Application of Metal Bonding in Glider Structures

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In this paper I will give an introduction to metal bonding and its application to light aircraft structures.

The paper is based on experiences obtained in the University Gliding Club in Copenhagen, where we have for some years been interested in the subject, and have applied it to our Polyt IV glider project. Information has also been obtained from Fokker Aircraft in Holland and from Bonded Structures Ltd. in England. Fokker is using metal bonding to a great extent, both in their F-27 and F-28 aircraft, and Bonded Structures are one of the main suppliers of adhesives. The gliding club has performed tests on bonding partly in cooperation with the university departments in Copenhagen and partly with Imperial College in London, where the main part of the sandwich panel testing has been carried out.

In the paper I will deal briefly with the physics involved in bonding, give a general description of some structural adhesives, bonded structural elements, production of bondings including quality testing and also show the methods used in our Polyt IV glider.

The physics of bonding

Principally, in a metal bonding two relatively stiff materials are connected with a layer of a far smaller stiffness. Fig. 1 shows two sheets connected with layer of adhesive in a simple overlapped joint. The upper drawing shows the unloaded case, the lower the loaded case. The sketch shows,

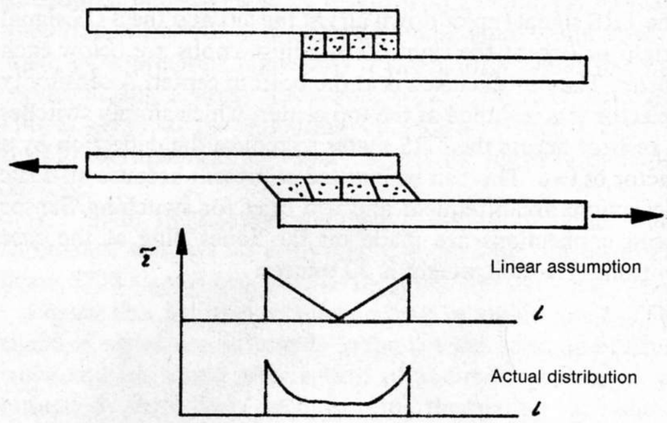


Fig. 1. Stresses in a adhesive bond

that the largest shear stresses are found near the edges of the bond, and that the adhesive is unstressed in the middle. The sketch has been based on linear conditions. The true conditions are strongly nonlinear, so the stress distributions are more like those shown on the lower diagram.

Experiments show, that the stress concentrations in the ends of the bonding line are relatively independent of the length of the overlap, provided that this is more than 3 times the thickness of the adhesive layer (Mylonas). From this it follows, that a joint cannot be made infinitely strong by simply increasing the length of the overlapping. This is shown at Fig. 2. The ordinate shows the mean shear stress

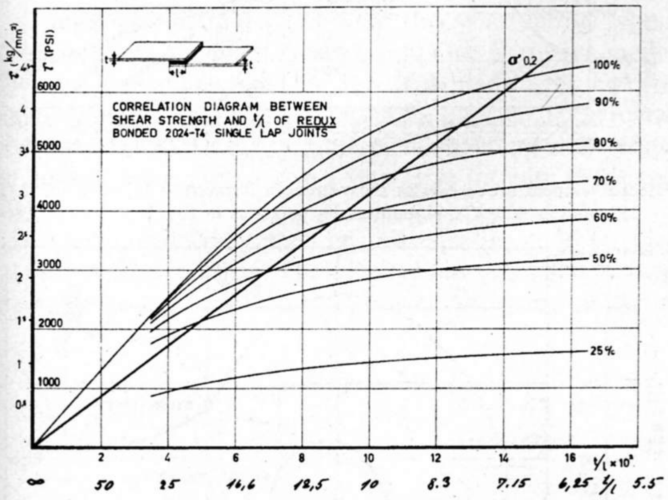


Fig. 2. Jointlengths vs mean shear stresses in a single lap joint

τ in the joint, and the abscissa the ratio between sheet thickness and overlapping length 1/t. As shown in the diagram, τ has its max value for short overlaps, and decreases towards zero when 1/t goes to ∞. The line $\sigma_{0,2}$ is intersecting the curve at a point corresponding to plastic deformation of the metal sheets.

About the bonding mechanism: The loads from one metal part, the adherent, is passed to the adhesive through adhesion, is carried through the adhesive by cohesion and is again passed to the other adherent by adhesion. The condition for a satisfactory bond is that both adhesion and cohesion is sufficiently good.

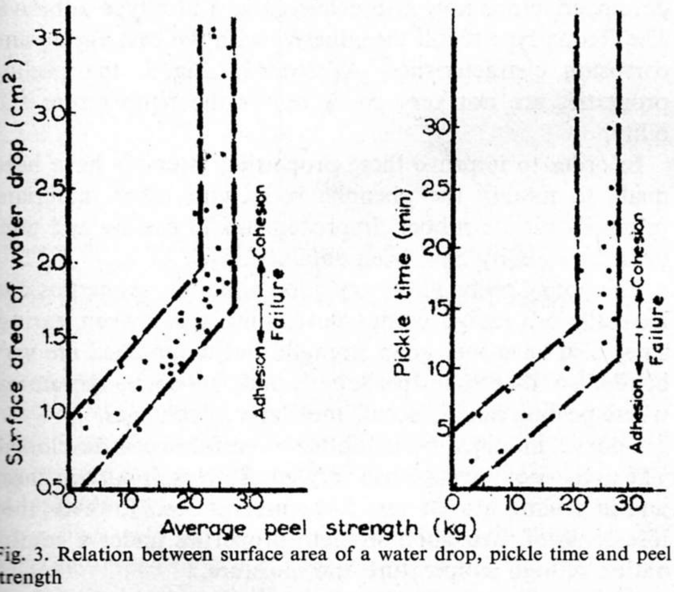


Fig. 3. Relation between surface area of a water drop, pickle time and peel strength

