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Joint Design for Primary Structures

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Introduction

Glued joints have been used in primary structures for over 50 years. Otto Hetzer (DRP 197773 of 1906) introduced the use of large wooden arches laminated with casein glue. Figure 1 shows Anthony Fokker in the 1930's standing in front of an all-glued wing of an FXXXVI having a span of 33 meters.

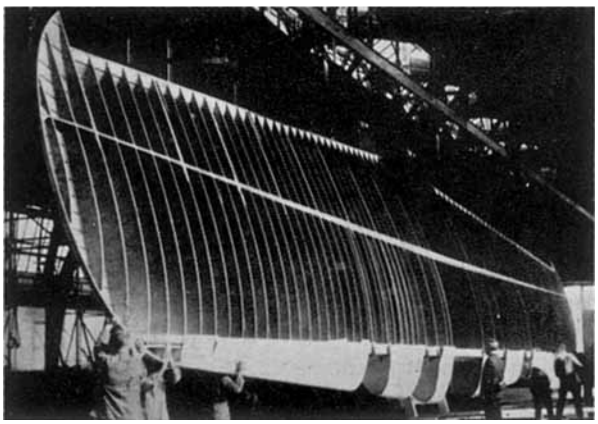

Fig. 1. All-glued wing structure of a Fokker monoplane.

The author's introduction to glue as an engineering material came through the design and building of a four-seater cantilever air-plane 30 years ago, and when metal replaced wood it struck him forcibly that it would be highly desirable to be able to glue high-strength light alloys together. After a good deal of "Edisonian" research the vinyl-phenolic adhesive which has since become known as Redux was developed in 1941.[1] It is now therefore 20 years old. This first saw service in the primary wing structure of the de Havilland Hornet fighter[2] which took to the air on July 28, 1944 and attained a speed of 485 m.p.h. in level flight—quite good for a propeller-driven machine! This was a wooden machine but the tension flanges in the spars were of light alloy; the joint between was made with Redux. Some metal-to-metal adhesive bonding was also used to build up sheet thickness at points of attachment such as that of the tail wheel bracket. When naval requirements called for the Hornet to have folding wings the hinges were bolted to light alloy sheets glued to the spruce stringers. The success of bonding in the Hornet led to its adoption in stringer-skin joints in the all metal Dove, which is still in production after 16 years, and also in the Comet.

The Fokker Friendship (made in the United States by Fairchild Aircraft Corp.) makes extensive use of this type of bonding and similar applications have been made by Svenska Aeroplan Aktiebolegat (SAAB) in Sweden and by many other firms.

Bonded Compression Members

With a suitable adhesive, two bonded sheets of metal can behave as a solid piece of their combined thickness with regard to buckling resistance. This is dependent upon the adhesive having both high strength and relatively high stiffness. This assumption may not be valid with rubber-based adhesives having values of elastic modulus several orders lower, because shear strains between the sheets can then be sufficiently large for the sheets to bend about different centers of curvature. Provided the adhesive has sufficient rigidity it is a sufficiently accurate assumption to calculate the buckling stress of a compression element composed of two sheets, as that of a metal sheet of their combined thickness including about 0.008 in. for the glue line. The load carried is, of course, reckoned on the cross-sectional area of metal. The SAAB Aircraft Co. have conducted many tests on compression elements to verify these assumptions.[3]

In the development of the Friendship airplane a series of tests on spar booms laminated up from sheet angles was made by the Nationaal Luchtvaartlaboratorium and these showed that their behavior was comparable with that of solid metal.[4] The Fokker Co. chose to laminate their spar booms

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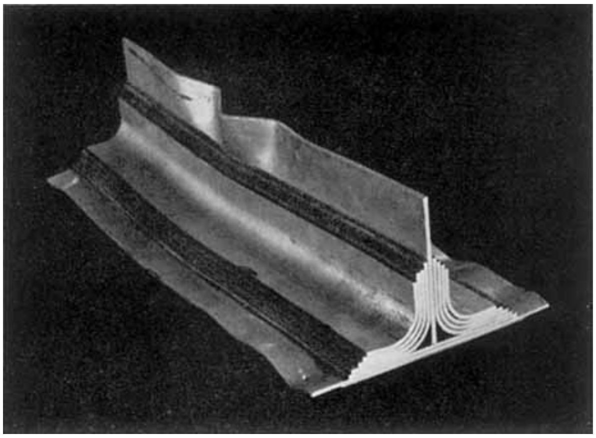

Fig. 2. Laminated spar boom specimen after fatigue failure in compression (note that the bonds are intact).

