pound, twin-engined, high-speed airplane, designed in a very short time largely on the basis of experience with the "Comet" racer and the "Albatross" transport. The wing span is 54 feet 2 inches and the length 40 feet 9-1/2 inches. Designed as a bomber, the Mosquito has found extensive adaptation for special purposes. It functions mainly as a day and night reconnaissance bomber, bomber destroyer, and night intruder fighter--a triple threat airplane with flying speed reported to exceed 400 miles per hour. A special feature of the design is the plywood-balsa-plywood sandwich construction, employed in the fuselage, which affords a skin of substantial thickness and exceptional strength and rigidity.

It is difficult, if not impossible, to make direct comparisons between different airplanes and their suitability from the standpoint of different materials of construction. Best results with any material are attained when the design is based on full consideration of the properties. With wood design this means special consideration of joints and fastenings, and as was done in the Mosquito, their elimination as far as possible.

Special effort was made to obtain information on difficulties with wood aircraft in England with respect to design, fabrication, or maintenance and repair. The general conclusion is that no major difficulties or problems were encountered in its use in England, and that wood airplanes have given satisfactory service.

Officials of the Flying Training Command state that the question of airplane preference must be considered from the standpoint of use, that is, whether for training, fighting or ferry service. In light training, durability does not count so much as ease of repair. In operational aircraft, the life is shorter still.

It was indicated that wood aircraft have been used all over the country, and that it is amazing what they have stood up to. The Horsa glider was an agreeable surprise in this respect, as it is understood that it was not designed for continuous service.

Also it is reported by the Flying Training Command that there have been periods when all airplanes have given problems, as no airplane has come off the drafting board without the need of some modification. When structural failures or difficulties are evident, they are given immediate attention.

They state that it is easier to tell whether wood has shown deterioration than it is with metal, and it is often possible to make repairs with wood than would not be possible with metal.

Repair of aircraft, always important, assumes major prominence in wartime. Repairs are made after damage up to 75 or 80 percent of the value. No airplane is discarded that can be repaired. For each airplane flying, five are grounded. Approximately 40 percent of all combat airplanes in use have been repaired.

With respect to repair, officials of the Flying Training Command and the Directorate of Repair and Maintenance state that wood airplanes are the easiest to repair, take fewer tools and equipment, and require only about 60 percent as much personnel to maintain as do other types.

Likewise wood aircraft are reported to be the easiest to repair in the field, can even be repaired after a belly landing, and have a decided advantage for desert service where a minimum of facilities are available. In a belly landing, a metal airplane suffers general distortion, and must be fitted into a jig before repair can be made.

It might be assumed also that wood aircraft would be more susceptible to fire, but experience has not borne this out. It was stated that if the gasoline catches fire, any airplane will burn out, whether of wood or metal. Fires in training are usually due to electrical faults or spilled gasoline. Special tests have shown the Mosquito to withstand incendiary bullets satisfactorily.

Some officials emphasized the advantage of composite construction for aircraft, taking advantage of the combined qualities of materials, from the standpoint of ease of repair, protection of personnel, and serviceability.

The Francis Francis crash of a Mosquito was described as the most remarkable on record. In taking off, one engine failed, and the airplane went into the ground at 100 miles per hour. The pilot emerged with only a black eye and injured knee, and was well enough to take a bus to the doctor's office. Opinion is that had the accident occurred in any other type of airplane the pilot would not have survived.

Propellers

All of the fixed pitch and approximately half of the controllable-pitch propellers now used in British military aircraft are of wood or some form of modified wood. The original reasons for the use of wood blades, similar to the conditions surrounding the production of aircraft themselves, were the lack of metal forgings in the early stages of the war and the availability of skilled woodworkers. Even today there is not sufficient productive capacity, for any one type of blade, to meet all needs and it is regarded as essential that all types be kept in full production.

Either wood or metal propellers may be used in training or combat aircraft. The all-metal Spitfire is normally equipped with a variable-pitch wood propeller, while the all-wood Mosquito uses metal blades.

Ministry of Aircraft Production officials report that on modern airplanes it is possible to use wood blades without loss in performance over metal types. In fact, in several experimental installations, the flight data on wood propellers indicated slightly faster rate of climb, and higher ceiling, with either small losses or gains in top speed, than the comparable metal type, and with no appreciable difference in the stability of the airplane. In one particular installation, some additional trim was required on the wood propeller.

In England wood propellers of the variable pitch type are used with the Rotol hub of British manufacture. The blade root is adapted to this hub by a conical metal ferrule threaded and cemented to the blade. Wood blades are difficult to attach to the Hamilton Standard hub, which requires a blade with a hollow root.

Data from the Ministry of Aircraft Production indicate that current production costs of wood blades are from 10 to 50 percent higher than metal blades of similar size and shape on a full production basis. It is reported, however, that on a basis of total costs (including repair), this differential is much less because of the facility of repair and maintenance of the wood blade. Wood accomodates itself much more readily to changes in design, and probably has the advantage in cost for new types under limited production. Wood blades are somewhat lighter than metal blades. This advantage, however, is greater with engines of high horsepower. Advantages of the wood propeller include ease of manufacturing new designs and types, and ease of repair. Many wood blades in service have been repaired as many as four times.

Damage to propellers in service results mainly from bullets, empty shell cases, stones thrown up in taking off or landing, and crash or belly landings. Some officials of the Flying Training Command report wood blades are less harsh than other types because of their ability to absorb vibrations. From another standpoint some preference is expressed for metal blades in the event of a belly landing; they fold under the airplane and form skids which tend to reduce damage to the airplane itself and injury to its occupants. Wood blades characteristically fail by breaking off in such landings. Other officials, from the standpoint of maintenance and repair, stress the advantage of wood blades in that damage to the engine is minimized with such a type of failure. The use of wood blades is reported to be of special advantage for use with contrarotating propellers, to avoid serious damage to the gear mechanism and engine in an accident involving the propeller.

II. DESIGN DATA AND METHODS

Methods of Design of Wood Aircraft

In England

As in the United States, the basic formulas for structural design with wood plywood and sandwich construction are far behind those used for metal. Data sheets have been published that give the strength characteristics of metallic elements, but very little similar data are available for wood and plywood. Some of the British designers recognize fully that the best type of wood aircraft structure is necessarily very different from the best type of metal. The development of the Mosquito is a good illustration.

Officials of one large company point out that, in their opinion, there has occurred a greater development of wood aircraft in the United Kingdom during and after the last war than in the United States. When this company turned to metal it was thought a remarkable accomplishment to develop a design that was as light and as strong as a similar wood aircraft while in the United States some difficulty is being met in designing wood aircraft as light and strong as metal aircraft. In both countries the difficulty results from a lack of full appreciation of the fundamental differences of design in the two materials. This company indicates that it is easiest to design larger aircraft in metal and smaller aircraft in wood, and suggests that the dividing line is a gross weight of about 10,000 pounds for commercial aircraft.

DeHavilland, on the other hand, does not see any limit to the size of properly designed wood airplanes, such as the Mosquito. The gross weight of the Mosquito is 23,000 pounds.

Each company has its own design methods. In general, the design methods apply only to the particular type of airplane being designed and are determined largely by tests upon the airplane parts. The ultimate stresses used in the design are determined in the same manner. The result is that different design stresses may be used in different parts of the same airplane; and very different design stresses are used for parts of different types of airplanes. These design stresses embody correction factors or form factors which allow for errors in the methods of computing the stresses in any particular part.

The ultimate strengths of different species of wood, determined in the laboratories, are used mainly for inspection and specifications. It follows that no unified system of design stresses for wood is in effect. In speaking of design stresses or design methods, therefore, it should be understood that they refer to but a single type of airplane and, in some cases, to a single airplane or even to a single part of the airplane.

Design of the Mosquito

General description.--The method of design used in the Mosquito is of special interest. The Mosquito is of all-wood construction, and of dimensions and characteristics as follows:

Overall length 41 feet 2 inches; wing span 54 feet 2 inches; root chord 12 feet 3 inches; tip chord 3 feet 10 inches; aspect ratio 7. Gross wing area 436 square feet; loaded weight about 23,000 pounds; power plant, two liquid-cooled Rolls Royce Merlin Engines.

The wing is made of one piece from tip to tip, and employs two spars with the usual interspar rib structure. The stressed skin covering, however, is a distinct departure from usual types. It consists of a birch plywood skin, 1.5 to 2 mm. thick, reinforced by closely spaced, spanwise stringers of Douglas-fir about 1-1/4 inches square, which, over the upper surface of the wing, are sandwiched between a double covering of skin. On the under surface, the outboard panels of the skin are of identical construction but with only one skin. Over the center portion of the span, where the fuel tanks are housed between the spars, the wing undersurface is completed by stressed covers to the tank bays. Both main spars are of box construction, with laminated spruce flanges and plywood webs.

The fuselage, which is composed of a plywood and balsa wood sandwich about 1/2 inch thick, is of special interest, as the construction is reported to afford one of the simplest and quickest methods of producing a monocoque type unit. The internal stiffening structure is produced integrally with the shell. The fuselage is cut out at the bottom so that when lowered from above, it will fit onto the wing structure to which it is attached at four points. The division of the fuselage into halves along a vertical center line simplifies fabrication and subsequent assembly operations, particularly in the stages where services and equipment are installed.

Design details.--From experience with two airplanes that preceded the Mosquito, it was known that sufficiently stiff structures of the sandwich type could be designed so that no local buckling would take place. Knowing the loads on the airplane, the compressive and tensile leads in the fuselage shell were computed, and a thickness of core material selected from previous experience. It was assumed that all the stress was concentrated in the faces of the sandwich so that by the adoption of previously used maximum stresses the thickness of the plywood was determined. Specimens of this construction were tested in compression in the short column range and from them the design compression stresses obtained. The stresses determined for yellow birch plywood (three equal plies) were:

Parallel to face grain 7,200 pounds per square inch

45° to face grain 6,800 pounds per square inch

Similar panels 6 inches square and tested in a shear frame gave the following design stresses for shear:

45° to face grain 5,400 pounds per square inch

(The 45° shear panels were tested to the capacity of the machine and were not broken.)

90° to face grain 4,200 pounds per square inch

These design stresses were used as applying to the faces of the sandwich alone and the strength of the core was neglected. Their use determined the thickness of the faces to be used in the final design.

To ensure that buckling does not take place, the following formula (similar to the Forest Products Laboratory (Madison) formula for cylinders in compression) was used:

$$p = k \frac{h}{r}$$

where p = stress in pounds per square inch

k = a constant for the particular sandwich construction

h = thickness of the sandwich

r = radius of curvature of the shell

The value of k was determined from tests on an experimental fuselage, and from the equation and the stresses involved, the exact shape of the fuselage was determined. The final cross section was egg shaped because the concentrations of bending stresses at the top of the fuselage required a small radius of curvature there. The spacing and stiffness of the ring bulkheads within the fuselage were predicated by experience and confirmed by test of a completed experimental fuselage.

The fuselage was designed for torsional strength and stiffness by a similar process. It developed that the face grain of the sandwich should be longitudinal to the axis of the plane over the central part of the fuselage for bending strength and be at 45° in the tail section for torsional stiffness.

The wings were designed in a similar manner. The first experimental wing developed a computed tensile strength in bending of 12,000 pounds per square inch in the spruce flanges of the wing beams. This value was used in the design of the final wing. In the computation it was assumed that the skin material was located upon the chord of the wing rather than upon the arc. In this way, a certain allowance for shear lag was introduced. The load distributed between the front and rear spars was computed by the shear center method used in the United States.

Experience has shown that if glue joints are required to take tensile stresses normal to the glue plane, the strength is improved by the use of screws in addition to the glue. This was established in the case of the Mosquito, by testing duplicate wings with and without screws. The one without screws failed at a lower load than the one with screws.

The final design was put through rigorous tests by the DeHavilland Company and small changes were made to overcome local weaknesses. The total weight of the plane has been increased from 17,000 pounds to 23,000 pounds since the first design by the addition of armament. New tests have been made considering the larger weight, but only small changes in the design were found necessary. It was stated that no strain measurements were made during the tests. It is evident, therefore, that the true stresses are not known since the methods of computation are only approximate.

In general, the design stresses are obtained from tests on full-sized structural parts rather than from tests to determine fundamental data for general application. The design values thus obtained depend on the kind of structure and the method of calculation used as well as on the strength of the wood.

Design of the Hamilcar Glider

General description.--The Hamilcar is an all-wood glider of exceptional size. The general characteristics are as follows:

Length about 68 feet; wing span 110 feet; root chord 18 feet 6 inches; tip chord 8 feet 9 inches; loaded weight about 32,000 pounds; wing loading about 22 pounds per square foot.

The wing is of the conventional two-spar type. It is in three sections, joined by bolted strap fittings. The covering is three-ply birch plywood assumed to act in shear only and, therefore, placed so that the face grain direction is 45 degrees to the spanwise direction. There are no spanwise stringers and the ribs are spaced at 14-inch intervals. Every third rib is of the full depth, full web type. The intermediate ribs consist of shallow lower and upper box sections. The spars are of the box type with laminated spruce flanges and 45-degree birch plywood webs.

The fuselage is of square section with four continuous spruce longerons of laminated spruce construction. The longerons are connected by frames, the lighter of which are made of box sections and spaced about 18 inches on centers. The covering is three-ply 45-degree birch plywood stiffened by light longitudinal intercostal stiffeners, spaced about 9 inches.

Design details.--General Aircraft Ltd. designed the Hamilcar glider completely by mathematical methods and no actual tests were made, although a half-sized prototype was constructed to check flying characteristics. The full-sized glider was then built and flown without being statically tested.

In the design all the fundamental data available were employed, including much from the Forest Products Laboratory. Checks on the validity of the fundamental data are made by the research department. These tests are not made upon components of the aircraft under design, but rather are of a fundamental character, such as would be made in a research laboratory. This company feels that their methods apply to aircraft of any design and size.

The following data were used in the design of the Hamilcar:

Modulus of Rigidity of plywood parallel and perpendicular to the face grain, 10.5×10^4 pounds per square inch. At 45° to the face grain, 21.0×10^4 pounds per square inch. This value is admittedly low.

These figures are for three equal plies of birch. When the panels buckle, an apparent modulus of rigidity is obtained. A value of 0.4×10^4 pounds per square inch was used for this modulus although test results gave twice this value. A report provided the distribution of torsional shear between the beam webs and the skin. The shear stresses in the wing were low because the thickness was chosen to obtain the necessary torsional rigidity.

The limiting shear stress in the 45° plywood webs of the wing beams was 3,000 pounds per square inch. Near the tips of the spars the size of panels was limited by the buckling stress, determined by substituting the elastic properties of wood in the formula for sheet metal. The glue shear strength of the joint between the webs and flanges was assumed to be 250 pounds per square inch and the depth of the flanges was limited by this value. The width of the beams was determined by the bending moment to be carried and the modulus of rupture of 8,000 pounds per square inch modified by a form factor obtained from report M.T.11799. The compression strength of the wood was assessed at 5,000 pounds per square inch. Spruce was used.