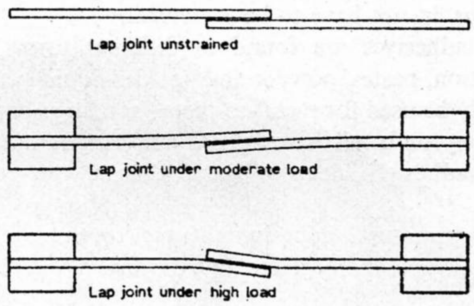
The adhesion is created by a very close contact between the adherent and the adhesive giving a purely molecular attraction. The mechanical connection, which can be expected from a very roughened surface has very little significance, and sometimes gives stress concentrations.

The condition for having the close contact between adherent and adhesive is that the adhesive has a large wetting ability, which again depends on the adherents electron emission energy. This can, for most metals and for a number of other materials, be modified advantageously by a suitable chemical treatment.

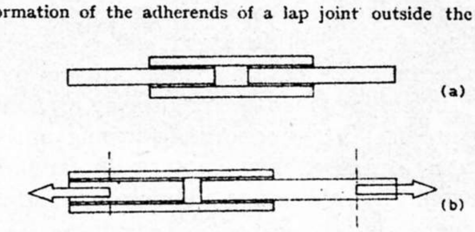
In practice a very simple test can be used to check the surface quality of the adherent. A water drop of a known volume is placed on the adherent and its contact angle to the adherent is measured, or more easily, its diameter on the adherent is measured after it has spread out. Fig. 3 shows the relation between bonding strength (in peel) and drop area. The bonding is failing in cohesion, when the drop area is 2 cm² or more. On the figure is also shown the correlation between the drop test and a much used chemical pretreatment of al-alloy.

The cohesion is solely a question about the mechanical properties of the adhesive after curing.

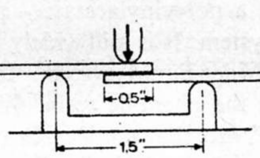
Testing of adhesives



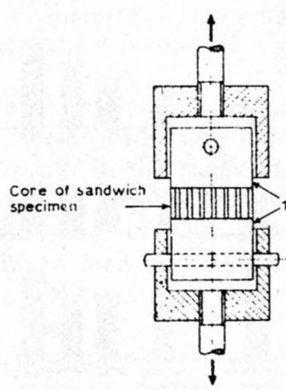
Deformation of the adherends of a lap joint outside the overlap



Double-lap shear test joints. The lower is of the pattern used by Convair (Ref. 7.)



Bending peel tests.



Flatwise tensile test of adhesives for bonding skins to a core in sandwich construction. (Grips shown sectioned.)

Fig. 4. Standard tests on bonded joints

In order to compare adhesive types, it is necessary to show some of the standard tests used to describe adhesive characteristics. Fig. 4 shows some of these. There are several variations of the tests, and standardization would be useful.

As a general rule all adhesive joints should only be loaded in shear, and must never be designed to carry loads in peeling. Never the less it is always demanded from a structural adhesive that it has good peeling characteristics. Without this, the joint will be brittle, and a minor defect or a slightly incorrectly designed detail could cause a catastrophic failure of the structure.

Adhesive types

In this chapter I will discuss different types of structural adhesives. The expression structural adhesive is used for an adhesive whose characteristics are such, that it will not fail even if the metal is loaded above its plastic limit. It also must have temperature and ageing characteristics corresponding to its application. Structural adhesives are used in primary load carrying structures. Adhesives used in secondary structures do not have to be structural.

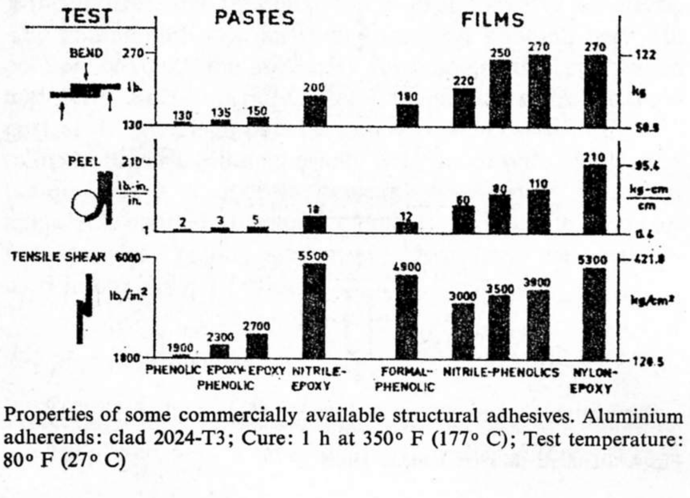
Structural adhesives are found in different forms, i. e. as films, solution, pastes, powder and powder-liquid systems. Some can only be used for metal-to-metal bondings, some as metal to honeycomb adhesives and some can be used for both. Some adhesives develop gases during the curing, some do not.