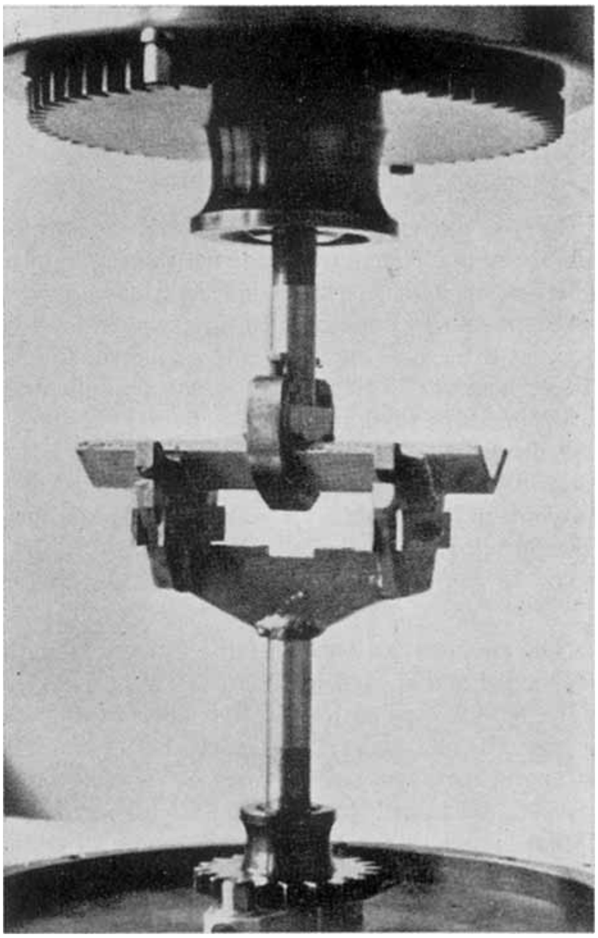

Fig. 3. Test setup for three-point bending fatigue tests.

instead of milling down extruded sections. The booms were subjected to static and fatigue tests in axial compression (Fig. 2) and flexure under three-point loading (Fig. 3). Sheet material has good mechanical properties in transverse directions which are sometimes unobtainable with extruded light alloys.

In stiffened shear and compression panels a gain in strength is achieved by the use of glue due to the continuous attachment between the sheet and the stiffener flanges. Inter-rivet buckling is eliminated and this continuous attachment provides useful improvements in the wrinkling resistance and in the torsional instability stresses of compression panels which buckle before failure.

The short-column strength of built-up compression structures is generally limited by wrinkling. The National Advisory Committee in Aeronautics (NACA) has shown[5] that if rivets are spaced closely enough to prevent inter-rivet buckling, a further strength increase can be obtained by making the rivet line nearer the corner of the stringer. However, there is a practical limit to the closeness at which a rivet can be driven to the corner of an angle, and the effective attachment line achieved by bonding is nearer to the stringer web than is possible by any other means.

The only way possible for making fully efficient attachment of the skin to the stiffener web without offset is by integral machining, but panels so made can fail by cross-grain rupture at the junction in a form of wrinkle, because the panel has to be

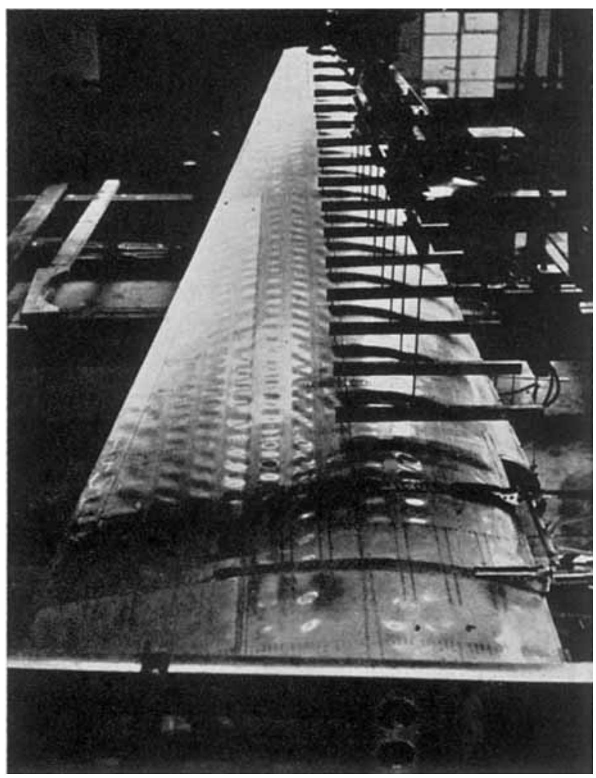

Fig. 4. Wing of the de Havilland Dove under structural test.