In the design of fittings, a bolt bearing curve is used similar to that of the Forest Products Laboratory except that the knee of the curve is more sharp and the curve above the knee becomes rapidly horizontal.

The longerons in the fuselage were designed at 5,000 pounds per square inch. It was assumed that the load might be reversed and, therefore, this value was used in both top and bottom longerons. The resulting longerons are accordingly very strong in tension under normal load conditions.

 (p. 23b follows)

The fuselage covering was 1/16-inch three-ply birch plywood in panels about 15 by 9 inches. Thicker panels were used at points of high shear stress. Thicknesses as high as 1/4 inch were used in some of these locations. A shear stress for 45° plywood of 6,500 pounds per square inch was used. In tension fields a value of 10,000 pounds per square inch along the grain was used.

In general, the design methods employed were the best available. It was considered, however, that the glider was slightly above the best size for an all-wood construction from the point of view of maximum strength for the weight. General Aircraft officials indicated that if they were asked to design a glider twice the size of the Hamilcar, they would use metal parts at the wing root, probably a tubular construction, but would use wood for the major parts of the wings and fuselage.

DeHavilland Aircraft Co., Ltd., and General Aircraft Ltd. are two of the most forward looking companies now designing in wood and set an example of what can be done through a proper understanding of the properties of wood and experience in its use.

In general, the design stresses are obtained from tests upon completed structures rather than from tests upon the wood itself. They therefore depend upon the kind of structure and the method of calculation used, as well as upon the strength of the wood.

Stringer Construction

The National Physical Laboratory has published two papers upon the elastic stability of stringer constructions and a third paper is in preparation. The first has to do with a gridwork not covered by a sheet. The gridwork is loaded in compression in a direction parallel to the ribs; the second relates to a gridwork covered by a sheet and similarly loaded; the third paper has to do with the design of the lightest possible structures of this type.

The analysis has been done for isotropic materials, but no experimental confirmation of the theory has been made. The work has a bearing upon that for plywood skin construction under way at the Forest Products Laboratory.

Aircraft Design Requirements

Flight load factors.--In an effort to determine a better method for specifying the design load factors for new types, a statistical study has been made by the Royal Aircraft Establishment of all structural failures resulting from exceeding the design load factor for the type.

When design load factors for all satisfactory types were plotted against gross weight, military aircraft could be roughly divided into two classes. One class, represented by an upper curve, applies to airplanes whose tactical use required high maneuverability in the vertical plane; and the other, represented by a lower curve, applies to airplanes not requiring such maneuverability. These curves could be approximately represented by an equation of the form:

$$n = K_1 + K_2 \frac{1}{\sqrt{W}}$$

giving curves of a shape similar to those in U. S. Civil Air Regulations, part 04. In an attempt to eliminate arbitrary classification on a maneuverability basis, it was reasoned that an airplane with a high ratio of cruising speed to stalling speed is likely to be subjected to higher load factors, either intentionally or unintentionally, than one with a low ratio of cruising speed to stalling speed. The ratio of Vc/Vs is also a combined measure of power loading and cleanness. Points for all airplane types for which statistical data were available were then plotted on a graph of

$$n \text{ versus } (Vc/Vs)^2 \frac{1}{\sqrt{W}}$$

and it was found that a single sloping line would divide all those that had suffered structural failures in maneuvers from those that had not suffered such failures. As a result of this investigation, an equation for design load factor was proposed in the form:

$$n = K_1 + K_2 (Vc/Vs)^2 \frac{1}{\sqrt{W}}$$

This gives a family of curves on the n versus W graph, one for each value of Vc/Vs. However, the spread of the curves appears to be excessive; Vc/Vs instead of $(Vc/Vs)^2$ might be more reasonable.

The importance of flight-control characteristics in avoiding structural failures due to excessive loads in maneuvers was brought out by the fact that such failures in Spitfires have occurred almost entirely in airplanes in which the center of gravity was so far aft as to make the "pull-out" stick forces very light. The required stick force per "g" of acceleration is now:

Fighters	3 - 8 pounds
Medium bombers	25 - 30 pounds
Heavy bombers	40 - 60 pounds

A study of design diving speeds showed that the ratio to level high speed should be 1.3 for bombers and 1.5 for fighters.

<u>Ground loads</u>.--The airplane is designed for an <u>inertia</u> load factor equal to the acceleration developed in drop tests of the shock struts

by the "wing lift" method, assuming that the lift on the wings is equal to the dead weight of the airplane during the entire impact. A minimum value of $n = 2.5$ is specified. The sum of the ground reactions on the landing gear is then equal to the inertia load factor minus 1.0, and an upward airload equal to 1.0 g is applied to the wings to complete a rational dynamic condition for the airplane. The safety factor is 1.33. The full vertical ground reaction is then combined with an aft component of 0.4 n, and a side component of 0.3 n, as separate cases. There is also added a special case for landing on concrete. The vertical component is then 50 to 70 percent of the foregoing, but the aft component is 0.8 n. Although these requirements may give lower vertical loads on the gear than do American specifications, they appear to be more rational and may result in better proportioned gears.

A theoretical study has been made of a tricycle gear airplane making 3-point contact, and the following formula derived for the mass to be dropped with the nose gear in drop tests:

$$W_e = W \left(\frac{b + \mu h_2 + \frac{r}{n} \frac{K^2}{a}}{a + b} \right)$$

Where W_e = Mass for nose wheel drop

W = Gross weight of airplane

μ = Coefficient of sliding friction during "spin up" period of wheels,
or
= 0.4 for gross

K = Radius of gyration of airplane in pitch

n = Acceleration at center of gravity (in g's)

r = Additional acceleration of point in airplane above nose wheel, due to pitch. $r = 0$ to 0.3 depending on relative characteristics of shock struts. For new designs r may be assumed = 0.2 a, b, and h_2 as shown in figure 1

Stiffness criteria.--The original purpose of stiffness criteria was to insure favorable conditions for flutter control from the beginning of the design. In fact several designers stated that they began the design of a wing or fuselage by determining the skin thickness required to meet the torsional stiffness requirements. In the course of time, however, the criteria had to be extended to cover cases such as an airplane that was longitudinally unstable due to the flexibility of the fuselage in bending, and another type which suffered "elevator reversal" because the stabilizer twisted too much and reversed the effect of elevator deflection. The form of the torsion stiffness criteria is:

$$\frac{1}{V}\sqrt{\frac{m_e}{dc^2}} > K$$

where m_e = twist for unit torque

d = 0.9 semi-span

c = chord

V = design dive speed

K = required value

Static testing.--The general policy in the United Kingdom is to test new types statically, but in some cases analysis alone is accepted. The tests are frequently performed at the constructor's plant if he has the facilities; otherwise at the Royal Aircraft Establishment. At present, static tests are required to be carried to 120 percent of design load to allow for variations in materials properties, unless the actual properties of materials in the test specimen are determined and the test results corrected to minimum guaranteed properties. However, the Ministry of Aircraft Production and Royal Aircraft Establishment are concerned over the apparent severity of this requirement, and perhaps some discretion is required in administering it. One representative interviewed suggested that design be based on average values, test corrections omitted, and any adjustments necessary to safely put this policy into effect be made on the design load factors. The Civil Aeronautics Administration policy of not requiring correction for material variations on static tests of complete structures was regarded as meritorious.

Supplementary design requirements and acceptable methods.--Quick additions or revisions to design requirements are issued in the form of "Aircraft Design Memoranda." These are drafted by technical subcommittees under the direction of the "Joint Committee on Aircraft Requirements," which consists of Ministry of Aircraft Production representatives and three leading designers. Aircraft Design Memoranda can be made effective by the Ministry of Aircraft Production without repetitious circulation of rough draft to the industry. An example is the requirements for controllability with one engine inoperative. Acceptable methods and procedures (similar to CAM 04) and information on service difficulties and their remedies, are issued in the form of "Airworthiness Technical Notes" by the Ministry of Aircraft Production.

Rate of Loading

The question of the effect of rate of loading and duration of stress on the strength properties of airplane materials, both in relation to the rapid stressing of an airplane in a maneuver and the slow static testing of an airplane structure, is a complicated one requiring further study and analysis, particularly with respect to wood.

The Royal Aircraft Establishment has been working upon the effect of rate of loading, and has an approximate method of analysis (fig. 2).

In figure 2, the time-stress curve MPN is determined by experiment using different rates of loading but maintaining for each rate of loading a constant rate of stress. The line OP indicates one such experimental loading. Failure occurred at point P. σ_c, the critical stress below which no failure can take place, must be determined by test.

$\phi(\sigma)$ is an unknown function of (σ). It is assumed that when

$$\int_{\sigma_c}^{\sigma} \phi(\sigma - \sigma_c)\, d\sigma$$

reaches a certain value, failure will occur, as at point P, when reached along the path OP. Now assume that the path OP' is followed, and then path P'C', such that A'C' equals AC. The integral will have a value at C' equal to the value it had at P and failure will occur at C'.

Further study on rate of loading should include tests to check the theory and its application.

Wood-water Relationships

The Forest Products Research Laboratory has been studying wood-water relationships. It seems possible to determine the elastic constants of wood by the use of vapor pressure methods. These methods may be of value in formulating a theory regarding the failure of wood.

Sandwich Construction

The Royal Aircraft Establishment is much interested in the further possibilities of sandwich construction, particularly for high-speed aircraft where it is essential that the surface of the aircraft (especially the wings) be free of small buckles. Wind tunnel experiments show that, roughly, the dimensional limits of waves whose crests and troughs are spanwise are such that the amplitude should not be more than 0.001 the total wave length. If the crests and troughs run chordwise, the amplitude should not be more than 0.002 the total wave length. Also, the shape of the wing section should be held within 0.10 inch of the designed shape.

Sandwich construction is thought by the Royal Aircraft Establishment to be one of the few which will meet these limitations. If the outer skin is of a dense material and is too thin to withstand stones, bruises, and the like, it should be backed up with a material of density intermediate between that of the skin and the core. The core should be, of course, a light material such as balsa.

Royal Aircraft Establishment staff members are interested in determining a proper test for various core materials and feel that tests on struts made of the complete sandwich might be satisfactory. The tests should be made on struts of various lengths of the same material. The length should range from short columns to columns well within the Euler range. It is recognized, however, that such tests are not at all conclusive and that the results may lead to erroneous judgments because the sandwich should be designed in each case to fit best the special requirements of a special position in the aircraft.

Fundamental Properties

Research at the Forest Products Research Laboratory has included experiments for determining certain of the elastic properties of wood by methods not commonly used or well established in the United States.

Moduli of rigidity.--Tests have been made to determine the moduli of rigidity of wood by means of observing the frequency of vibration of thin strips, and computing the elastic constants by means of the torsional pendulum equation. The equation is used in series form and the first two terms are employed. In the calculation, the modulus of rigidity in the plane of the thin edge of the specimen does not influence the results greatly because of the proportions of the test specimen. Experimental data have been obtained on beech and Sitka spruce that agree reasonably well with the calculated values.

In the tests, the specimen (0.5 cm. by 2.5 cm. by 20 cm.) is rigidly clamped with its length vertical, a bar of moment of inertia (I) attached rigidly to its lower free end, and the period of the resulting vibrations timed with a stop watch. The axis of the steel bar is horizontal, and vibrates in a horizontal plane. A bar 5/8 by 5/8 by 24 inches is used, but other sizes are also employed, depending on the size of the test specimen. The frequency of the system employed is such that the period can be conveniently timed. The method is also of interest for plywood as well as wood.

Young's Modulus (Pendulum oscillation method).--As with the moduli of rigidity, the values of E (Young's modulus) are measured by timing the frequency of flexural vibration. The specimen is clamped by one end as a cantilever beam with the broad face horizontal. A suitable weight is attached rigidly to the free end, and with the pendulum system in motion the period of the resulting vibrations is timed. The specimens were of similar size to those employed for measuring the moduli of rigidity. Allowance was made in the calculations for the rotary inertia of the load and of the mass of the specimen. The agreement between experimental and theoretical values is considered reasonably satisfactory.

Indications reported are that the values for E parallel to the grain are about the same whether determined statically or by oscillation methods (electric or vibrational). The transverse moduli and moduli of rigidity seem to be independent of frequency provided the vibration method is used, but there is a difference between static and dynamic determinations. Further study should be made to compare the results with those obtained by the usual more complicated stress-strain methods, to determine the significance of the values and the magnitude of the differences.

Young's Moduli (Electrical vibration method).--Apparatus has been developed at the Forest Products Research Laboratory for determining Young's modulus by the electrical vibration method, using a thin flat specimen clamped as a cantilever beam, rather than the specimen of larger size supported as a simple beam employed in the experimental work at the Forest Products Laboratory in Madison. The specimen is approximately 1/8 by 1 by 12 inches. The apparatus employs an oscillator, a magnetic attachment or driving element for transferring the frequency to the specimen, and a pick-up element connected to an oscillograph. The driving element is employed at the free end of the cantilever specimen, and the pick-up device is about midway between the support and the free end.

Some preliminary experiments have been carried on at the Forest Products Research Laboratory, but results have not, as yet, been published.

Related experiments are also being made with similar apparatus on specimens having magnets attached to the end grain.

Damping measurements.--The damping characteristics of wood can be measured from the width of the resonance curve on the oscillograph. In this evaluation the frequency is varied by small stages, and the amplitude of response measured. When the resonance curve is plotted, an estimate of the damping is obtained from the width of the curve.

Poisson's ratios.--No work is in progress at the Forest Products Research Laboratory to determine Poisson's ratios, and no special apparatus has been designed for this work.

Moisture-strength Relations for Glued Wood Airplane Structures

Studies of the effect of moisture on the strength of wood made at the Forest Products Laboratory (Madison) and elsewhere have resulted in the establishment of formulas for moisture-strength adjustments of wood. In the testing of wood airplane structures with the wood at moisture contents below the 15 percent design value, it has usually been assumed that the resulting test values for the structures should be adjusted to the 15 percent moisture basis, by means of the established formulas for wood. Grounds for this assumption have been further indicated by the data on moisture-strength relations for glued joints, based on shear tests of small specimens. That this assumption may be in error, and that the strength of glued wood airplane structures is not so greatly affected by moisture as the wood itself is indicated in recent tests at the Royal Aircraft Establishment on casein-glued joints and on full-sized tail plane sections of the Master.