Almost all structural adhesives belong to the chemical groups phenolic and epoxy resins, but they are always modified.

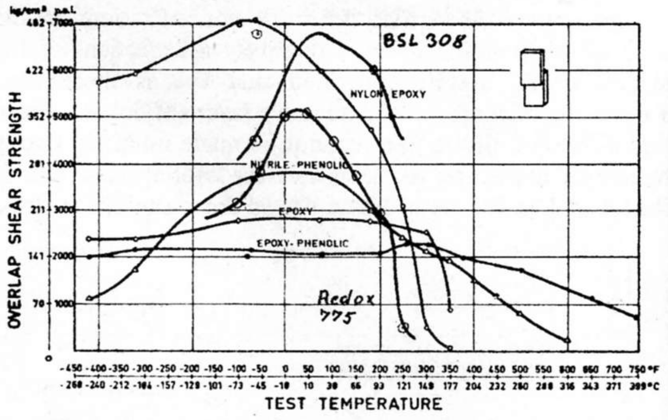
Adhesives can be divided in two main groups: hot curing and cold curing. Almost all structural adhesives are hot curing. Partly because they have far better strength properties, especially in peeling, than the coldcuring ones. Partly because they are far better concerning ageing and have better temperature stability. They are normally far easier to use in production. The cold setting adhesives are sometimes used in montage.

The first structural adhesive, already developed in the middle thirties, was a polyvinylacetate – phenolic type, the much used Redux-system. It is still widely used. Originally it was made as a powder-liquid system. It is used by first applying the liquid, the phenolic resin on the metal, where it is allowed to dry. Next the powder, the polyvinylacetate is

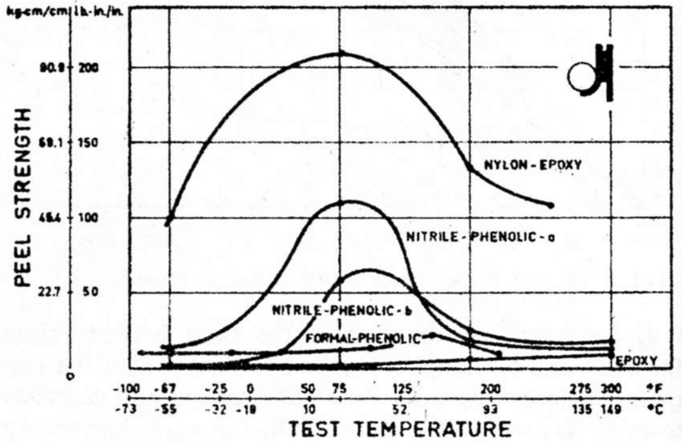
Fig. 5. Adhesive properties



Properties of some commercially available structural adhesives. Aluminium adherends: clad 2024-T3; Cure: 1 h at 350° F (177° C); Test temperature: 80° F (27° C)



Effect of temperature on overlap shear strength, between — 423° and + 750° F (— 253° and + 400° C); aluminium lap joints as in Fig. 2



Effect of temperature on metal-to-metal climbing-drum peel strength. Aluminium: clad 2024-T3. Peel strength values already corrected by subtracting the force to bend the facing sheet

spread over the now sticky surface, and the exess is shaken off. During the curing the thermoplastic powder melts and dis-solves in the phenolic resin. The result is a combination of the phenolic resins in good adhesion and the toughness of the polyvinylacetate. The Redux system has been further developed and is now also delivered as a film type adhesive. The Redux type is still the adhesive with the best ageing and corrosion characteristics. As seen in Fig. 5, the peeling properties are not very good, nor is the temperature stability.

In order to improve these properties, attempts have been made to modify the phenolic resin with other materials, primarily nitrilic rubber. Improvements in peeling and temperature stability have been obtained.

The epoxy resins have very good adhesion properties and have the advantage of not developing gases when curing. They also have very good strength, but unmodified are very brittle, so that their peeling is bad. In some structures, where peeling cannot occur, they haev advantages.

Epoxys, modified by nylon have recently been developed. The nylonepoxy system has very good strength both in shear and in peeling, also at very low temperatures. However, they lose some of their good strength properties under a combination of high temperature and moisture.

We are using an adhesive for our glider project, which as far as I can see, belongs to this type. We are using it primarily because it does not develop gas when curing, and because it can be used both for metal-to-metal bonding, and for honeycomp-metal bonding. It is delivered as a film. Its temperature stability is certainly good enough for glider applications.

Most of the hot curing adhesives are cured at temperatures between 140° C and 180° C with one to two hours curing time.

Cold setting adhesives are seldom used as structural adhesives. They are normally two-component types, but one-component types exsist. These are stored under very low temperatures, and harden when heated to room temperature.

I have information about only two cold curing types. They are both modified epoxy types. One is rubber modified, and is manufactured by 3M. It is used in the Fokker Fellowship (per author) for joints in the fuselage. These joints are also rivetted, so the purpose of the bonding is to create an airtight joint, and to give a very large increase in fatigue life.