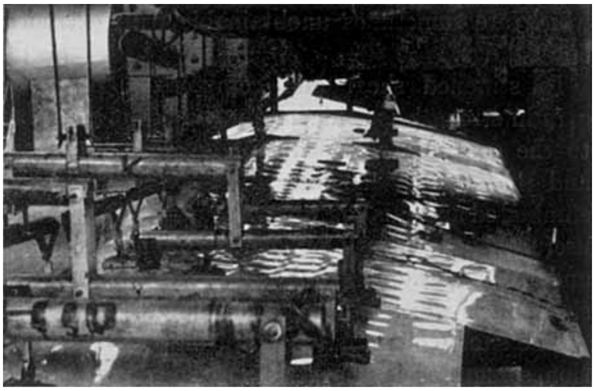

Fig. 5. Test wing of the Fokker Friendship under load.

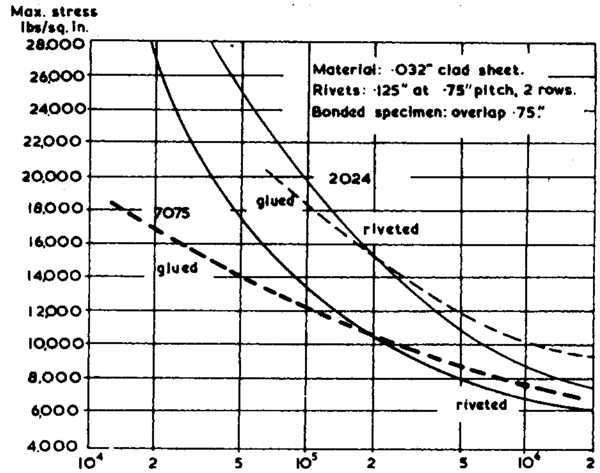

Fig. 6. Fatigue curves for bonded and riveted lap joints of 2024 and 7075 alloys.

milled out of thick-section plate. Integral panels are not normally made with bulbed or flanged stiffeners, so they show no advantage over bonding.

The effective unsupported width between bonded stiffeners is reduced compared with riveted designs, so that the initial buckling stress will be higher. It is found empirically, that where skin and stringers are of similar thickness, the buckling width of skin (normally the pitch of rivet lines) is reduced by about two thirds of the bond width, and where the stiffeners are of heavier gages, by the full bond width.[3] Photographs of bonded structures under test (Figs. 4 and 5) show that where the unsupported sheets are well buckled, the areas bonded to stiffener flanges remain plane until failure occurs.

Giddings[6] indicated that this improvement in initial buckling stress also causes an improvement in the overall (Euler-type) instability stress of panels in which the skin buckled first, because the skin elements will be stiffer if less buckled. He described comparative tests of heavy-gage riveted and bonded compression panels of identical geometries. For many reasons, in riveted panels the failing stresses are usually about 5% lower than the design optimum, but with bonded panels, these stresses were, in fact, achieved.

These remarks make it clear that the direct substitution of bonding for riveting on a stiffened panel is not the best design practice because the optimum proportions will be different for riveted and bonded constructions. A comparison of strengths or weights for the same strength should take this into account. It has been claimed[3] that weight savings of up to 25% in compression structures and 10 to 15% in shear loaded structures are possible, but the magnitudes of the savings depend upon the structural loading intensity (load per unit width of panel), being greatest for lightly loaded panels. The weight savings with heavily loaded panels are still worth while, however.

Bonded Shear Members

For the design of bonded shear webs, many of the remarks for compression structures still apply. One has to allow for the additional loads on the web attachment bonds due to the diagonal tension present after buckling, as with a riveted design. It is, however, recommended that a mechanical attachment be used at the ends of the web stiffeners due to the load concentration there and the difficulty of assessing the stress concentrations present in the bond. In a riveted design, one uses heavy rivets or bolts at these places.

Fatigue Strength

The comparative curves of the fatigue strength of bonded and riveted joints are fairly well known (Fig. 6). A bonded joint of the same overlap as a riveted one will show much better fatigue strength, perhaps nearly twice as good. Some people are misled by noting that the ratio of fatigue strength for a given endurance, to static strength, may be lower for the bonded than for a riveted joint.[7] This does not matter, because if a smaller overlap by bonding gives the same fatigue strength as the riveted joint, there is a weight saving. The fact that this bonded joint has a higher static strength is not a disadvantage.