The strength of casein-glued joints was appraised by means of test joints that were conditioned for test by being stored in the starboard outer wing of a Master. Individual specimens were removed and tested from time to time. The test pieces consisted of 6-inch squares of plywood with a spruce rib 1/2 inch wide running across the middle at right angles to the direction of the grain of the face veneers. The side of the plywood to which the rib was attached was left bare; the other side was painted with a standard finish of two coats of red dope (madapollam); and two coats of cellulose lacquer pigmented with aluminum powder. Specimens after storage in the wing of the plane were removed at intervals over a 5-month period. The tests consisted of tension perpendicular to the plane of the joint, so as to produce stress concentrations on the edge of the joint. Control tests were made on test pieces which had been aged for one week in a warm room. For further comparison with the tests in the wing, six test specimens were treated for two days in a warm box over water before test.

The results showed that the exposure to water vapor may not reduce the failing load of a casein-glued joint. Although there is no doubt that the casein glue itself becomes weaker when damp, it also appears to become more ductile. The effect of the increased ductility is to allow the glue, and possibly the wood, to yield at points where stress concentrations arise, so that when the joint is damp, stress concentrations are relieved to the end that progressive failure is retarded and the structure as a whole may not be weakened so much by higher moisture contents as is commonly expected.

Since a high relative humidity is not so harmful as has been frequently assumed, the Royal Aircraft Establishment suggests that the use of heaters to dry the space inside the wings and cockpits of wood aircraft is probably not worth while. Experience has shown that deterioration of glued joints in service is nearly always caused by the accumulation of free water in badly drained corners of the structure.

Tests of Master tail planes.--Closely related to the results of the glue joint tests, are the tests of 100 tail planes for the Master at Royal Aircraft Establishment. Seventy were tested dry with but small variations in moisture content, and 30 were alternately dry and wet. The bending tests were made to permit any weakness to develop so that the spar could fail or the torsion box could fail. The results of these tests have not yet been made available in report form. Preliminary analysis showed that for 60 tail planes tested dry, the standard deviation of an individual was only 7 percent of the mean strength; that there was little difference between the Beetle glue and the casein glue in the tests; and that full tail surfaces do not give large reductions in strength when wet, as do lap joint specimens for glue tests in tension. The results of the tail-plane tests are in general agreement with the results of the Royal Aircraft Establishment joint tests reported.

These data are of great significance and far-reaching import in relation to the correlation of design moisture conditions with the static test moisture-content-strength relations for airplane structures, particularly in United States practice.

Effect of Defects on the Strength of Plywood

A comprehensive series of tests was made by the Forest Products Research Laboratory to determine the effect of various defects in relation to their size and position on the shearing strength of plywood panels. Included with the investigation was the development of a test method, and a strain gage for measuring deflections.

Test panels with a plywood shear area 9 inches square were made up with cleats glued to both faces at each edge, the panel then being bored at the cleats for bolting into a special testing frame. The panels included controls for comparison with others containing splits, dead streaks, knots (pin knots, small knots, and large knots), irregular grain sloping grain, wild grain, dote, inserts, and manufacturing defects, such as overlap. The results in general show that for the panel sizes used, the shear strength is less affected by defects than is commonly supposed.

Izod not Recommended as an Inspection Test

Perhaps because of its simplicity, the Izod test has gained prominence in certain specifications as a requirement for aircraft woods. It is an impact test conducted on a notched specimen, and has long been regarded by some engineers more a measure of notch sensitivity than a criterion of general strength qualities. From the analyses of data from a number of different kinds of tests on aircraft woods made at the Forest Products Research Laboratory, it is shown that the Izod test exhibits a better relation to the tensile strength of wood parallel to the grain than to any of the other properties, but even this relationship is not a consistent one. Individual Izod tests on specimens taken side by side throughout the cross section of a single plank have shown a maximum range of 13 foot-pounds per specimen. The general conclusion is that density affords a more reliable criterion of quality than the Izod test. It has been recommended by the Forest Products Research Laboratory that the Izod test be omitted from specification requirements for aircraft woods.

Spruce Substitutes

The demand for high quality aircraft lumber has lead to the need in the United Kingdom for species that can be substituted for spruce in airplane construction. In the United States four species are admitted as spruce substitutes in spruce sizes as follows: noble fir, Western hemlock, yellow-poplar, and Douglas-fir. As a result of tests made at the Forest Products Research Laboratory specifications have been recommended for noble fir and for Western hemlock, and these species are already in use in England. Western hemlock is being used exclusively by Airspeed Ltd. for spars and other parts of the Oxford trainer. Officials of Airspeed Ltd. stated that the quality of Western hemlock received since the first shipment has declined somewhat but with increased knowledge of the species it is giving good results. Observations of Oxford spars in manufacture indicated a good quality of material and a good finished product. No similar opportunity occurred to observe the use of noble fir.

The necessity of employing spruce substitutes was again brought out in propeller construction. The Airscrew Company, Ltd., has successfully substituted Douglas-fir for spruce in the propeller. Douglas-fir is now received in balks 6 inches in thickness, at a moisture content of about 24 percent. It is cut into 5/8 inch thick boards for laminations and then dried. While the use of spruce was abandoned reluctantly, Douglas-fir is now being used with success. Its adoption is regarded as a good move, aside from the question of supply, now that the company has become familiar with methods of classifying the material for the exacting use of propellers requiring close balancing.

Testing Machines and Test Methods

Glue-shear testing machine.--In order to expedite the testing of the standard-notched glue-shear specimens, a special testing machine was designed. The machine is a small horizontal unit, adaptable to tension or compression, with a capacity of 2 tons. It has a mechanical drive by an electric motor, and a hand adjustment for quickly positioning the loading head. The load is measured through a mechanical linkage on a hydraulic system and is observed by a mercury column in a graduated glass tube. For glue shear tests the machine is operated with special tension grips (described later), but a cradle for compression tests is also available. The machine as now used is made and sold by Tensometer, Ltd. A new small testing machine having similar characteristics, and the additional advantage of control to apply a uniform rate of stress, is made by W. and T. Avery, Ltd. The machine for glue-shear tests is an alternate for the modified cement-briquette testing machine now used in the United States for glue-shear tests. It is recommended by the Forest Products Research Laboratory principally for production or quantity testing. It lacks the accuracy of the usual testing machine.

Special wedge grips.--Special self-aligning wedge grips are used for the glue-shear tests. The grips were developed by and are sold by Tensometer, Ltd. A further improvement to the wedge grips is the special facing, developed by the Forest Products Research Laboratory, providing a roughened surface that affords a quick contact and positive gripping.

Tension test specimen.--A new form of specimen for the tension-parallel-to-grain test of wood has been developed. The specimen features a smaller fillet radius for the reduced section that was previously regarded as essential, and hence requires a relatively small specimen. The details of the specimen are as illustrated in figure 3. This specimen does not provide a uniform cross section at the center of the length for strain measurements to determine E, but satisfactory results are reported with its use.

Extensometers and Strain Gages

Plywood shear extensometer.--An extensometer especially adapted to the measurement of shear deformation in plywood (for use in the plywood-panel shear test) has been designed by the Forest Products Research Laboratory. Special advantage claimed is simplicity of construction and use. The strains are easy to read on a simple dial gage of the usual type. The instrument consists of two arms connected by a steel hinge, with three pointed feet to register with gage points on the test piece. The dial gage is attached to one arm, while the plunger of the gage contacts the end of a bracket on the other arm. The angular and linear motions of the two components are reconciled by interposing a short push rod with pointed ends which locate in countersinkings in the end of the plunger and in an adjusting screw in the bracket. This device is said to result in very smooth movement of the exceedingly sensitive dial gage employed. The error in measurement over the total range of movement involved is only one-sixteenth of one percent.

N. P. L. type strain gages.--The National Physical Laboratory strain gages employ the same principle as the "metalectric" gages made in the United States. The gage consists of a length of fine resistance wire wound upon a flat fold of resin-impregnated paper. Nicrome leads are spot welded to the winding which is then placed between further layers of impregnated paper and is bonded by heat and pressure. In operation, the gage is glued to the test surfaces so that the gage is strained with the particular test surface to which it is attached. The strain of the test specimen is indicated by the change in electrical resistance that arises from the change in dimensions and specific resistance of the wire when the test specimen is strained. Information on various features of use, including the all-important problem of glue attachment, has been studied and made available.

Included among the applications is the use of the gage to determine the setting time of glues. For this purpose, the glue to be studied is used to attach the gage to the wood.

IV. GLUES AND GLUING

Glues

Three types of glues are used extensively in the construction and repair of aircraft, namely phenol-formaldehyde, urea-formaldehyde, and casein. The use of phenolic glue, mainly in the form of film, is exclusively used in the manufacture of aircraft plywood. Liquid phenolic glues are used some in the gluing of thicker aircraft veneers, above 1/16 inch in thickness, but otherwise find minor application in aircraft construction. Urea resin glues are used mainly for laminating and assembly gluing and to some extent in propeller manufacture. Most urea glues used in aircraft are cold setting and are designated "gap-filling." The Ministry of Aircraft Production plans to cancel Specification D.T.D. 335A, covering non-gap-filling cold-setting synthetic resin glues, in the near future. Hot-press urea-formaldehyde glues are used to a limited extent in curved and flat aircraft plywood. Casein glues are used some in laminating and assembly gluing, mainly in propeller manufacture, and exclusively in maintenance and repair.

Phenol-formaldehyde glue.--No specifications for phenolic glues are in effect, except that low-temperature phenolic adhesives are tested for compliance with Specification D.T.D. 484, covering "Synthetic Resin Cement (Gap-filling)." The principal check on quality of high-temperature phenolic glues is the provision in the plywood specification (British Standard Specification No. 6V3), that requires a 3-hour boiling test. It is known, however, that the requirements of the plywood specification can be met by glues other than straight phenolics, such as a combination of thermosetting, synthetic resins. While such combinations would apparently meet the requirements of the plywood specification, their use is limited.

Low-temperature-setting phenolic resins have limited application and appear to have received less attention, either by research agencies or the glue manufacturers, than they have in the United States. Two adhesives of this type, approved by the Ministry of Aircraft Production under Specification D.T.D. 484 for use in aircraft, are sold under the trade names of Catacol and Cellobond. The early form of Catacol is reported to have been strongly acid and to have been recently replaced with an alkaline catalyzed resin. It is reported that since the return of the Mission a large user of wood in aircraft has adopted low-temperature-setting phenolic glue.

The Jicwood Division of Airscrew Co., Ltd. is using a cold-setting phenol type glue, reputed to be their own formulation, for gluing a metal-faced, wood veneer to a core consisting of a wood frame and onazote (an expanded rubber) filling, for bomb-bay doors of the Halifax bomber. The wood veneer is glued to a sheet of aluminum or dural with phenolic-resin film in hot presses and the veneer is then glued to the wood-onazote core with the phenolic type glue at room temperature.

Urea-resin glues.--Urea-formaldehyde resin glues for use in aircraft are required to meet the requirements of British Specifications D.T.D. 484 and 335A, for gap-filling and nongap-filling, cold-setting synthetic resin cements, respectively. The nongap-filling type is considered by the Ministry of Aircraft Production as unsatisfactory for aircraft use and it is expected that Specification D.T.D. 335A will be cancelled in the near future. The nongap-filling glues are, however, used for marine, war office and commercial grades of plywood and other forms of gluing in these fields.

The cold-setting urea-formaldehyde glues, approved for use in aircraft in accordance with Specification D.T.D. 484, are produced by three companies, namely the Aero Research Ltd., British Industrial Plastics Ltd., and I.C.I. (Plastics) Ltd. Beetle A glue, made by the British Industrial Plastics Ltd., is by far the most commonly used cold-setting, urea-formaldehyde glue in laminating and assembly gluing operations. Beetle A.F. is also an approved urea-formaldehyde glue and was developed because of unsatisfactory results in gluing skins on the Mosquito fuselage using Beetle A with low-pressure application. It is reported to be a significantly thinner glue than regular Beetle A. Five different Aerolite urea-formaldehyde glues with several different hardeners are approved as conforming to D.T.D. 484 but are not so extensively used in aircraft construction. Likewise one approved urea-formaldehyde glue made by the I.C.I. (Plastics) Ltd., is not much used in aircraft.

Specification D.T.D. 484 provides in paragraph 2(b) the following general requirement: "Before any particular manufacturer's material is approved for use in aircraft structures, the manufacturer must demonstrate to the satisfaction of the Director of Technical Development that the material retains adequate strength on aging." Under this provision further tests and limitations (in addition to those specifically provided for) are being applied to gap-filling, cold-setting urea-formaldehyde glues. These additional tests and limitations are discussed later.

Casein glues.--Casein glues for aircraft use are covered by British Standards 4V2, entitled "Casein Glue for Aircraft Purposes." So far as is known none of the available casein glues, which meet the specification, contain toxics for the inhibition of micro-organic deterioration, since no fungus test is required. Also, it is common knowledge that the casein glues being used deteriorate in aircraft structures under conditions favorable for the development of micro-organisms. In wood airplanes being repaired there was considerable evidence of casein glue failure where drainage was inadequate and moisture had accumulated. This condition was usually found in wing and control parts where drain holes were absent, inadequate, misplaced or for other reasons had not functioned properly. Damage to casein glue joints was also observed in the rear floor section of a trainer fuselage.

The problem of increasing the mold resistance of casein glues by the inclusion of toxics was discussed with members of the Ministry of Aircraft Production, and the results of tests and a proposed method of determining the resistance of glues to micro-organisms developed at the Forest Products Laboratory was left with the Forest Products Research Laboratory, where some work is in progress on the problem.

There is considerable current sentiment for a further replacement of casein glue with cold-setting urea-formaldehyde glues in laminating and assembly gluing operations and even in aircraft repair. In this substitution, the advantages of urea-formaldehyde resin glues with respect to higher moisture resistance must be weighed against the disadvantage of using them much of the time at relatively low gluing temperatures, such as 50° to 70° F., and a probable more rapid deterioration under higher temperature exposure in service.

Research on Glues and Gluing

Research on glues and gluing, as related to aircraft, is in progress on a number of projects at different government agencies and by various private concerns. The following is a listing of public agencies and research projects upon which work is in progress.

A. Forest Products Research Laboratories

1. Chemical factors involved in gluing wood with cold-setting urea-formaldehyde resins.

   (a) Effect of acidity of glue and wood on joints.

   (b) Fillers -- their function and effect on glue properties.

   (c) Buffers and compensators.

   (d) Nature of adhesion between glue and wood.

2. Tests on glues, gluing, and joints.

   (a) Weathering and aging tests.

   (b) Cyclic tests on glues.

   (c) Routine glue tests for Ministry of Aircraft Production.

   (d) Gap joint tests.

   (e) Separate application of hardener in Beetle A.

   (f) Gluing of balsa, plywood, and other timbers.

   (g) Gluing preserved veneer and weathering tests on it.

   (h) High frequency gluing.

   (i) Effect of toxics in casein glues.

   (j) Effects of freezing water-logged plywood.

(k) Moisture transfusion through plywood.

(l) Moisture relations of improved wood.

(m) Moisture content and temperature in airplane wings.

(n) Up-graded plywood.

(o) Identification of glues in joints.