We have made some tests on this adhesive at PFG. The results are seen in Fig. 6. The adhesive has very good peeling strength, as good as many hot curing adhesives, at room

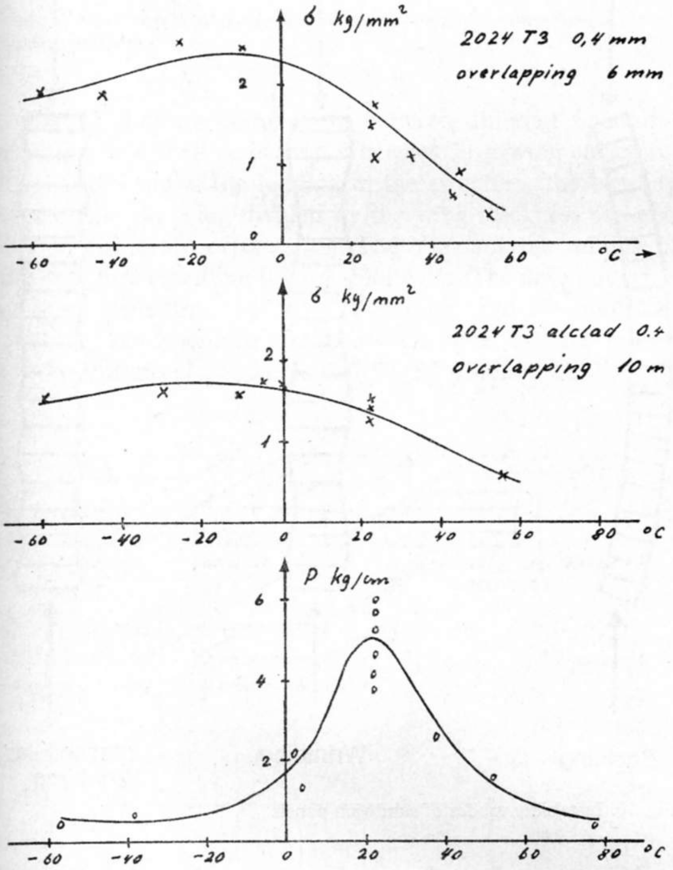


Fig. 6. Temperature dependency of EC 2216 coldsetting adhesive

temperature. It is the only cold setting adhesive I know, which has anything resembling peeling strength at all. Unfortunately the good strength decreases very fast at both higher and lower temperatures, for the shear strength only at high temperatures.

Another cold setting adhesive for structural purposes has been developed by Bonded Structures Ltd. It should only be used in connection with riveting as its peeling strength is very low. The shear strength is good both at higher and lower temperatures. (We have made tests from —60° C to +80° C).

The normal Araldite type adhesives are not good enough as structural adhesives, primarily due to rather bad ageing properties.

Bonded structural elements

The advantages in using bonding for structural elements in aircraft structures are:

- a bonded joint gives a continuous connection;
- the strength of a bonded joint is normally better, both statically and dynamically, than other connections;
- it is possible to build a structure with a very smooth and accurate surface;
- the corrosion resistance of the joint is improved.

We are using bonding in the Polyt IV primarily because the method gives the possibility of producing a very accurate surface and a high structural efficiency.

The structure of an aircraft is built up by elements, which should be able to carry loads in tension, compression and to some extent, bending in two planes. The loading of the elements varies from point to point, and in many cases the loads must be taken out of the elements at points.

In Fig. 7 it is shown how the loading is taken out of a point of a structural element loaded in tension. It is a helicopter rotor from a 'Kolibri'. The area around the point has been reinforced by lamellating.

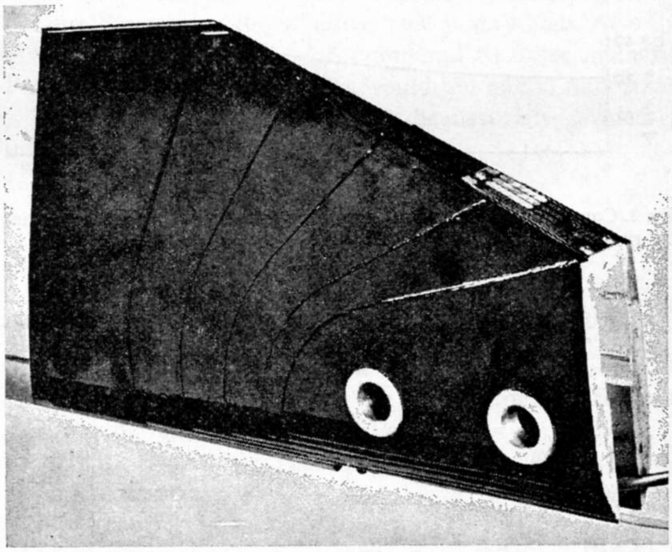


Fig. 7. Helicopter rotor from 'Kolibri'

In all aircraft with an advanced structure, this is built up in elements consisting of shells and plates. In a wing for example the upper and lower surfaces are plates connected to each other with vertical webs. These plates are loaded in compression, tension, shear and bending in their own plane, and to a small degree, bending perpendicular to their own plane. The normal loading is a combination of all these loads.