For the arresting of fatigue cracks, should they occur, bonded crack stoppers have proved demonstrably effective. Some work done by Bristol Aircraft in England during the development of

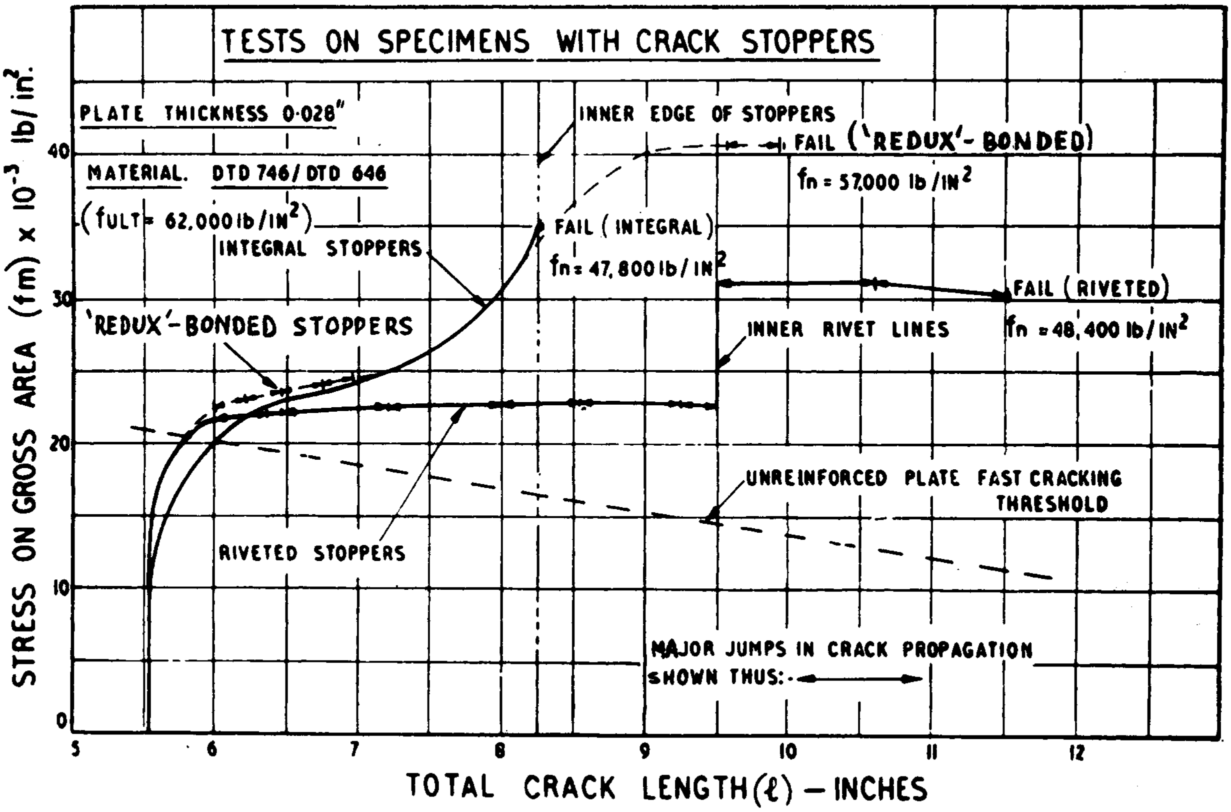

Fig. 7. Diagram illustrating tests on sheet specimens with crack stoppers.

the Britannia[8] showed this vividly (Fig. 7). To be effective, the crack stopper needs to be of a gage or two heavier material than the sheet in which the crack may occur. This is also true with other means of attachment.

The NACA conducted some tests in 1956 on fatigue crack propagation of aluminum-alloy box beams with riveted, bonded, and integrally machined stiffeners.[9] The clear result was that the crack propagation rate was lowest for the bonded design and highest for the one with integral stiffeners (Fig. 8).

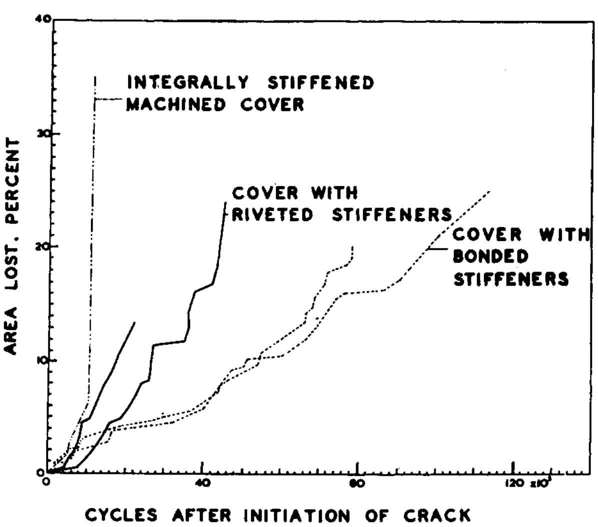

Fig. 8. Crack propagation rates in 7075 alloy.