(p) Development of laminating process by wrapping.

(q) Tests on lend-lease plywood for Ministry of Supplies.

B. Royal Aircraft Establishment

1. Improving the gluing properties of plywood surfaces by sanding and other treatments.

2. Adhesion between glue and wood.

3. Tests on glue joints at different moisture contents.

   (a) Small specimens.

   (b) Tail planes.

4. Tests on cycleweld and other metal-to-wood adhesives.

C. Chemical Research Laboratory and National Physical Laboratory

1. Setting of glues by strain-gage method.

   (a) Effects of time, temperature and acid concentrations.

   (b) Correlation with joint strength tests.

2. Properties of sandwich-type construction.

D. Cambridge University

1. Basic research on adhesion.

Research on glues.--Much of the research on glues, now in progress, relates to the durability of urea-formaldehyde glue bonds in wood, means of increasing their durability, test methods, and specification requirements for this class of adhesive. Considerable attention is also currently being given to the nature of adhesion between glue and wood and methods of modifying the glue and the wood surfaces to improve adhesion. Closely related to both is the requirement that glues shall be capable of forming good and durable bonds when the glue film is of variable thickness, particularly in thick films.

The Forest Products Research Laboratory has recently released a second progress report on "Chemical Factors Involved in the Gluing of Wood with Cold-Setting Urea-Formaldehyde Glues" and a third report under the same general title is being prepared. These reports deal with:

(1) The effects induced by cold-setting urea-formaldehyde glues on the physical properties of the wood in wood-glue composites.

(2) An interpretation of the results of exposure tests on joints made with cold-setting, gap-filling glues.

More specifically, the second and third progress reports include a discussion of the following:

(1) Assessment of the acid condition, induced by urea-formaldehyde glues in wood joints and a proposed method of determining acidity ("reference pH" method).

(2) Effect of aging on the strength of plywood, glued with cold-setting urea-formaldehyde adhesives of different "reference pH" when stored at three different temperatures for varying periods up to 28 months.

(3) Relation of relative humidity during aging to the strength of thick (0.03 inch) joints of casein and cold-setting urea-formaldehyde glues of fast- and slow-setting types.

(4) The function of fillers and compensators in urea-formaldehyde glues.

(5) A theory of chemical adhesion in which it is claimed that both cold-setting casein and urea-formaldehyde glues adhere to wood chiefly by complex association through hydrogen-bonding between OH groups of wood and water and CO, NH, and OH groups in the disperse phases of the glues and an interpretation of this theory in relation to the constitution and setting of urea-formaldehyde glues.

Current tests at the Forest Products Research Laboratory show that well-bonded joints, made with the best gap-filling, cold-setting urea-formaldehyde glues, decline substantially in strength when exposed at elevated temperatures. For example, plywood joints exposed at 158° F. and 100 percent relative humidity lost approximately 25 percent of their original strength after 20 days' exposure. The results also indicate that reduction in strength of cold-setting, urea-formaldehyde glue joints on aging is associated generally with a reduction of wood failures in test. It was also reported that one of the better aging urea-formaldehyde, cold-setting resin glues does not meet the requirements of D.T.D. 484 when tested with a 1/16-inch gap but does with a 1/20-inch gap.

One American-made urea-formaldehyde glue, in common use in aircraft manufacture in the United States, has been tested at the Forest Products Research Laboratory and found to meet the gap-filling test requirements of D.T.D. 484.[1]

The results of research and testing do not appear, however, to have developed, as yet, a sound basis for distinguishing between durable and nondurable urea-formaldehyde glues by short term tests. Under paragraph 2(b) of Specification D.T.D. 484, tests are being made on cold-setting urea-formaldehyde glues, in an effort to give greater assurance of quality in those glues which otherwise conform to the requirements of the specification. Currently, the Ministry of Aircraft Production gives approval to a cold-setting synthetic resin glue under Specification D.T.D. 484 for aircraft use, provided that:

(1) Joints made in accordance with the specifications and exposed at 25° C. and 45 percent relative humidity for 3 months show the required breaking load, at which time tentative approval is given or the glue is rejected. Final approval is given only after 12 months' aging at the same condition.

(2) Joint specimens made in accordance with the specifications and soaked in water at 158° F. for 3 hours and tested wet give the required wet-test value.

Investigations are in progress on other tests and conditions, as requirements for urea-formaldehyde glues, such as:

(1) Joints exposed to 194° F. without humidification for 3 hours, cooled and tested dry.

(2) Exposure of joints to 158° F. and 100 percent relative humidity up to 20 days, followed by soaking in water at room temperature for 24 hours and tested wet.

(3) A pH test on the glue or glue and wood combined.

The Forest Products Research Laboratory questions the pH determination of a dry film of urea-formaldehyde glue, as specified in Army-Navy Aeronautical Specification AN-G-8, as a satisfactory method of evaluating durability of urea-formaldehyde bonds in wood. Preference is expressed

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[1] Tests made at the U. S. Forest Products Laboratory on 23 urea-formaldehyde glues of U. S. manufacture show that 19 meet the requirements of both AN-G-8 and D.T.D. Specifications, that three failed to meet the requirements of both specifications, and that only one met the requirements of one specification but not the other.

for the "reference pH" method, previously referred to and described in the second progress report. There remains some doubt, however, as to whether the natural pH of wood of various species and of heartwood and sapwood does not complicate the proposed method unnecessarily and whether a pH test on the glue itself is not a more direct method. There is the further thought that "total acidity" should be taken into consideration as well as pH. Further research is needed on these points.

The development and standardization of short term tests on cold-setting urea-formaldehyde glues that will assure the maximum durability under service conditions and the correlation and interpretation of the tests and requirements in terms of crazing, allowable glue line thickness, time of setting, working life, and allowable assembly times are considered of great importance. Close cooperation of the research at the U. S. Forest Products Laboratory with British agencies, in view of the work under way in the two countries, should accelerate progress and developments in this field.

At the Chemical Research Laboratory studies have been made of the setting time of glues by means of a strain gage of the National Physical Laboratory type, which is similar to the metalectric type. For this work the strain gage is glued to a wood specimen using the particular glue being studied. The amount of strain observed in flexing the specimen at different time intervals is taken as the degree of set of the glue.

Urea resin glues have been investigated, covering such factors as time, temperature, and concentration or proportion of accelerator. The galvanometer readings are considered to indicate plastic flow or rigidity. The results obtained by this method have been compared with the results obtained on the strength of joints tested in shear and tension. On joints in spruce, good correlation was reported between the strain gage method and strengths in shear and tension, but in birch the results obtained with the strain gage seem to indicate a faster set of the glue than is indicated by the joint-strength tests.

Some research is in progress on the durability of phenol-formaldehyde and casein glues, particularly under different moisture and, to a less extent, temperature conditions, and their gap-filling properties. The testing and evaluating of two or three low-temperature phenolic glues is in progress, but melamine- and resorcinol-type resin glues are receiving very little attention. One glue is available in which a small amount of melamine is added with the accelerator. The question of availability, and the cost of melamine and resorcinol resins appear to be significant factors in their lack of development and the small amount of attention they are receiving in the United Kingdom.

Saro Laminated Wood Products Ltd., reported some unsatisfactory results in gluing plywood with glue film; the difficulty was attributed to different degrees of precuring the resin. As a result, perhaps of the same factor, different batches of glue film showed some difference in sensitivity to the moisture content of the veneer. These factors have not, however, received careful investigation.

Gluing investigations.--Gluing investigations, which are in progress or have been carried out in the past, have been directed for the most part at the solution of specific application problems. Investigations now in progress (see list of research projects previously outlined) relate largely to problems such as (1) the application of the hardener of a cold-setting urea-formaldehyde glue separately to the wood or in combination with the resin, (2) rate of setting of glue in joints with its acceleration with heat, (3) improving the gluing properties of plywood surfaces, (4) gluing normal wood into combinations with compressed wood or paper, and (5) laminating veneer by a wrapping method. Past investigations, described in various reports and papers, have covered certain other phases of gluing technique and procedure.

Limitations on gluing conditions are in general based on the recommendations of the glue manufacturers for specific adhesives. Investigations of permissible limitations in gluing conditions for specific adhesives appear to have been carried out largely by glue manufacturers and to some extent by the aircraft manufacturers. A report obtained from Phillips and Powis Aircraft Company, Ltd., is of this type and relates to investigations with a urea-formaldehyde glue in which tests were made of various application conditions.

More emphasis has been placed in England on the use of gap-filling and noncrazing glues, especially of the urea-formaldehyde type, and less on the development of allowable limitations in gluing conditions and their control in aircraft construction than in the United States. Current gluing practices in England are believed to reflect somewhat this difference (see Fabrication Technique and Methods). In the United States there appears to be more emphasis on having intimate contact of wood surfaces and thin glue lines, with less reliance on thick glue joints, than in prevailing British practice. There is no fundamental difference of opinion, however, on whether a glue that makes good joints under a wide range of operating conditions is preferable to one of more exacting requirements, other things being equal. The principal points of difference relate to methods of testing and evaluating resin glues, and need for control in gluing practices to assure strong and durable joints.

V. FABRICATION TECHNIQUE AND METHODS

In certain details of aircraft fabrication the practices vary, more or less, between England and the United States and among individual plants of both countries. The more significant characteristics of English practices that vary from American practices, are: Higher moisture contents of wood at the time of fabrication, lower temperatures within the plants during much of the year, more hand surfacing of parts to be joined, more extensive hand spreading of glue, separate application of glue hardener to the wood, and lower application of pressure in certain gluing operations.

Veneer and Plywood Production

In the production of aircraft veneer and plywood, the equipment used and the general practices employed are the same as, or similar to, those employed in the United States. Most aircraft veneer is cut on rotary lathes, dried on mechanical driers, and bonded into plywood on hot presses with phenol-formaldehyde glues with equipment that is similar to American equipment. The principal differences in methods have to do with the better or closer utilization of timber, veneer, and plywood.

Better utilization is accomplished chiefly through the following methods and practices:

(1) Cutting logs into bolt lengths that yield the maximum amount of straight grain veneer; (2) careful clipping methods; (3) utilization of narrower widths of veneer; (4) manufacture of more sizes of panels and manufacture to required sizes, shapes and grades for specific airplanes; and (5) utilization of cuttings and trimmings, from plywood panels, for other purposes.

Aside from birch, the principal veneer used in plywood for aircraft frames and in propellers, the following species are used in plywood: Gaboon, English beech, hard maple, yellowpoplar, and red gum. Large quantities of birch, a part of which is cut in England and a part in America, and small quantities of hard maple go into aircraft frame plywood and propellers. Small amounts of American-cut yellow-poplar and red gum are made into plywood for lightly stressed aircraft parts. Gaboon and beech are used chiefly for boats and War Office supplies.

American lathes, driers, and clippers were being extensively used at the plants visited and the quality of veneer produced with respect to tightness of sheet, smoothness, and freedom from wrinkling and wavy edges compares favorably with the quality of veneer manufactured at the better plants in the United States.

Considerable care is exercised in cutting logs into bolt lengths that minimize crook and other irregularities and thereby avoid excessive cross grain in the veneer. The use of bolts as short as 3 feet in length facilitates the getting of maximum yields of aircraft veneer.

The prevailing practice of winding the wet veneer on drums as it comes from the lathe tends towards more care in clipping and better utilization. At Factories Direction, Ltd., three clippers were provided for each lathe which permitted more time for evaluation of defects and cutting to the most economical widths. However, the officials are of the opinion that the system in effect of clipping the wet veneer by prevailing inexperienced help into sizes needed for plywood, did not lend itself to maximum utilization, and to obtain best efficiency with the method employed, experienced help, which is not generally available, is essential.

Some yield data were obtained from Factories Direction, Ltd. Yields of aircraft veneer from American birch logs, based on a square foot basis were: grade A, 40 percent; grade B, 40 percent; and commercial, 20 percent. Based on a cubic foot, log volume basis, the combined yield of aircraft and commercial yield of aircraft veneer from American birch was 36.4 percent. Yields are affected considerably by end dote, especially during summer shipments. It was reported that half of the logs in the last shipment received contained dote of varying amounts. The principal limitations in yields of aircraft veneer were given as (1) wild grain, (2) roughness, knots, and (3) dote.

Plywood is generally manufactured in sizes required in the various parts of different aircraft. The Saro Laminated Wood Products operation, in which some half dozen hot presses of various sizes are in operation, uses essentially this procedure. Maximum press capacity is sacrificed to produce the panels of the required sizes and for which the veneer is best suited. The new plant of Factories Direction, Ltd., however, is similar to American plants and operates along similar lines in that standard sizes of panels are produced and supplied to other operators who cut to the required sizes and shapes.

In general, it appears that in England more veneer of smaller sizes is utilized by edge-jointing than is commonly done in the United States. Saro Laminated Wood Products, Ltd., reports that the average width of veneer received is 9 inches with considerable volume running 3 to 6 inches in width. Occasionally, strips of veneer as narrow as 2 inches were being edge-glued into larger sheets.

Most aircraft plywood is glued with film glue, although veneers thicker than about 1/16 inch are sometimes glued with a liquid phenol glue. Saro Laminated Wood Products, Ltd., report some nonuniformity of glue bond strengths with film glue and regard the liquid phenolic glue as more dependable on thick veneers. They report that better results are obtained with two layers of thin film glue per joint than one thick film and associate the difference with precuring of the resin during the film production.

A special study was made on film gluing with veneers ranging in moisture content from 5 to 50 percent. It is reported that perfect results were obtained from 5 to 15 percent; acceptable results from 5 to 25 percent; and above 25 percent, it was impossible to get acceptable gluing. As a result, a moisture content range of 10 to 12 percent, with a maximum of 15 percent, is considered to give best results with film glue for veneers thinner than 1/16 inch. This company believes 8 percent gives better results in veneers that are thicker than 1/16 inch.

Marine plywood is made in hot presses, using urea-formaldehyde glues. Pressures used were reported to be between about 230 and 300 pounds per square inch. Platen temperatures of about 300° F. for film glues and 250° F. for urea-formaldehyde prevail.

Plywood, upon removal from the hot press, was receiving an application of water at both plants. At Saro Laminated Wood Products, Ltd., the panels were dipped in water and then stacked solid to condition. It was stated that the purpose of the moisture treatment was to bring the panels to a proper moisture content and that it did not remove the necessity for sanding or sand blasting for secondary gluing. At Factories Direction, Ltd., the panels were passed horizontally between sprays, which left a liberal amount of water on the upper surface. This surplus water was later wiped off with cloths. The moistened panels were first stacked in solid piles and later put between the platens of the hot press, but without pressure, to dry the surfaces and "lift the fibers." Factories Direction, Ltd., feel that the treatment removes the glaze and prevents difficulties in secondary gluing, and that sanding of the surfaces is unnecessary to get good adhesion. An examination of the panels, which are pressed between aluminum cauls, showed pronounced glaze which seemed to be removed by the moisture treatment. Tests made at the Royal Aircraft Establishment on the effect of sanding plywood surfaces on joint strength is discussed under "Glues and Gluing."