Except for tension and bending perpendicular to the plane all these loads are liable to create instability in the element in the shape of buckling or wrinkling, and in by far the majority of cases these instabilities determine the dimensions of the structure. Some type of stiffening is thus always used in order to increase the structural efficiency of the plate. Here the bonding of elements shows many advantages.

Looking at a plate stiffened with 'hat stringers' as shown in Fig. 8, the curves at the upper diagram show the maximal load such panels can take in compression, with the stringers bonded and rivetted. The lower curves in the upper diagram show the weigth gains possible. The reason for the higher efficiency of the bonded panel is, that the sheet in the rivetted panel is wrinkling between the rivets.

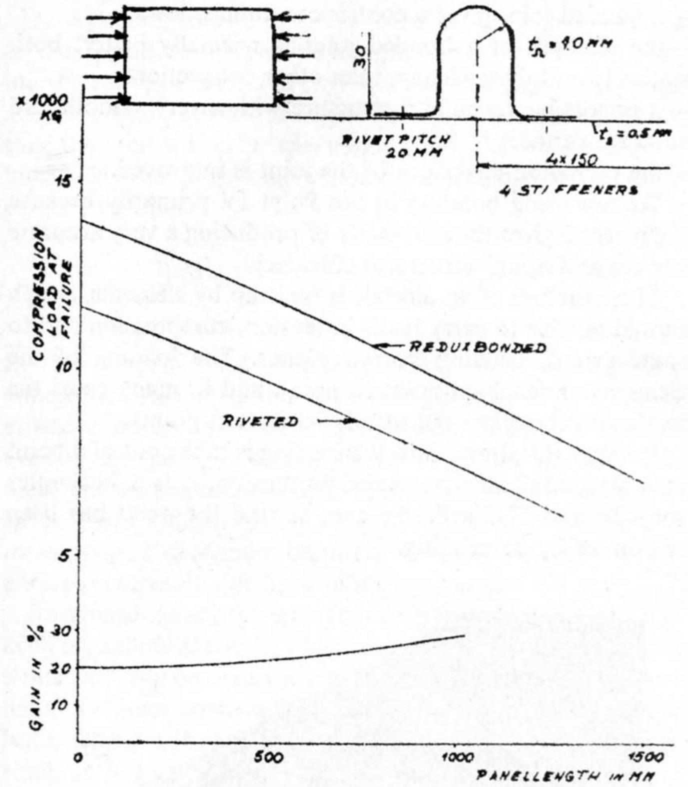


Fig. 8. Comparative strengths obtained in compression using Redux bonding and riveting

In Fig. 9 the fatigue properties of the same panels are shown. The bonded element also has advantages here.

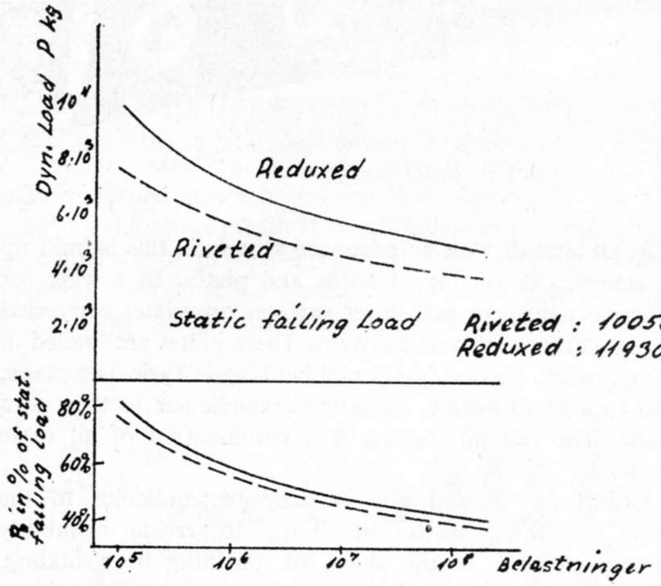


Fig. 9. Fatique of compression panels

As the loads in a panel often vary from point to point, it is often an advantage to be able to vary the sheet thickness. Bonding allows this by laminating the panel in thin sheets.

Another typical bonded element is the sandwich plate, which is built up of two relatively thin sheets of high strength material. Between the sheets a layer of low strength, low density material like foam, balsa or honeycomb is bonded. The result is a very light, stiff plate.

At PFG, we are using this element in the Polyt IV, and have therefore carried out a number of experiments with sandwichplates. I want to say something about these experiments, as they might be characteristic for light aircraft construction.

We are using sandwichpanels with very thin outer sheets in al-alloy (0.3 mm), which is somewhat thinner than normally used in aircraft. The honeycomb used is in aluminium. Due to the very thin outer sheets a possible instability exists, which is not normally found in sandwiches with heavier sheets.