Reinforcements

It has not in general proved convenient to employ bonding for major wing joints since these often have to be dismantled. However, an obvious bonding application is the attachment of a reinforcement to permit a flush joint in thin skins or where fatigue considerations are critical (Fig. 9). Despite the increased offset of such reinforcements on a flush joint, significant improvements of fatigue life can be achieved (Fig. 10).[3] Clearly, over a wing skin it would not be economical to employ chemical or other milling to provide edge reinforcements when these could be attached so easily by bonding.

Little need be said about the analytical aspects of using bonded doublers. Lamination is advantageous if the load changes along a component because tapered sheet is limited in availability and use. There appears to be no problem due

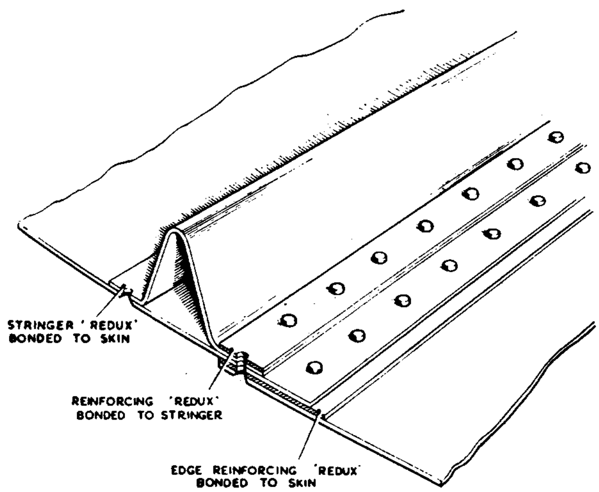

Fig. 9. Flush wing joint on the de Havilland Comet

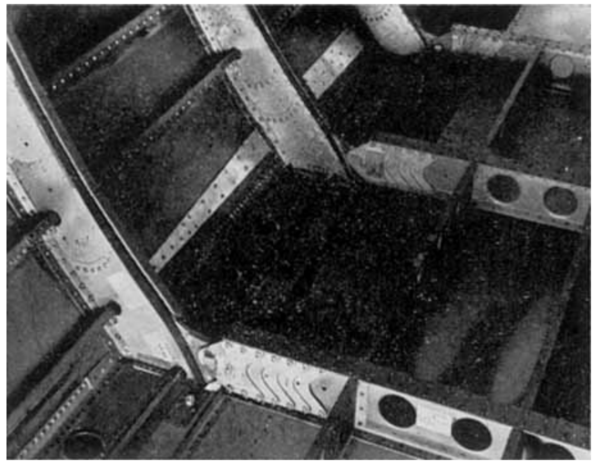

Fig. 11. Multiple sheet laminations on a floor beam of the Armstrong-Whitworth Argosy.

to stress concentration at the abrupt step in sheet thickness (which would be severe with a machined step) because with adhesives one-twentieth as stiff as the sheet material (or less) there is sufficient shear lag to relieve the possible stress concentrations. Usually reinforcements are built up using laminations of similar thickness to smooth the stress distribution as well as to economize (Fig. 11). The attachment of a thick reinforcement in one step would tend to cause high stress concentrations in the bond. Perhaps the most frequently occurring problem of detail design in aircraft is that of doublers or bearing plates at attachment points. The load put into a doubler by a large bolt has to be transferred to the sheet, but with a high-strength structural