The trimmings, which result from cutting panels to exact size and shape required for various parts of aircraft, are utilized for other aircraft parts, occasionally for packing cases, or other uses. In general, more labor is employed to utilize small sizes of veneer and plywood more completely than is done in the United States.

Scarfing

Scarfing is extensively used in both solid wood and plywood and in general is done by methods similar to those used in the United States. Scarfing is perhaps used even more in England than in the United States in utilizing short lengths. Based on the operations observed, it is concluded that there is no essential difference in methods, except that more surfacing of the scarf surfaces is done by hand than in the United States.

The slope of scarfs in spar flanges and other highly stressed solid and laminated wood parts were usually made 1 in 15. In the Weybridge propeller the slope of scarf between the compressed and normal wood was reported to be about 1 in 20. Scarfs in plywood varied from 1 in 9 to 1 in 15.

The cutting of scarfs was accomplished in a number of ways. For plywood scarf joints made in presses the scarfs were usually cut on a cutter head, saw, or machine sander. In laying skins over wing and fuselage surfaces, however, the scarfs were usually cut by hand in position. In one operation all scarfs in laminations for spar flanges were cut by hand with a chisel and plane. Scarfs in most solid wood parts, however, were usually cut on a saw or cutter head. The scarfs in Douglas-fir laminations for the Weybridge propeller were cut on a combination saw and cutter head with a second saw that trimmed the lamination to length. In cutting scarf joints in the repair of Weybridge propellers a large cutter head was used.

The employment of electrical resistance heating and pressing units in the gluing of scarfs of spruce laminations for spar flanges at the Harris Lebus plant appeared to be particularly effective. A battery of six units, mounted in two sets of three each on two special transformers, permits the making of six joints at one time. The units are mounted on rollers that allow the operator to move the presses along the lamination to the position of the scarfs. The units are equipped with thermocouples for the measurement of temperature. The device is particularly applicable to the use of synthetic resin glues on moderately thin laminations.

Special hydraulic hot presses for the making of scarfs in plywood panels were observed in two plywood operations. These presses had steam-heated plattens approximately 8 inches by 6 feet, with three openings.

Laminating

The practices and methods used in laminating spar flanges, reinforcing blocks, and other parts are, for the most part, conventional. In some operations special attention is given to arranging the laminations so as to reverse the direction of grain in adjacent pieces. In others, the position of the growth rings as received on the end section is reversed in adjacent laminations to effect a herringbone pattern.

The glue is commonly spread to both surfaces of the laminations by hand, using scrapers or small rollers to even it out. With some urea-formaldehyde glues, the catalyst or hardener is spread to one surface of the joint and the resin to the other.

Most laminating is done in screw presses or with hand clamps with cold-setting glues. Wood wedges are sometimes employed for the application of pressure. The amount of pressure applied is not definitely known, but, judging from the kind and spacing of the pressure members, it is believed that the pressures applied are in general lower than those used in the

United States and are seldom more than 100 pounds per square inch. In one plant, the pressure being applied in the laminating of spar flanges was given as 60 pounds per square inch. In others, it is believed that still lower pressures were being applied.

In a laminating operation that appeared to be quite efficient at the Stanley Smith plant, electrical resistance strip heating was being used in connection with a screw press of conventional design. Sheet metal on the faces of wood cauls were connected to an electrical transformer after the assembly was under pressure. With a temperature of 194° F. and a urea-formaldehyde glue, laminated members approximately 5/8 inch thick were removed from pressure in 20 minutes. Both flat and slightly curved members up to several feet long and 4 or 5 inches wide were being glued.

A pressure jig for the production of curved members from thin laminations was of interest at the Phillips & Powis plant. A form with outer cauls to match and clamps, similar to jigs used in the production of grand piano runs in the United States, were mounted on a revolving stand. The glue coated laminations were placed around the form and the sectional cauls were clamped in position one at a time, beginning at one end. A roller mounted on a lever arm brought the laminations into position as the form was progressively turned and each succeeding clamp was placed. The form was turned by means of a hand wheel connected by gears to a vertical center shaft, on which the form was placed. After the clamps were set, the form was removed and another put in place. Some 75 different forms were made to fit the stand. The pressing operation was completed by two men after the laminations were coated with glue.

A rather unique and apparently efficient method of producing laminated, circular, or other continuous members by the wrapping of the glue-coated veneers around a form has been demonstrated by the Forest Products Research Laboratory. A description of the method has been published and is reported to be in use.

Assembly Gluing

In the various assembly gluing operations, such as the production of ribs, box spars, air frames, fuselage frames, and the application of plywood skins, conventional methods are, for the most part, used. The gluing of the many individual wood and plywood pieces into the various parts, substructures, and assemblies is often accomplished by methods that have generally been supplanted in the United States.

In the application of pressure in assembly gluing the use of wedges, nails, and screws is more universal and has not been replaced by the use of clamps and hydraulic pressure to the same extent as in the United States. The use of rubber or other elastic cauls for the equalization of gluing pressure, and the use of heat to accelerate the setting of glues in assembly operations does not appear to be common.

Bag Molding

The production of aircraft parts or assemblies by bag molding methods is used only to a limited extent, two companies being reported in commercial production. One operation was observed in which aircraft parts were made by this process. Stanley Smith Ltd. is producing plywood skins for the Mosquito nose by bag molding.

Of special interest in the process is the use of flat 45° 3-ply plywood sections with scarfed edges, precut so as to form the desired surface. Otherwise, the method is similar to existing processes in the United States, employing plywood male forms, rubber bags, a pressure cylinder, and a steam and air mixture for required temperatures and pressure. A special urea-resin glue is used and the temperature and pressure were reported to be about 200° F. and 55 pounds, respectively. It is claimed that the bag is usable for about 140 cooks. The same operator is making bomb-bay doors for the Mosquito, using a urea-resin glue at a temperature of 212° F. with only approximate atmospheric pressure obtained by drawing a vacuum.

A somewhat unusual method of making compound-curvature plywood was observed at the Harris Lebus plant. Pieces of plywood were cut with V-shaped slots over the double curvature area with the point of the V at the apex of the double curvature. Two such pieces were then glued together with the V's staggered between rigid male and female heated forms. As the plywood layers were pressed into the forms, the V's closed, giving a fairly smooth, even surface.

VI. WOOD AND PAPER-BASE LAMINATES AND OTHER MATERIAL DEVELOPMENTS

Veneer-base Laminates

So far as could be determined no form of impreg (uncompressed resin-impregnated veneer or plywood) is in use for aircraft in England. Various forms of compressed veneer-resin materials are made, however, and are extensively used, particularly for propellers. Other direct aircraft uses of compreg include bearing plates of one sort or another and fan blades. Also, substantial quantities are used for jigs, dies, and forms.

Saro Laminated Wood Products, Ltd., is now making a semicompreg, partially impregnated with a water-soluble phenol-formaldehyde resin, of specific gravity 1.0 for use in the Mosquito for engine bearing blocks, bolt-bearing blocks, and as wedge blocks in the bend of the tail plane spar. The Ministry of Aircraft Production reports that 2.5 cubic feet of this material goes into each Mosquito. This "compregnated wood" is supplied under Specification D.T.D. 370.

Both Saro Laminated Wood Products, Ltd., and F. Hills and Sons, Ltd., are making bearing plates for spars for the Airspeed Oxford. The blanks are about 1 by 12 by 18 inches from which a wedge-shaped bearing plate is cut. The specific gravity is 1.0. Every fifth ply of the Hills' material is crossed to give greater splitting resistance. To avoid warping the taper is cut equally from each face, although this procedure involves a considerable waste of material.

Several flat plates of "compregnated wood" are used in the roots of the spars of the outer wing panel of the Albemarle. These are scarfed to natural spruce laminations and lie between the duralumin root fitting members. Bolts pass through the compreg and aluminum plates. At the plant of Harris Lebus, Ltd., where the Albemarle wing panel is made, strips of compreg were also in use as bearing tracks for the spar milling jigs. Compreg was used because woodworkers could shape it and because of its hardness and durability. It also causes less wear on the rollers on the milling cutter than do metal tracks.

Molded Components, Ltd., makes aluminum forming dies of "Jabroc," which consists of beech or birch veneers interleaved with film glue and compressed to high density. In a second form of Jabroc, the veneers are impregnated with phenolic resin. A third form is essentially a veneer-paper plastic composite.

Paper-base Plastics

Paper-base plastics are not much used in British aircraft at present. Aeroplastics, Ltd., is molding a pilot's seat using a Manila paper impregnated with phenol-formaldehyde resin. High pressure and steel dies are used and it is said that the product has an undesirable variation in resin content from point to point due to resin migration during pressing. A gunner's saddle and other minor parts are being molded at other firms.

A great deal of research on paper-base laminates has been carried on for the Ministry of Aircraft Production, however. The Chemical Research Laboratory has shown that while the tensile strength of such a laminate depends upon the nature of the fiber, the other mechanical properties seem not to depend on this factor. High laminar shear strength requires complete impregnation of the paper. Supercalendering of the paper after impregnation does not improve the strength of the plastic but does reduce the pressure necessary for full densification. Reduction in the volatile content before pressing improves the modulus of elasticity and water resistance of the plastic, particularly if a high resin content is used. Nearly all of the work at the Chemical Research Laboratory was done using water-soluble phenolic and cresylic resins. No impact tests have been made, but a mandrel bend test is used to measure toughness. It is agreed that a suitable laminate must give a value Et/2r of at least 50,000 where E is the modulus of elasticity in bending, t is the thickness of sample, and r is the minimum radius of bend.

Members of the Ministry of Aircraft Production are of the opinion that in the ordinary paper-base laminate one resin does two different jobs; it protects the filler against moisture and it acts as a bonding agent. Any single resin may be quite inefficient for one or the other purpose. Accordingly, a research contract has been let to Tootal Broadhurst Lee, Ltd., to study the first function of the resin. Data already obtained have shown that by the incorporation of about 1 to 3 percent of early condensed urea-formaldehyde or phenol-formaldehyde resin in the fiber, the wet bursting strength of the paper can be increased about eight-fold and the water imbibition and dimension movement can be reduced by nearly half. This was accompanied by a negligible loss in dry tearing strength, which is a measure of toughness. A suitable catalyst, $(NH_4)H_2PO_4$, was also found, and its optimum concentration (1 percent), and the proper curing conditions were determined. Paper made according to this process is now in production by R. & W. Watson, the resin solution being sprayed on a felt pressed into contact with the fiber mat after the second wet press. The impregnated paper then passes through a third wet press that removes a small excess of resin, and then passes to the driers. In a second operation the resin is polymerized for 1 minute at 160° C. in a hot air tunnel. An infrared curing chamber will be installed shortly.

Tootal Broadhurst Lee, Ltd., have also found that urea-formaldehyde stabilized paper can be mercerized like fabric and in the process acquires increased dry strength and absorbency.

Some very recent experiments with "Velan," a water repellent sold as "Zelan," have given the following remarkable results. A certain fabric has a water imbibition of 140 percent; when treated with 5 percent Velan, it also absorbs 140 percent; when stabilized with urea-formaldehyde resin, the absorption is 75 percent; but when treated with mixed Velan and urea-formaldehyde resin, the absorption is only 20 to 25 percent. It is hoped that similar results will be obtained with paper.

The implications of these findings are far reaching. If the stabilizing function of the resin can be performed by relatively minute quantities of resin in a pretreatment, the maker is then free to select the most suitable impregnating and bonding resin without regard to its ability to stabilize the fiber. This will probably be a resin with much greater ductility than phenolics have. The whole field of thermoplastic impregnants is thus thrown open, and even a material such as lignin may be capable of giving a highly desirable plastic without the inclusion of phenolic resin. A program is about to be begun at the Chemical Research Laboratory to investigate the use of a very wide variety of resins as massive impregnants for stabilized paper.

Since the return of the Mission, laminates have been prepared at the Forest Products Laboratory from base papers treated by the stabilization process described. The results indicate that the stabilization effected by very small quantities of resin is chiefly of an inter-fiber nature and hence may have less effect on the properties of the laminates than was anticipated. Another process has just been discovered at the Laboratory, however, which appears to give intra-fiber stability, that is, the actual hygroscopicity of the fibers is reduced. If these results can be confirmed, there is reason to believe that a wide range in resins may prove suitable as mass impregnants.

Three serious shortcomings of laminated plastics were pointed out by Ministry of Aircraft Production officials: low specific laminar shear strength, difficulties in fabricating any but simple shapes, and dimensional instability. The hope is expressed that the effect of low specific laminar shear strength may be minimized by the use of laminates as the skins of sandwich materials, that difficulties in fabricating may be solved in part by the use of contact-pressure resins as the massive impregnants, and that dimensional instability has been solved by the methods developed by Tootal Broadhurst Lee.

Veneer-paper Plastic Composites

"Zebwood" is a composite material consisting of veneers interleaved with phenolic-impregnated kraft paper and compressed at a relatively high pressure. It has a specific gravity of about 1.3 and is being considered for propellers. Its primary advantage is that it saves veneer. At present further development is delayed until root-pull tests upon it can be completed.

A similar material is one form of "Jabroc" produced by Molded Components, Ltd., and is used for dies for pressing aluminum sheet. It consists of veneers interleaved with a chipboard previously impregnated with phenolic resin, the whole assembly being consolidated with heat and pressure.

Upgraded Plywood

Upgraded plywood is the name given the product resulting from the laminating and cross banding of veneer and paper. It was developed as a direct substitute for birch plywood of aircraft grade. It was to meet the requirements of Specification 5V3 and it was to be capable of being prepared on plywood presses. The development work was carried by the Chemical Research Laboratory and the National Physical Laboratory and by British Resin Products, Ltd. The present material is of this type:

	Phenolic-	Impreg-	Phenolic-		Phenolic-	Impreg-	Phenolic-	
Veneer	resin	nated	resin	Veneer	resin	nated	resin	Veneer
	film glue	paper	film glue		film glue	paper	film glue	

The veneer used is one of the lower density, lower strength species less critical than birch, such as poplar, sweetgum, yellow-poplar, or gaboon. The paper is impregnated with 30 to 35 percent of a water-soluble phenolic or cresylic resin. Since it is desirable to obviate the necessity of using glue between the paper and the veneer, further experiments will be made in giving the paper a second coat of spirit-soluble resin to act as the adhesive. This may also improve the aging characteristics of the paper. A contract is about to be let for the production of a small quantity of upgraded plywood from yellow-poplar.

Since the technique of making upgraded plywood is now rather well developed, further work is to begin on other veneer-paper plastic composites especially designed to have certain properties suggested by aircraft engineers. These materials will vary in the geometry of the layers and in the relative proportions of veneer and plastic.