The possible types of instability in sandwich panels are shown in Fig. 10. There is the normal Eulerian case with long wave buckling, where the outer sheets are still parallel, the wrinkling case still with rather long wrinkles in the sheets but independant on the two faces, and the intercellular

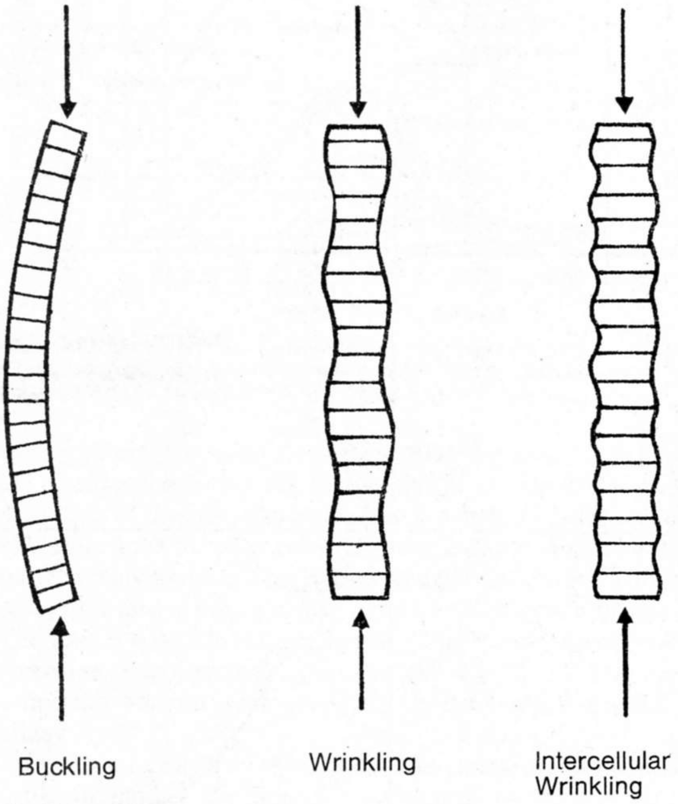


Fig. 10. Instability modes of sandwich panels

wrikling case where the wavelengths correspond to the diameter of the honeycombcell. This is the case we have investigated. The work has been done in cooperation with Imperial College in London. At the same time an investigation into using a cold setting adhesive in sandwich panels has also been carried out.

Fig. 11 shows a couple of typical stress-strain diagrams showing such panels in compression. One test is for a panel bonded with a cold setting adhesive the other for a hot curing one. The panels are otherwise identical. The stress-strain curves are identical at the lower end in the elastic region, but parts at the beginning of the plastic region, where the brittle cold setting adhesive fails, and the load carrying ability of the panel drops instantaniously to zero. The panel with the hot curing adhesive reaches a max load of 39 kg/mm², which is above the al-alloys ultimate tensile stress. After this the intercellular wrinkles have developed so much that the load carrying ability decreases, but does not disappear completely. In this case the bonding is still integral, but the honeycomb is failing.

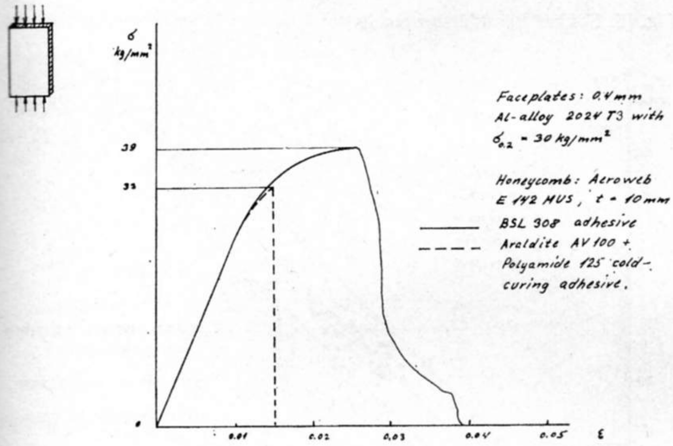


Fig. 11. Stress-strain diagram for sandwich panel in compression. Intercellular wrinkling

Fig. 12 shows a comparison between different structural elements and their structural efficiency in a wing structure. The X-axis shows the loading in the structure, the bending moment in the wing divided by the wing thickness squared and by the width of the wing. The Y-axis is the solidity of the structure equalling 1 for a solid wing. The different types of wing structures used are: Y-stringer and rib multicell, multirib, sandwichbox and sandwich plate. All the curves are for optimised structures in 7075 ST al-alloy.