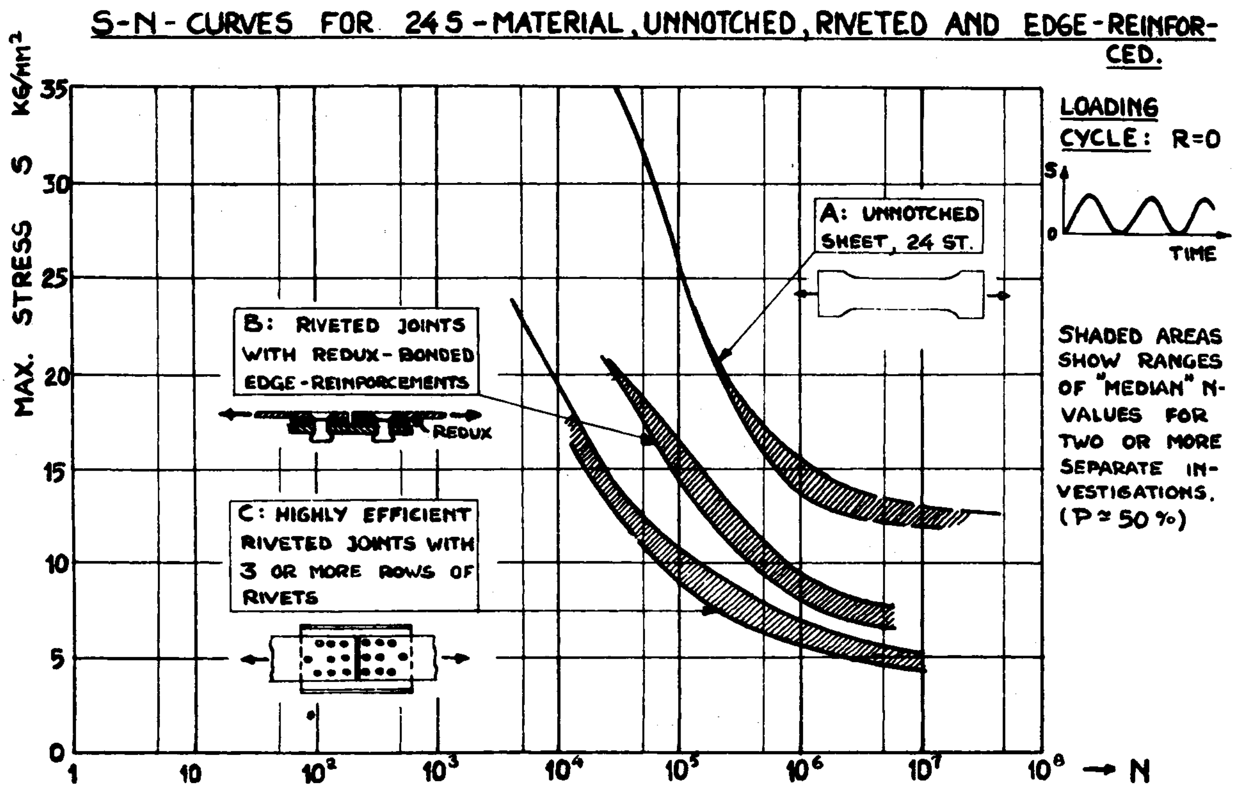

Fig. 10. Fatigue curves for riveted joints of 2024 alloy with and without bonded edge reinforcements.

adhesive the bond area provided by a moderate size doubler is more than sufficient to carry the load.

Applications

The F-27 Friendship employs the above-mentioned techniques to the full.[10] Practically all stiffeners are bonded and in all places of load concentration, doublers or laminations have been used. The production has been planned so that panels are bonded with all these reinforcements attached in one operation (Fig. 12). This results in a very substantial cost saving. Particular attention has been devoted to the reinforcements of stringers at wing joints to improve fatigue resistance (Fig. 13).

The lamination technique has been thoroughly utilized in Holland and in the United States on helicopter blades (Fig. 14) where the loads become severely concentrated at the root attachment bolts. Another vital application of bonded reinforcement is around windows of pressurized fuselages. On the Comet 4 particular attention has been paid to this matter (Figs. 15 and 16) and on the Friendship, too. Fokker claims that by its choice of reinforcement and the continuous attachment provided by bonding, that neutral holes are achieved, that is, the panel with the window cut-out behaves as an uncut sheet with regard to overall strength and stiffness. The designers' confidence is illustrated by the thick extruded stringer sections which are bonded to thick skins (of the order of 0.1 to 0.2 in.) on the Friendship inner wing and on the Comet. A

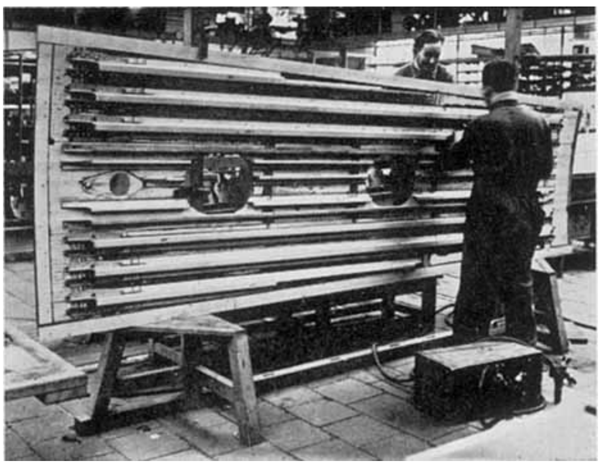

Fig. 12. Outer wing panel of the Friendship; 88 parts are bonded together in one operation.

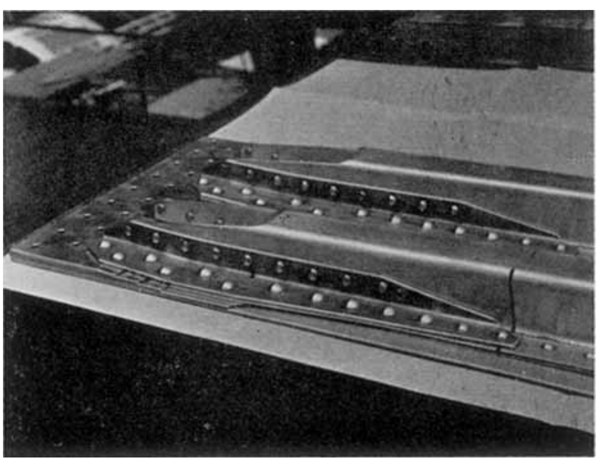

Fig. 13. Stringer reinforcement at a wing joint on the Friendship. There are doublers bonded to the skin and to stringer flanges in the region of the riveted reinforcement.