Filler Materials for Sandwich Construction

Great interest is shown in the possibilities of sandwich construction for aircraft. At present this type of construction is used in the fuselage of the DeHavilland Mosquito and, in a modified form, in the upper surface of its wing, for floors in the York, for landing-gear skirts on the Halifax, and for certain bomb-bay doors manufactured by Jicwood, Ltd. The principal core material so far has been balsa, but the limited supply of this wood has stimulated interest in possible substitutes. In addition to the search for other woods, considerable study has been given the development of various foams.

Low-density woods.--Balsa is used in the Mosquito fuselage and has proven satisfactory. The principal problems arise from limited available supplies and nonuniform density. Tests made on quipo at the Forest Products Laboratory (Madison) have shown it to be generally similar in mechanical properties to balsa, and it is a promising substitute. Some field work has already been done to locate supplies. It is reported to be alkaline in nature (pH about 10), however, which would probably necessitate the use of a glue other than urea-formaldehyde, which is acid-catalyzed.

Artificial foams.--Low density materials have been made in at least four ways:

(1) The felting of fibers.

(2) The "baking-powder method," which involves the incorporation of gas producing chemicals, such as zinc dust and hydrochloric acid in a synthetic resin.

(3) The "soda-pop method" of dissolving a gas in uncured rubber or synthetic resin under high pressure and then releasing the pressure.

(4) The "whipped-cream method" of whipping a synthetic resin into a froth and causing the froth to harden.

Rather little work has been done on felts because the British feel that felts are inherently of too high density to make efficient sandwich fillers. The baking-powder method is difficult to control. Discrete-bubble Formvar foam is made by swelling polyvinyl formal sheet in a suitable solvent and subjecting it to a pressure of about 3,000 pounds per square inch of nitrogen and then suddenly releasing the pressure. The dissolved gas reappears in the form of bubbles, which expand the sheet. Driving off the solvent, however, is a slow process because the bubbles do not intercommunicate. Even after a month's drying, enough residual solvent remains to give a softening point of about 90° C. The product has promising mechanical properties at a specific gravity of 0.1, and has good moisture resistance, but is expensive.

A method for producing Formvar foam with a continuous porous structure has been developed recently by Albright and Wilson, Ltd. A partially hydrolyzed polyvinyl acetate is homogenized with a calculated amount of paraformaldehyde, whipped to a foam, then set by the addition of a quantity of strong acid. This causes formalization to take place and a foamed material results in which perhaps 90 percent of the voids communicate with each other. This permits rapid washing and drying of the foam, but gives much lower mechanical properties and water resistance.

Calcium alginate foam is also produced by the "whipped-cream method." Here the setting reaction is brought about by the introduction of a calcium salt to a foamed solution of ammonium alginate. The gelled alginate is soaked several days in calcium formate and then in water. Drying is very slow and results in warping and considerable degrade. The warping is corrected by soaking in water and redrying under light pressure. A plant is being set up at Albright and Wilson's which can produce a maximum of 1 ton of alginate foam a week. The foam will be used in landing-gear skirts and for experimental work. Though having promising mechanical properties and resistance to heat, alginate becomes quite soft when moist.

Attempts have been made to incorporate cellulose fibers in alginate foams. With kraft fibers the mechanical properties appear to fall off in proportion to the amount of fiber added, but a foam containing 15 percent of a highly beaten straw fiber gave properties equal to those of the pure alginate. Further experiments now under way will determine the limits to which such fiber can be added without loss in strength and it is hoped that the figure may reach 75 percent. If so, it may be possible to develop a foam in which the strength is due to the fiber, and the bubbles are just intercommunicating. In other words, the calcium alginate would merely act as a convenient setting agent for the production of a very low density, easily dried felt. Such a felt could then be lightly impregnated with a urea-formaldehyde or phenol-formaldehyde resin to increase the stiffness and water resistance.

Expanded rubber, "Onazote," which is used in bomb-bay doors, is produced by the Expanded Rubber Company, Ltd., by a modified "soda-pop" technique. The setting reaction is the vulcanization of the rubber at high temperature. Since this is a dry process, the difficulties in washing and drying a discrete bubble foam are obviated.

"Onazote" is characterized by low strength and low softening point. An improved material, "Onazote GRS," has been developed with much better properties. It is made from 25 percent Buna S, 25 percent reclaimed rubber, and 50 percent mineral loading, the latter being chiefly carbon. Involved in its production is the question of availability of synthetic and reclaimed rubber.

Mechanical equivalents of foams.--The upper surface of the Mosquito wing is made of two skins of birch plywood separated by spanwise Douglas-fir stringers of about 1-1/4 inches square cross section. These stringers thus constitute the equivalent of a foam in sandwich construction.

"Celluboard," an ingenious core material, has been developed by Wood Development, Ltd. Plywood panels about 1/16 inch thick are glued in alternate layers to strips of spruce, balsa, or other light material to make up a strip-panel assembly. When pieces are sawed from an edge of this assembly at right angles to the strips, a grid is obtained which may be used as the core in sandwich construction. This grid core material may then be glued between plywood skins, each piece of plywood in the core and each short length of strip being normal to the skins. When the strips are staggered in alternate layers, the core material may be bent to a single curvature. By properly sawing the strip-panel assembly, it is possible to form Celluboard to moderate compound curvatures.

"Exton board" is made of plywood skins glued to a cellular core made of corrugated paper, the axes of the cells being normal to the skins. Because the cellular filler cannot be bent to any extent, it is not well suited to general construction, but it is used for doors and table tops.

A somewhat similar filler material, "Balsolite," was developed by Plasticrete Products, Ltd. Thin-walled tubes of paper are made with a casein adhesive, coated with a vinyl resin, assembled, and cut transversely to give a cellular material of tubes with their axes normal to the faces. This structure permits the material to be given a marked double curvature. The properties of Balsolite can be controlled by varying the wall thickness, tube diameter and arrangement of the tubes.

"Holoplast" is another development that is not a filler but an entire sandwich of paper-base phenolic plastics. It consists of two faces separated by parallel stringers molded integrally around slightly tapered rectangular steel-bar cores. The mechanical and physical properties are reported to be high, but it contains a large percentage of critical phenolic resin. It has been suggested that this might be a possible application for lignin laminates.

General

In the opinion of the De Havilland Airplane Co., Ltd. balsa of low density is the most satisfactory filler now available for use in sandwich construction. It is nonuniform, however; large quantities are not available, and it is not moisture resistant. The artificial foams and mechanical equivalents have been developed chiefly as substitutes for balsa but, except for Celluboard and Balsolite, they appear to be somewhat inferior in strength when substituted directly for balsa. Since it is possible to make the artificial materials of varying density and in some cases to control the relation of properties, they may, however, find some satisfactory applications.

Some of the artificial foams are expensive largely because of the difficulty of washing and drying them. For example, it is said that the cost of alginate foam is about $2.00 per pound and that the raw materials cost only 40 cents. Calcium alginate itself is not a particularly desirable structural material but is used because the formation of insoluble alginates is one of the few suitable setting reactions known. The hope is that the alginate can be used merely as a convenient setting agent for the production of a foam whose strength lies in another component, such as cellulose fibers. The alginate plant at Albright and Wilson's is being set up for the double purpose of providing a supply of uniform sandwich filler material for experimental work and to encourage the latent interest in sandwich construction.

VII. WOOD PROPELLERS

Three types of propellers made from compressed wood are now in production in the United Kingdom and several other types are in various stages of development. Fixed-pitch wood propellers of conventional type are in extensive use on various training airplanes.

Weybridge Blade

This blade, which is made by the Airscrew Company, Ltd., is carved from a blank glued from boards of Douglas-fir scarf joined, at the root end, to "Jicwood" or to similar "compreg" supplied by firms in the United States. Jicwood, supplied by the firm, Jicwood, Ltd., associated with the Airscrew Company is prepared by coating Canadian birch veneers with about 4 percent by weight of a spirit-soluble phenolic resin, drying, and then consolidating the pack under heat and pressure. The resin content and the conditions of pressing are such that Jicwood is not stabilized appreciably either by the resin or by the action of heat and moisture. The blank is rough-carved by machine and then finish-carved and balanced by hand. Due principally to the time required for conditioning at various stages of manufacture, the elapsed time for a blade in production is from 7 to 12 weeks.

In one type of finishing, the blade is covered with hessian cloth cemented in place. A brass leading-edge strip is sweated to brass gauze and hammered, screwed, and riveted in place. A thick sheet of either cellulose nitrate or cellulose acetate is cemented on and the whole blade is placed in a rubber bag and put in an autoclave. In the autoclave treatment the coating is said to penetrate the Douglas-fir blade to a depth of about 1/8 inch. In the second type of finishing the blade is liberally spread with a thick lacquer and a sheet of cellulose ester is rolled into place on each face, forming laps at the leading and trailing edges. After the coating has shrunk, the laps are carefully sanded. Final balancing is done by local scraping, and, if necessary, balancing paint is used locally.

These blades are repaired by splicing a new piece to the undamaged portion. Although repair of a damaged root is never attempted, the entire Douglas-fir portion of the blade may be replaced, the new scarfs nearly coinciding with the old. If the coating is not too badly injured, it is repaired locally.

Hydulignum Blade

The Hydulignum blade is manufactured by Hordern Richmond Aircraft, Ltd. One thirty-sixth-inch birch veneer is coated with approximately 20 percent of Formvar (polyvinyl formal) by weight. After the solvent (trichlorethylene and alcohol) has been driven off, the veneer is pressed into panels of specific gravity 0.95 at an elevated temperature and then cooled in the press. Two corners of the board are trimmed off and that end is then further compressed sidewise to a specific gravity of 1.3. The final board thus has a high-density double-compressed root, a transition zone, and a medium-density blade and tip. After rough patterning, several boards are assembled into a blank with a cold-setting urea-formaldehyde glue and the blank is carved in the same way as the Weybridge blade.

After several coats of primer containing chlorinated rubber, and of Formvar varnish have been applied, a brass leading-edge strip is riveted and screwed in place. About 14 additional coats of Formvar complete the blade.

A particular advantage claimed for the Hydulignum propeller is that the equalized shear strength in the root, in the two planes parallel and perpendicular to the glue surfaces, permits the use of smaller diameter hub fittings. Practical considerations requiring the use of a standard hub for all-wood blades, however, has precluded the use of a smaller hub for the Hydulignum blade.

Jablo Blade

This type of blade is manufactured by F. Hills and Sons, Ltd., and Jablo Propellers, Ltd. Veneers 0.6 mm. (1/42 inch) thick and of varying length are interleaved with phenolic-resin film glue and assembled in such a way as to give boards of 69 plies at the root and 48 at the tip. The assembly is pressed to a uniform thickness at a gradually increasing temperature reaching a maximum of about 280° F. The boards are roughly profiled, then assembled with casein glue. Carving is done by machine, followed by manual final carving.

A stocking of phosphor-bronze gauze is stretched over the blade and soldered along the trailing edge. After application of a brass or steel leading-edge strip, many coats of phenol-formaldehyde enamel are brushed on and baked so as to build up the surface flush with the metallic sheathing. After a final balancing, the blade is given a coat of grey primer and one of cellulose-acetate lacquer.

(Since the return of the Mission, it has been learned that the type of finish described for the Jablo blade is no longer employed and has been replaced by a finish similar to that of the Hydulignum blade. This leaves two types of propeller finishes in use; namely, (1) cellulose acetate or cellulose nitrate (cellulose esters), and (2) "Cristofin," as developed by Hydulignum.)

Experimental Blades

F. Hills and Sons, Ltd., have three new types of propeller blades in development: the Norton, the Trafford, and the King. The Norton blade is made from boards each of which has approximately the same density throughout its length. The blank is glued up with four outer boards of specific gravity 1.3, and three inner boards of specific gravity 1.1.

The Trafford blade has a root consisting of alternate boards of specific gravity 1.3 and 0.9 scarfed to a blade of natural spruce to which are also glued densified birch leading and trailing edges of specific gravity 0.9. Both these types were designed to minimize the strain on the press caused by eccentric loading. In addition, the Trafford is expected to be lighter and stiffer than the Jablo.

The King blade is a molded, uniform-density, hollow blade. Birch veneers 0.3 mm. (1/85 inch) are tailored to a calculated shape, rolled into long tubes, impregnated with a phenol-formaldehyde resin, and dried. A large number of these tubes are loaded side by side into a steel die having a solid steel core. Heat and pressure flatten the tubes and consolidate them into a blade of specific gravity 1.3 with a maximum wall thickness of about 3/4 to 1 inch. The core is removed after the pressing. If successful, this type of blade will have equal shear strengths in two directions, will save veneer and resin, and will be adaptable to the Hamilton standard hub.

F. Hills and Sons, Ltd., is also considering the use of Zebwood, a veneer-plastic composite for propellers.

Molded Components, Ltd., have molded experimental blades of impregnated veneers pretailored to shape. Each of the two faces of the blade consists of nine continuous plies, a feature that avoids excessive exposure of end grain and glue lines and provides a skin running the full length of the blade.

None of the wood blades now in production can be fitted satisfactorily to the Hamilton Standard hub, which requires a hollow root. They are all used with the Rotol hub of British manufacture. A threaded conical ferrule is used on all wood blades and is cemented in place with "Semtex," a mixture of Portland cement and rubber latex. Considerable interest has been shown in the new lag-screw retention developed at Wright Field.

Although Jablo and Weybridge blades are balanced against masters, Hydulignum blades are still furnished only in matched sets and are not interchangeable.

VIII. SERVICEABILITY IN RELATION TO MOISTURE,

DRAINAGE AND FINISH

Moisture Content

Moisture, through its various effects, is recognized as one of the most important factors in the satisfactory use of wood and in its serviceability for aircraft. Best results are obtained when the moisture condition of the wood at time of manufacture approximates that of service conditions. While this is seldom fully achieved, its attainment usually suggests the use of factory control of temperature and humidity.

In England, control of temperature and humidity in wood-airplane-manufacturing plants is seldom used, nor, with exceptions, is it considered necessary because of the moderate range of natural conditions encountered. Factors influencing the current practice are the moderate temperature extremes prevailing in England as compared to those in the United States; and the avoidance of overheating in the winter season.

Wood aircraft used in England do not, as a whole, appear to give much trouble from shrinkage, according to officials of the Ministry of Aircraft Production, although when sent overseas to some theaters of operation the tightening of bolts has been necessary. Likewise in propellers, the change in moisture content when used in very dry climates becomes important.

The Royal Aircraft Establishment reports that dampness in itself does not weaken structural elements of wood aircraft as much as was anticipated before the war. In tests under way at Royal Aircraft Establishment on Master tail planes, all the wet assemblies are reported to have failed in the compression flange of the spar rather than at the joints. Also the full tail planes did not give as large reductions in strength when wet as do lap joint specimens commonly used in glue-shear tests.