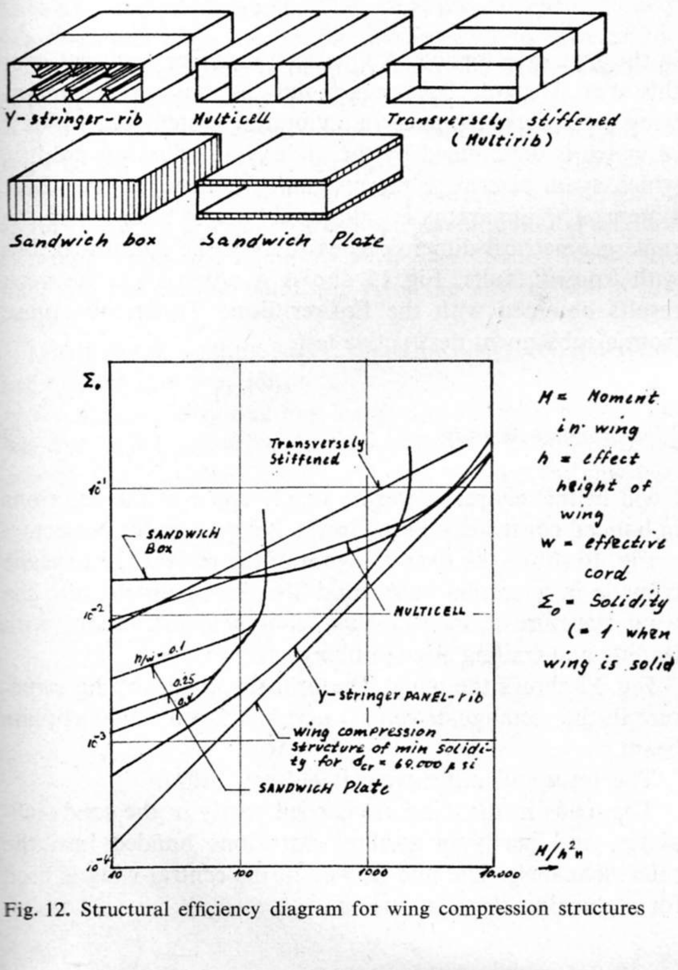


Fig. 12. Structural efficiency diagram for wing compression structures

The lower curve shows the theoretically most efficient structure. The Y-stringer and rib construction is for low and medium loads the most efficient, but is inferior to sandwich-box and multicell construction for highly loaded wings. The sandwichbox type layout is here approaching the ideal. At very low loads the sandwichplate construction is almost as good as the Y-stringer and rib layout. The traditional layout for light aircraft, the multirib method, is seen to be inferior over almost the whole region. All the other methodes are dependent on either bonding or milling to give optimum results.

Production of adhesive joints

The economy for a larger aircraft utilizingbonding is relatively good compared to other types of construction giving the same degree of structural integrity, mostly because the investment in tooling is much lower than for other methods, e. g. milling of the whole panels. How the economy will be for light aircraft and gliders compared to other types of constructions, I dare not say at the present time. The price of the material here is going to be of high importance and is at present very disadvantageous, Especially because the price of the adhesive itself is very high. Also the investment in tooling is high compared to other methods. For a reasonably big series this would not be too important.

The production of a bond can be naturally divided in three sections.

1. The pretreatment of the metal.
2. The bonding process.
3. Quality control.

1. *The pretreatment* of the metal is a very critical part of the production. A very high degree of control is necessary during the whole process, and extreme cleanliness is necessary. A widely used treatment for aluminium is as follows:

a) Tri-or per-chlorethylene vapour or bath.
b) Alkaline cleaner e. g. Henkel P_3 or Oakite . 20 min., 70° C.
c) Cold water rinse
   5 min. cold.
d) Chromic-sulphuric acid pickle
   (H_2SO_4 (spec. gravity 1.82) 15% vol., CrO_3 5% weight, H_2O remainder)
   30 min. 60° C.
e) Cold water rinse.
   5 min. cold.
f) Hot water rinse.
   5 min. 40° C.
g) Drying.
   30 min. max. 40° C.
h) If the treated metal is not going to be used within 12 hours a primer can in many cases be used. It must be compatible with the adhesive. It will protect the surface for a long periods, especially if aluminium foil is placed over it. This also makes it possible to make a series of succesive bondings. Only when the actual bonding is done is the foil removed.

A roughening with steel wool is sometimes used. The shear strength of the bonding is not much reduced, but the peeling strength is reduced greatly, and so is the corrosion resistance.

Different types of pretreatments are given for other materials such as steel, brass etc.

2. *The bonding process.* The adhesive is applied, either as a film, liquid paste or powder. The parts are then placed in suitable fixtures or presses, and heat is applied. If the adhesive is producing gasses during the curing it is necessary

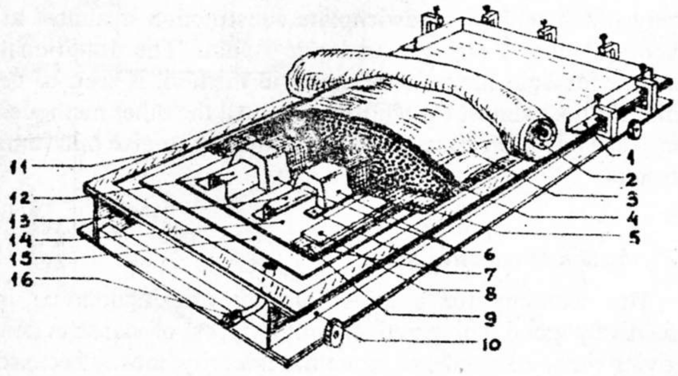


Fig. 13. Autoclave form

to apply a pressure to the bonding greater than this gas pressure, often up to 10 atm. A much used tool is an autoclave. Fig. 13 shows how the layout for an autoclave is made. Before the mould is placed in the autoclave, it is evacuated, having been made airtight with a blanket of some sort. (Here an aluminium foil is used.)

The aluminium balls are used for giving a sort of liquid pressure on the parts being bonded, and also reduces the stretching of the blanket. Thinner parts are being protected by 'hats'. The whole unit is introduced into the autoclave, where a suitable over pressure is applied, and where heat is also applied. The temperature is controlled by thermoelements placed near the critical places.