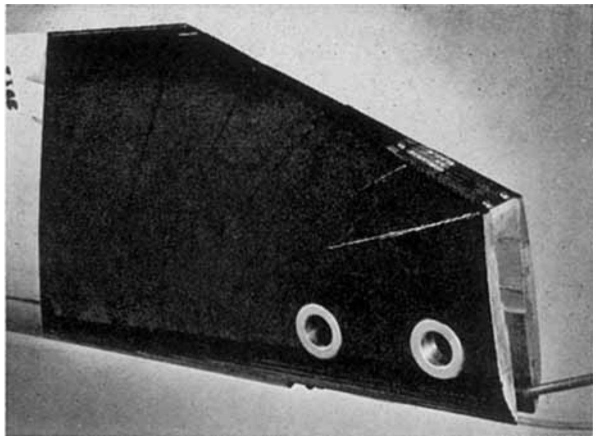

Fig. 14. Helicopter blade root made by lamination on the Dutch Kolibrie.

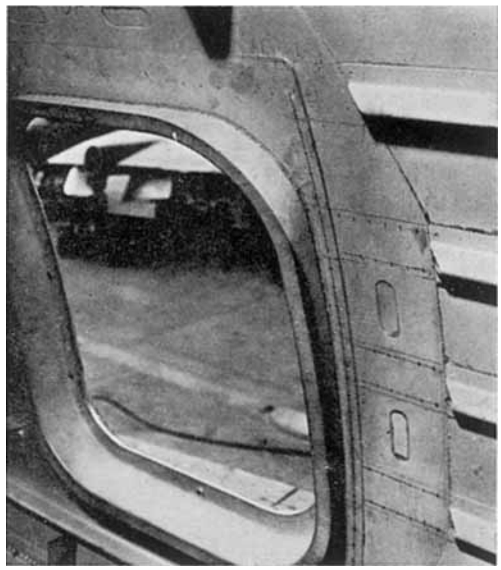

Fig. 15. Bonded reinforcement around an escape hatch of the Comet.

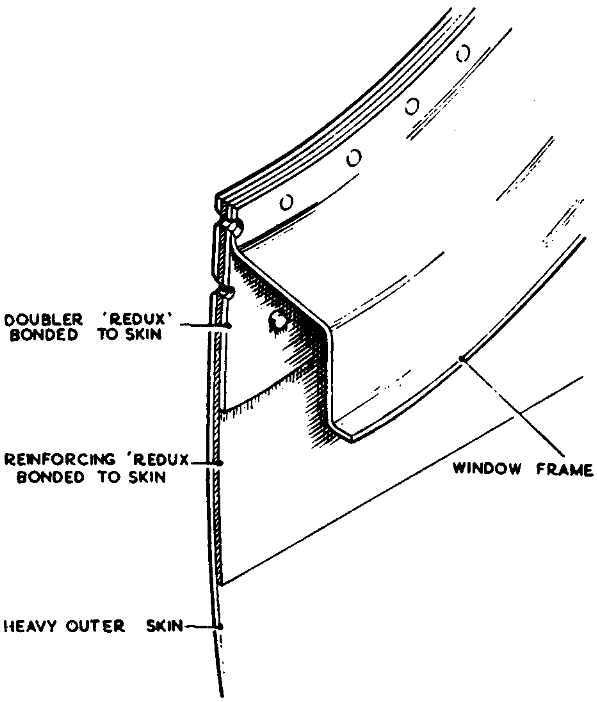

Fig. 16. Detail of a Comet window reinforcement.

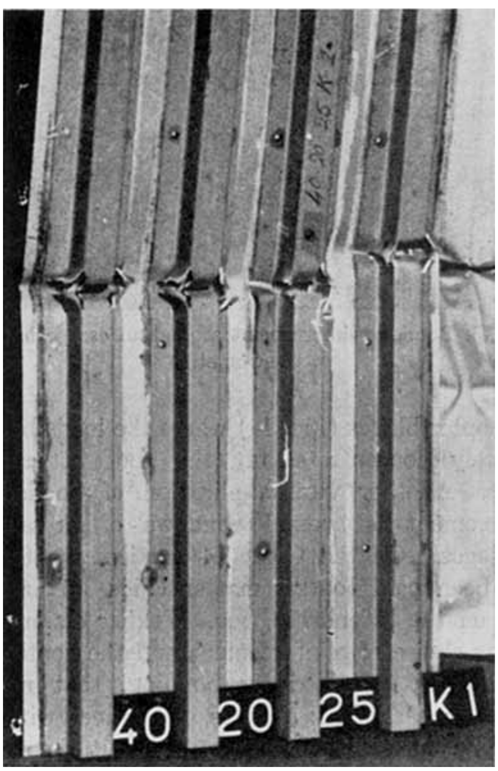

Fig. 17. Heavy gage test panel for the inner wing of the Friendship.