In the operation of the Flying Training Command, adequate hangar capacity is not available to house all airplanes in service. A substantial proportion (probably half) are not well protected, making it difficult to get aircraft properly dried out. Under these conditions, it is remarkable the way wood aircraft have stood up. Continued weathering has a deleterious effect on wood airplanes, but if slowly dried out they return to normal quickly, report officials of the Flying Training Command. From the standpoint of practical operations it is regarded as cheaper to anchor airplanes out, with some small breakage and loss in strong winds, than to provide expensive hangars.

Of the several airplanes used, the Anson (metal fuselage, wood wings) is reported to have stood the weather best. Some Ansons have been in service 7 years. The Horsa glider also was an agreeable surprise in its serviceability.

In the center section of the Oxford, some warping of the nose ply has been observed, and a distinct wrinkling of the skin may be apparent after absorbing moisture at night. The surfaces again straighten when exposed to the sun or are otherwise dried out.

Essential requirements with respect to improved serviceability include:

(1) Use of water-resistant glues that are also mold resistant.

(2) Adequate provision for drainage, with daily inspection of drain holes.

(3) Use of fabric (madapollam) covering over wood and plywood surfaces.

(4) Proper exterior finishing (interior finishing thought by some as desirable, but is not officially required).

Experience has shown the importance of providing drain holes to permit the egress of water, since water and water vapor cannot be excluded entirely under service and operating conditions. Where adequate drain holes were not provided in original plans for a particular airplane it has been necessary to have them added by the repair and maintenance units. Special drills have been designed for this work. Thus in the Horsa glider 1186 drain holes were cut in each of the airplanes in service, while in the meantime provision was made for taking care of this detail in the new airplanes coming from the production line.

Because of the importance of drainage, special attention is given to the installation of drainage holes in new designs, as well as the inclusion of suitable inspection holes. In the location of drain holes, a special mock-up model is used, and the particular unit is filled with water. Sufficient drain holes must be provided and their location must be such to permit all water to run off freely.

Finish for Exterior Surfaces

The finishing of all exterior surfaces of plywood on aircraft was modified in 1942 to require the use of a light-weight fabric as a part of the protective covering. Previously the use of the fabric had been optional and was used only on a part of the aircraft built. The universal use of the fabric is reported to have been put into effect because of (1) better life of the protective covering and the attendant better service of the airplane with less maintenance and (2) the supply situation with respect to nitro-cellulose and its butyl solvents.

The process now required for all exterior wood surfaces on aircraft is covered by Specification D.T.D. 912A and involves:

1. Two coats of aeroplane dope (Specification D.T.D. 83A);

2. Layer of light cotton fabric (Specification D.T.D. 343);

3. A third coat of aeroplane dope (Specification D.T.D. 83A), rubbed into fabric;

4. Two coats of aluminum pigmented cellulose enamel (D.T.D. 63A); and

5. One or more coats of camouflage colors (D.T.D. 83A).

An alternate method of Specification D.T.D. 912A provides for the use of precoated fabric (D.T.D. 482), applied over two undercoats of airplane dope, after which two coats of aluminum pigmented cellulose and one or more coats of camouflage colors are added.

The Ministry of Aircraft Production reports that the fabric finish as now required has given superior performance to the pigmented and clear finishes both in laboratory tests and in service. It is admitted that the fabric finish adds some additional weight over the formerly used pigmented and clear finishes but that the use of a light-weight fabric reduces this disadvantage. The Flying Training Command also stated that airplanes with the fabric finish give better service than the same airplanes without the fabric. The advantages given for the fabric finish were: less tendency for the finish to check, especially at joints between the tape and finish and along leading edges; smoother surfaces; added strength; and less maintenance and repair.

At the Royal Aircraft Establishment tests have indicated that the differences in the smoothness of fabric-covered and pigmented or natural finishes is not important and that it is not difficult to attain a satisfactory smoothness with either. It was further stated that a satisfactory wave-free surface is, however, difficult to obtain with plywood skins with either type of finish and that waves affect performance more than roughness of surface. Hence, any influence of a coating to reduce waviness in plywood surfaces is regarded as significant and is most important in types of airplanes, such as the Mosquito, where high speeds are essential.

Finish of Interior Surfaces

Applying a protective coating to all interior surfaces of wing and tail parts is not required and the trend at the present time is not to use such coatings in English-built, wood aircraft. The position taken by officials of the Royal Aircraft Establishment and the Ministry of Aircraft Production is that the coatings, as applied in the past, have left a part of the glue lines and wood immediately adjacent to them unprotected, which has largely defeated the purpose of the coatings. On the other hand, some opinion exists among airplane manufacturers and maintenance and repair men that interior coatings, even as they have been applied, are of some value.

The Ministry of Aircraft Production has a service test in progress on planes, in which the interior and the wings of half the airplanes were given a protective coating and the other half were left unprotected. After 7 to 8 months service the maintenance and repair organization is reported to have found no significant difference in performance. The Ministry of Aircraft Production no longer requires the finishing of interior surfaces in wing and control parts.

The Flying Training Command reports that plywood-covered wings on trainers that are exposed during the night to fog and mist show waves and tin canning, which largely disappear after a few hours of sunshine. Observations on a few trainers at one of the training bases indicated such irregularities in varying amounts on misty, damp mornings. Officials of the Flying Training Command expressed the belief that interior protective coatings are of some value in reducing surface irregularities and in reducing deterioration of wing and control parts. More emphasis is placed, however, on having adequate and properly-placed drain holes and in keeping the drain holes open.

While most wood airplanes are constructed and put in service without any interior protective coating, the Harris Lebus Ltd. plant was applying finish to approximately the lower half of the wing assembly of the Albemarle, after the bottom skin was glued in place.

At a flying-field repair station, it was pointed out that interior protective coatings are sometimes difficult to remove in preparing wood surfaces for gluing.

General Inspection Procedure

In United States practice, the quality of wood to be used in various structural parts of the airplane is fully covered in ANC-19, "Wood Aircraft Inspection and Fabrication," so that the same requirements are applicable to all airplanes and all designs. In British practice, there are no general specifications, similar to the fabrication manual, for aircraft manufacturers. Broadly, requirements regarding species and quality of wood are established by the individual manufacturer in the design of the airplane on approval by the Ministry of Aircraft Production, and these details are incorporated in the drawings. The choice as to quality of wood is limited to the grades defined in Specification D.T.D. 36B, however, and designated A, B, and C, and further, some overriding memoranda have been prepared that establish certain procedures. The inspectors then follow the manufacturers' drawings for conformity to requirements, such as grade, slope of grain, slope of scarf, number and size of laminations, and direction of laminations. Under this procedure the designer is given considerable latitude but the drawings are checked and approved by the Ministry of Aircraft Production.

For inspection purposes, the country is divided into 10 areas, with headquarters in each area. The inspectors are guided by a book of instructions.

The manufacturer has inspectors on the company payroll, selected with Aircraft Inspection Department approval. Over these company inspectors, the inspectors of the Aircraft Inspection Department have final authority. Checks are made on the company inspectors to see that they are doing a good job, and to maintain the standard of construction. Covering all phases of inspection (power plant, structure, and instruments) there may be as many as 50 Aircraft Inspection Department inspectors at one plant who are responsible for the complete aircraft inspection and assembly.

For wood, dependence is placed largely on visual inspection and density. Mechanical tests are not used much in inspection, and are used mainly in case of dispute. With present inspection methods, very few, if any failures are attributable to the wood itself.

Kiln Drying

In general, with the moisture content values prevailing, kilns are regarded somewhat as conditioning chambers. No complete kiln schedules are issued for different species as in the United States, but instructions are issued to cover the general principles of drying. Each kiln-drying plant is considered on its merits. Inspection is made of methods used, including the temperature, humidity, and rate of drying. Tests may also be made for brittleness.

At Airscrew, Ltd. Douglas-fir is used in the Weybridge (Schwartz) propeller. The material is received in cants 6 inches in thickness and is resawn elsewhere into 5/8-inch boards. These boards are dried from about 24 percent moisture content to a 12 to 14 percent condition in about 8 days. The highest temperature used in this drying is 96° F. dry bulb and 88° F. wet bulb; conditions are changed to drop the moisture content in stages of 2 percent.

Current practice for the kiln-drying of aircraft wood (Circular Letter No. C.I.S./1/36) recommends that the timber be reduced approximately to its ultimate dimensions, and that the drying of various cross sections at one time be discouraged.

Table 2 is the schedule established for 2-inch spruce, which can be reduced from 25 to 15 percent moisture content in about 10 days in an efficient forced-draft kiln.

A slightly modified schedule is provided for kilns that can attain only a temperature of 110° F.

Table 2.--Schedule for kiln drying 2-inch spruce

Moisture content of timber	Dry bulb temperature	Wet bulb temperature	Humidity
Percent	° F.	° F.	Percent
Over 30	110	104	80
30	115	107	75
25	120	111	75
20	125	114	70
17 to final	130	116	65

Suitable instruments must be provided in the kiln so that any variations in temperature may be detected. The instructions further require that an adequate number of moisture and impact tests be taken after the conditioning process has been completed, and that the test pieces be selected from various positions in the kiln in order that variations in the conditioning may be determined.

X. MAINTENANCE AND REPAIR OF WOOD AIRCRAFT IN SERVICE

General

Maintenance and repair of aircraft in service has become a major activity of the British Air Forces under the Directorates of Service and Maintenance and of Repair and Maintenance of the Ministry of Aircraft Production. In addition to inspection of airplanes after regular periods of service and the making of minor repairs by the service crews and repairmen located at the air bases, the British system involves many civilian repair units in which damaged airplanes are repaired and rebuilt. The civilian repair units are interspersed among the flying fields. A few aircraft manufacturing plants maintain repair departments, but many garages, small woodworking and other manufacturing plants have been converted into repair depots or units.

No hard and fast rule exists as to when a damaged airplane is repaired at the air bases and when it is turned over to the civilian repair units. However, repair jobs that involve more than 400 man hours are usually done at civilian repair stations, but this depends upon the amount of work on hand and the available repairmen at the air bases. The Flying Training Command aims to get the aircraft repaired within 48 hours. Decisions on where the airplanes are repaired is determined partly by this objective.

Separate maintenance and repair manuals have been issued for each type of aircraft in service. The manual describes and illustrates methods of repair of different parts of the airplane.

The great bulk of wood aircraft is used in the training of personnel, but with the development of the Mosquito as a fighter, bomber, and observation airplane, more wood craft are progressively being used in combat and must be maintained and repaired. The accumulated experience and records of repair relate in large part, however, to trainer airplanes of conventional types of construction. For propellers, however, large numbers of wood and modified wood blades have been used on both trainers and combat airplanes.

The Flying Training Command, which has the responsibility for maintenance and repair of training airplanes in the United Kingdom, and an air base repair station, supplied the following information:

(1) Of more than 6,000 trainers of several types and makes in use, about 3/4 are made of wood.

(2) For the past 2 years a system of dispersal of airplanes has been practiced, which has resulted in much of the craft being exposed outside with little or no hangar protection.

(3) Wood airplanes require more maintenance than do metal airplanes but are more easily repaired after crashes.

(4) Airplanes damaged up to approximately 80 percent of their value are repaired.

(5) The man-hours expended in the repair of airplanes that are damaged by accident far exceed the man-hours expended in the repair of airplanes from normal deterioration.

(6) The bulk of the training under the Flying Training Command is of an advanced type in which less accidental damage is done to airplanes than in intermediate training.

(7) Proper drainage of wing and control surfaces is extremely important, since much of the normal deterioration of wood airplanes is due to moisture accumulation. More drainage holes than have been used in the past and a warning conspicuously printed on the airplane surfaces to "clean drain holes daily" are favored.

(8) Differences of viewpoint were expressed as to the value of interior protective coatings from a service viewpoint, but it was agreed that unless the coating was applied over all surfaces and glue joints its value was questionable.

(9) Cloth (madapollam) covered plywood skins are considered distinctly superior to varnish or other similar finishes from a maintenance standpoint.

(10) Airplanes left out overnight under moist conditions show irregularities in the outer plywood surfaces, which largely disappear after a few hours of sunshine.

(11) Because of the character of service, fighters and trainers require frequent repairs, whereas transports, less subject to damage either from accidents or lack of proper care and maintenance, require less repair.

(12) Damage and deterioration in wood airplanes are more easily detected than in metal planes.

(13) Skilled woodworkers are more readily available than skilled metal workers for repair.

(14) Oxfords, stored outside without protection, have usually given 1,000 hours flying service, equivalent to about a 2 years' service period, without major repair. Thereafter the wood and glue joints usually need considerable repair. Ansons built in 1937 and 1938 have only recently been withdrawn from service; Tiger Moths have given good service for more than 2,000 hours of flying time; and the performance of early-built Mosquitos was considered satisfactory in the African desert.

(15) Most trainers have fixed-pitch, normal wood propellers--100 percent of the propellers on the Tiger Moth and Master and 80 to 90 percent of those on the Oxford are of this type.

(16) In a crash, the bending of the blades of a metal propeller frequently acts as a skid and may prevent serious accident to the occupants but may damage the engine more than does a wood propeller.

(17) A repaired wood propeller seldom fails at the point of repair.

(18) The difference in fire hazard between wood and metal airplanes is not considered significant.

Repair at Civilian Repair Units

Repairs at a civilian repair station are usually made on only one type of airplane in accordance with the repair manual for that particular aircraft. The larger repair stations may, however, repair several types. The airplanes are brought to the repair station on lorries or trucks in a partly dissembled condition. A thorough examination and assessment of damage is first made, after which the airplane is scheduled for repair in case the damage does not exceed about 80 percent.

A point of difference between wood and metal airplanes, made by Phillips and Powis, Ltd., who repair Spitfires and three types of wood trainers, was that damaged wood parts are more easily assembled into jigs than are metal parts. The wood members fail more locally, whereas metal members usually bend and distort. Phillips and Powis estimated that more than half (perhaps 70 percent) of the damage they repair is due to accidents. On the other hand, J. W. Walker and Sons, Ltd., who repair Oxford trainers exclusively, estimated that at the present time about 70 percent of their repair was due to the effects of moisture, particularly on the casein glue joints. The Oxford is used in advanced training where accidents are less frequent.

Assemblies that are severely damaged are replaced with new assemblies requisitioned from central supply depots. Broken ribs, stringers, and other parts are, however, replaced without removing the entire assembly. They are either scarfed in or extra pieces are glued to the sides of the member. Plywood parts and skins are scarfed and glued in place. The damaged plywood is usually cut out to the adjacent supports and a new piece inserted.

Repair of the Mosquito.--Because of the special construction used in the Mosquito, its repair has involved the development of special procedures and techniques.