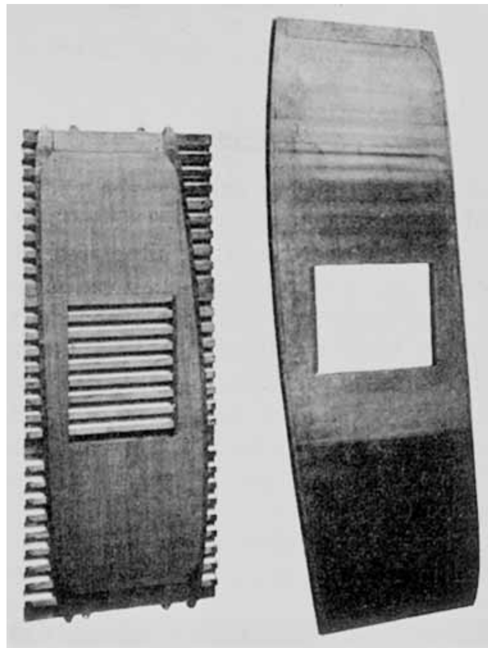

Fig. 18. Fuel tank end rib from the Bristol Britannia.

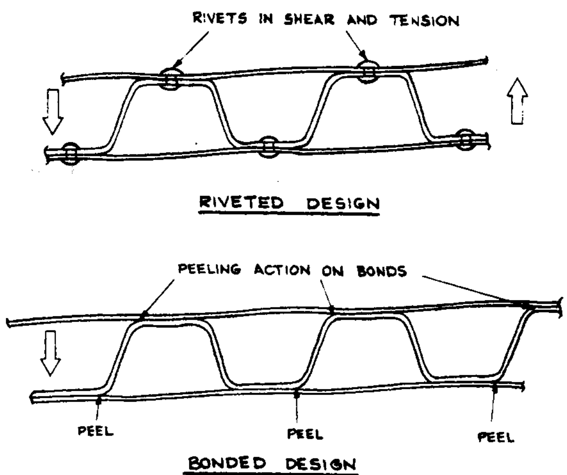

Fig. 19. Diagrammatic representation of peeling actions in a corrugated sandwich structure.

bonded panel for the former (see Fig. 17) in 7075 alloy failed at 55,000 psi in a compression test.

On the Britannia the wing ribs (Fig. 18), which are subjected to fuel pressure loads, have been made employing a bonded corrugated sandwich design. This would be difficult to make by spot welding and costly by blind riveting, quite apart from the problem of riveting sheets as thin as 0.012 in. The transverse shear strength of such corrugated sandwich panels is ultimately determined by the buckling of the corrugation or the tensile strength of the attachment of the core crests to the skins. In a bonded design the distance between the attachments will be less than in a riveted panel but a peeling action is introduced at the bond (Fig. 19) which is no more desirable than the tension applied to the rivets in the other case. However, a bonded design in fact generally exhibits a higher transverse shear strength than a riveted or spot-welded panel of the same dimensions.

While the foregoing remarks are concerned mostly with primary structural components, the greatest weight savings may be gained in secondary structure where it becomes possible to use thinner gage materials. Since all weight savings are precious, secondary applications are not to be despised.

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Synopsis

This paper describes European use of glued construction for structural joints in aircraft. It discusses the important considerations in design and strength analysis of stiffened compression and shear panels and considers aspects of detail design in bonded structures.

Résumé

Cette publication décrit l'emploi en Europe de matière fixative (colle) pour les joints structuraux dans l'aéronautique. Elle discute d'importantes considérations sur les projets et sur l'analyse de la solidité des panneaux renforcés par compression et cisaillement et considère des aspects des plans détaillés dans des structures reliées.

Zusammenfassung

Die vorliegende Mitteilung beschreibt die Verwendung verleimter Konstruktionen als Strukturelemente von Luftfahrzeugen in Europa. Die Bedeutung versteifter Kompressions- und Scherungpanelplatten für Konstruktions- und Festigkeitsanalyse wird diskutiert und die Aspekte von Einzelheiten beim Entwurf von Verbindungsstrukturen werden betrachtet.