The De Havilland Company maintains a repair department in which varied types of repair of the Mosquito are made. The following points are of interest:

(1) In repairing the shell of the fuselage, the inner plywood skin is left in place, if possible, and the rings inserted and aligned to the proper cross section. Longitudinal and vertical stringers are then scarfed in place, the surfaces being prepared with a chisel, bullnose planer, or a scraper, to a slope of 1 in 10. The balsa is then glued in place by nailing through strips to the framing members. The stringer and balsa are then surfaced by hand to the proper contour and the outer skin applied by nail gluing.

(2) To repair the upper wing covering of the center section, damaged by a bullet passing approximately parallel with the wing covering, the inner or under skin is first scarfed in place and glued to the wing-framing members. The Douglas-fir stringers are then scarfed into position, contoured and the outer skin glued in place using screws for pressure.

(3) Where the outer wing section is severely damaged an entirely new outboard wing assembly is supplied. The wing tip and accessory parts are all supplied in kit form, ready for assembly. A section of the upper plywood covering is removed and the under layers are cut off square at different cross sections but at definite and fixed positions that match similarly staggered cross cuts in the various layers of the new wing-tip section. Reinforcing members with tapered ends are then glued across the butt joints of the adjoining pieces. Strips of plywood, approximately 6 inches wide, are glued over the butt joints in the outer plywood skins and their edges beveled, forming, in effect, two bands over and one under the wing surface.

(4) Bullet holes directly through the skin are repaired by scarfing in small plywood patches.

(5) In repairing the double curvature parts of the nose section, plywood is scarfed and inserted in widths of about 6 inches that readily conform to the required shape.

In general, all repair is done with hand tools. The cutting away and surfacing is done with saws, chisels, hand planes, scrapers, and sandpaper. Pressure is usually applied to the joints with small hand clamps. Nails and screws are largely used in applying pressure to scarfed joints between two pieces of plywood and between plywood and framing members. Casein glues are used almost entirely in repair work, although some repair stations expect to use cold-setting urea-formaldehyde glues before long.

Repair at Air Bases

One principal air base repair station was visited. The tools and methods used in the repair of wood aircraft were similar, in general, to those employed in the civilian repair units. The repair was being done in open, unheated hangars, largely by civilian employees.

An Oxford, after 2-1/2 years and 1,600 hours of flying service, was undergoing major repair. Mold growth was observed at the base of the spar of the outer wing section, the trailing edge of the center wing section, and in the floor of the rear fuselage. The outer wing sections were to be replaced with new sections and the deteriorated parts of the other structures were to be replaced.

A Horsa glider, damaged in landing after 100 hours flying service, was being repaired. Previous repair had been made on the glue joint between the skin and main bulkhead rings of the fuselage by gluing reinforcing blocks or fillets to both skin and rings. Damaged parts of the nose and leading edge of the center wing section showed separation of the plywood from the framing members at which points the glue lines were thick and showed partial or poor contact over a considerable part of the joint area. At other points failure was completely in the wood.

Several Hotspur gliders were being remodeled after some 100 to 160 hours' flying time and 13 months' service, including one winter. They were reported to need very little repair. The wings, which had been finished without fabric covering, showed some cracking in the finish.

Repair of Propellers

Damaged propeller blades are repaired in large numbers by scarfing on a piece of the proper size and refinishing. Repaired blades are claimed to give the same service as a new blade, and it is further claimed that a repaired blade seldom fails at the scarf when damaged a second time. Weybridge blades have been reported repaired in as many as four different places. Repairs vary from small inserts to a replacement to half the radius, as in the Jablo, and to a replacement of as much as three-fourths of the blade, as in the Weybridge propeller.

In the repair of the Weybridge blades a block is first glued to the back face of the blade. This is used to hold the blade firm in cutting the scarf. The minimum slope of scarf used is 1 in 9 (in the Douglas-fir part of the blade). The plain scarfed surface is prepared for gluing on a large cutter head. Casein glue is used in making the joint. The finger type scarf for repairing blades near the hub section was being investigated and is regarded favorably. It is cut on a saw and is reported to have been used at some field repair stations.

Hills and Sons Ltd. also repair Jablo blades by scarfing, and gluing with casein glue.

XI. RECOMMENDED RESEARCH

War Research at the U. S. Forest Products Laboratory

The Forest Products Laboratory has been conducting an extensive research program relating to problems on the use of wood and wood-base laminates for airplane and glider construction and for other war uses. Allied with this program has been the preparation of the "Wood Aircraft Fabrication Manual" and the "ANC Handbook on the Design of Wood Aircraft Structures," issued by the Aeronautical Board. Supplements to these manuals have been issued from time to time, as material for revision became available. Under way at the present time is a complete revision of these two publications, incorporating the latest available data in the respective fields. These will appear under the following titles as unrestricted publications:

ANC-18 Design of Wood Aircraft Structures
ANC-19 Wood Aircraft Inspection and Fabrication

In preparation also is a "General Manual for Structural Repair," in which the section "Repairing Wood and Plastic Impregnated Plywood" is now being completed.

Included in the broad studies are investigations of the fundamental mathematics of plywood as a material, covering its basic properties, buckling formulas, and its use in sandwich constructions; studies of the design of box beams, including design stresses; investigations on the effect of rate of loading on properties in relation to design; bolt-bearing design criteria for plywood and impreg; influence of moisture on the properties of plywood; evaluation of properties of species; studies of glues, gluing methods, and gluing techniques; improvements in glues and finishes; seasoning studies and controls; developments and improvements in compreg, impreg, and paper-base laminates; and the use of lignin as a plastic material.

Many of the studies now concerned mainly with aircraft are of far broader basic value, and will have extensive and continuous post-war applications in the use of wood and wood-base products.

Further Urgent Research Needs

Considering the extended studies still necessary to fill in gaps of urgently needed data, in the light of the research under way in the United Kingdom in these fields and from the background of observed uses there, it is believed that special consideration should be given to the following:

Basic plywood research.--Continuation of the basic research on the mechanics of plywood, leading to the development of formulas covering its behavior as an orthotropic material and to the establishment of design values. Because of the start already made on this problem with the cooperation of the Army and Navy, substantial progress has already been obtained. The development of plywood design criteria is further advanced here than in the United Kingdom, and the available data have been in eager demand. It is especially important that the techniques and studies should be continued to a logical conclusion as the data are basic to the post-war use of plywood as an engineering material.

Mechanics of sandwich construction.--The effective use of plywood or other sheet materials as sandwich covering on a low density core provides one of the most effective structural elements from the standpoint of strength-weight relationship. Studies should be continued to establish the fundamental mathematical formulas necessary to predict the behavior of such structures and structural elements, as well as to effect comparisons of the over-all efficiency compared with possible alternate constructions with other materials.

Rate of loading and duration of stress.--Studies are under way to obtain data on the effect of rate of loading and duration of stress on several of the mechanical properties of wood with particular reference to aircraft design stresses. Suggestions for methods of interpretation were gained from the Royal Aircraft Establishment and Forest Products Research Laboratory, also directly interested in these problems. This work has a direct bearing on all timber design and construction, and underlies the whole program to increase stresses for wood. It should be pushed to conclusion.

Moisture-strength relations for glued structures.--Studies at the Royal Aircraft Establishment show that for elements consisting of plywood glued to stringers, the direct tensile strength of the joint is not appreciably affected by substantial increases in moisture content. These results are at variance with the usual results of glued test specimens in shear, which show marked increase in strength with decrease in moisture content. The tests on Master tail planes at the Royal Aircraft Establishment at different moisture contents also indicate less effect of moisture change than is usually associated with joints in glue shear. The implications are that in glued structures and structural elements the effect of increased moisture may be to relieve stress concentrations that have a deleterious effect on strength and that the usual moisture-strength relations established for wood itself may not be applicable to glued structures and structural elements. Because of the prevalence of static tests of glued structures at relatively low moisture content, as compared to the moisture content of design, and because of the developing structural uses of glued construction, a comprehensive investigation of the influence of moisture on glued structural elements should be undertaken at the earliest opportunity.

Evaluation of glues for aircraft use.--While there is general recognition of the importance of glues in aircraft construction and considerable research is in progress in both countries on glue properties and characteristics, there is, as yet, a lack of agreement on the necessary test methods and specification requirements for synthetic resin glues and there is inadequate data on the relation between specification requirements and durability and serviceability in aircraft. It is especially desirable to establish the relation of pH, filler kind and amount, "compensators," and other factors of resin glues to their strength in joints and their permanence or durability under the moisture and temperature conditions to which aircraft are subjected in use.

Limitations and control in gluing.--The nature and extent of control of gluing details required to make good glue joints is fundamental with all glues. Problems, such as the need for gap-filling adhesives, the properties of thick and thin glue lines, character and quality of joint surfaces, adhesion of glue to wood and the factors that influence it, the tendency of glue to craze, temperature and time required for setting and curing glues, and pressure requirements should all be more thoroughly investigated in the light of the experiences and practices of the two countries.

Special gluing problems.--The introduction and application of new materials in aircraft construction, such as modified and improved wood (resin impregnated and compressed), laminated paper plastics, metal-faced wood, and sandwich construction, present problems of selection of suitable adhesives and development of special gluing techniques. Associated with investigations of suitable adhesives and gluing techniques for such materials are problems of test methods and a determination of the permanence or durability of bonds between such materials and between them and wood.

Repair of aircraft.--The repair of aircraft under service conditions with the facilities available present many problems not encountered in regular production. Development of special methods and techniques, investigation of existing practices, and determination of the quality of repaired parts need further attention. Further work should include such investigations as strength tests of structural elements repaired by recommended methods and procedures, suitable methods of repairing plywood surfaces of compound curvature, and repair technique for open, edge-glued joints in the outer surfaces of plywood skins. Manuals for repair of wood aircraft should be currently reviewed and revised to bring methods and techniques in line with up-to-date information and practices.

Finishing wood aircraft.--To obtain satisfactory performance and to reduce maintenance in service, more satisfactory finishing should be provided for wood aircraft. Existing exterior finishes, which meet aerodynamic requirements, should be made more durable, inasmuch as none of them provide adequate protection for more than a fraction of the serviceable life of airplanes. Also the need for finishes on the interiors of wings, control planes and similar structures should be studied and, if it is found that interior finishes do have value, materials and processes to accomplish the desired result should be improved.

Substitute materials for sandwich construction.--Further work should be concentrated on the application of papreg to sandwich structures, where the somewhat lower laminar shear strength is of minor importance. The gluing of papreg to low-density core materials is another problem of fundamental importance that should be studied.

A program should be begun to develop mechanical equivalents of foams derived from wood or paper, in the density range of 3 to 6 pounds per cubic foot, as a filler material for sandwich construction. Such a material would be lighter than balsa.

Research should also be concentrated on the problem of assembling plywood or papreg skins to low-density cores, including a number of the substitute filler materials already developed.

Improved paper-base laminates.--Recent discoveries with regard to the stabilization of paper hold promise of giving laminates of high moisture resistance and high toughness. In the past these two properties have not been obtained together. Research on this problem with special consideration to Forest Products Laboratory base papers should be expedited. The use of stabilized paper for lignin impregnation may permit the making of a laminate containing virtually no critical resin and yet having properties suitable for large scale uses. A wide variety of other resins should also be tried as massive impregnants with stabilized paper.

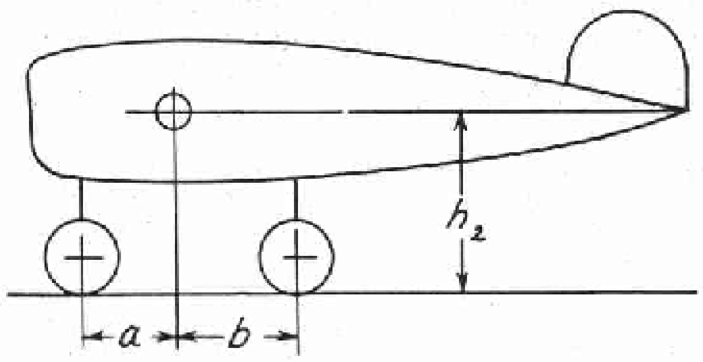

FIGURE 1- DIMENSIONS USED IN NOSE WHEEL DROP FORMULA

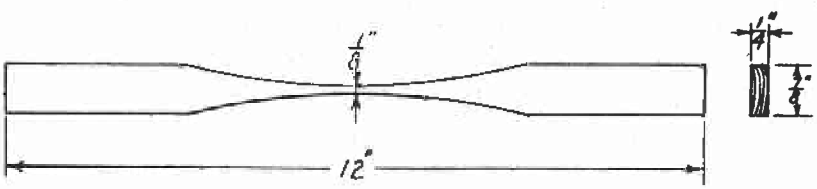

FIGURE 3 - TENSION TEST SPECIMEN

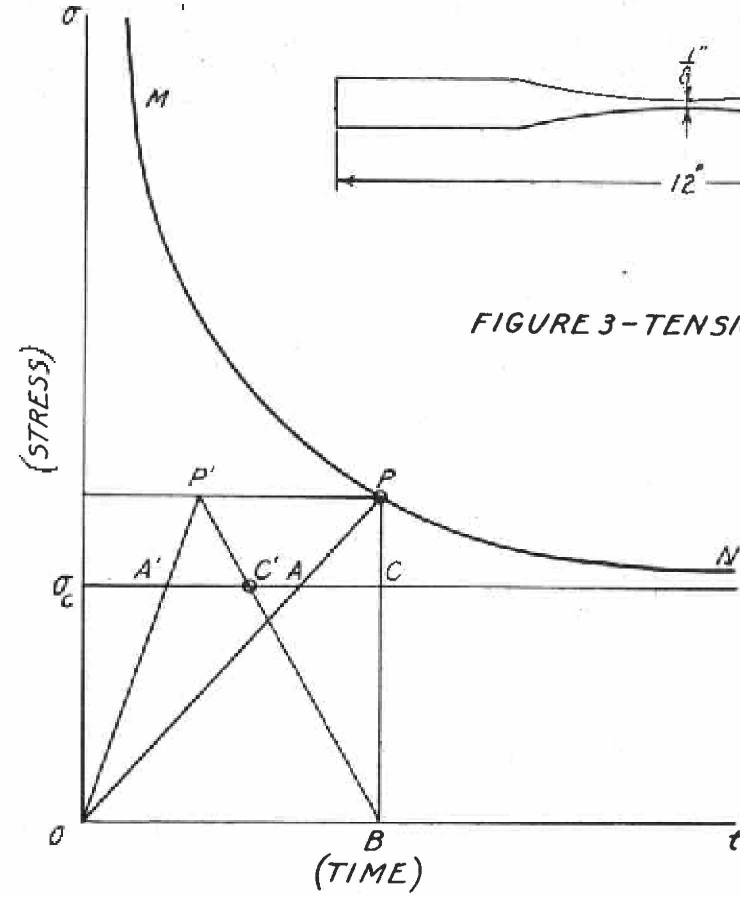

FIGURE 2 - APPROXIMATE ANALYSIS, EFFECT ON RATE OF LOADING

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