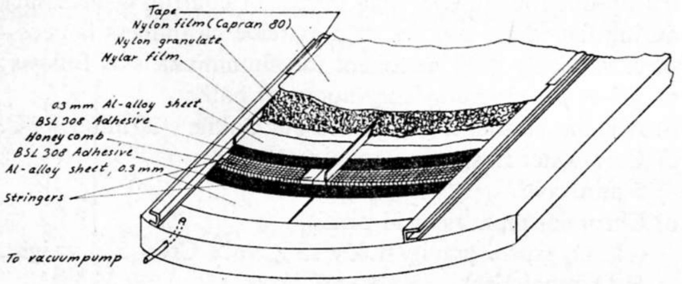


Fig. 14. Layout for vacuum bonding of sandwich panels for Polyt IV

We are using a similar method for the Polyt IV, as shown in Fig. 14. As we are using an adhesive which does not develop gasses, only a pressure to keep the parts together is required. We are using a vacuum to achieve this. The heat is applied by placing a box with electrical heating elements over the form. The BSL 308 adhesive used is cured at 170° C in 1 hour.

3. *Control of the bond.* The control of the bonding can be made destructive or non destructive. It is normal to let the test pieces go through the same pretreatment and bonding process as the actual pieces. The normal test performed is then a peeling test, as this test shows the adhesion quality better than other tests. Normally no other test is made on the adhesion.

The cohesion is normally controlled non-destructively. Different methods like X-ray, ultrasonics and coin tapping can be used. A test which is now used at almost all bonding factories is a method developed by Fokker. The method is based on the correlation between strength and modulus of elasticity of the adhesive layer, and furthermore on the fact, that bubbles in the adhesive decrease the apparent stiffness

Fig. 15. Fokker Bond Tester results

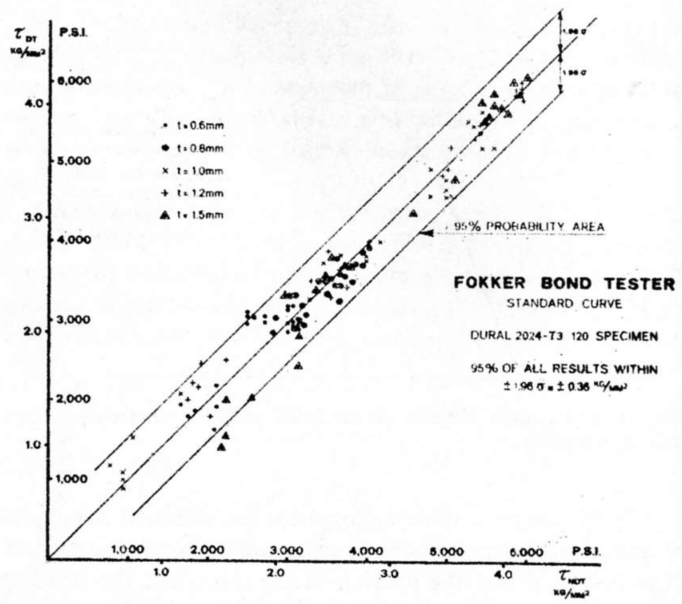


Fig. 15.24. Schematic arrangement for adhesive bonding of a skin with stiffeners and doublers in an autoclave. 1. Clamping profile; 2. Aluminium autoclave blanket; 3. Cotton cloth; 4. Aluminium balls; 5. Aluminium wire mesh; 6. Aluminium extruded protection covers; 7. Shims; 8. Pressure pad on doublerstrip; 9. Doublerstrip to be bonded on skin; 10. Standard autoclave table; 11. Heat resistant rubber edge-seal; 12. ⎍-stringer to be bonded; 13. ⌐-stringer to be bonded; 14. Skin to be bonded; 15. Tooling plate; 16. Vacuum connection.
Fig. 15.36. Comparison of shear test results τ_{DT} with the non-destructively estimated strength figures τ_{NDT}.

in the area investigated. A Quartz transducer is placed over this area. The transducer mass plus the mass of the underlying parts, form the mass in a vibrating system, the stiffness of which is determined by the underlying adhesives quality, which again determine the resonant frequency of the whole system. The apparatus is calibrated on test pieces with the same geometrical dimensions as those to be controlled, but with known faults. Fig. 15 shows a comparison between results obtained with the Fokker Bond Tester, ans those from a subsequent destructive test.

Metalbonding in Polyt IV

I will in this chapter describe briefly some of the solutions in bonded construction used in the Polyt IV glider project.

Fig. 16 shows the overall layout of the glider. The fuselage is made in a normal balsawood-fiberglass construction, the wing structure is in a bonded al-alloy construction, with leading and trailing adge in fiberglass.

Fig. 17 shows the wing. The primary, loadcarrying structure in the rectangular central part is a 2-cell sandwichplate beam.

The trapezoid outer wing is a 1-cell beam.

The loads in the wing are carried partly in the sandwichplates, and partly in al-alloy extrusions bonded into the sandwichpanels. The middle web in the central wing is used for stabilizing these extrusions.

Fig. 18 shows some details. A and C are details from the leading and trailing edge of the beam. The sandwichpanel edges are reinforced by U-shaped al-alloy extrusions, and the inner sheet of the sandwich is bent 16 mm from the

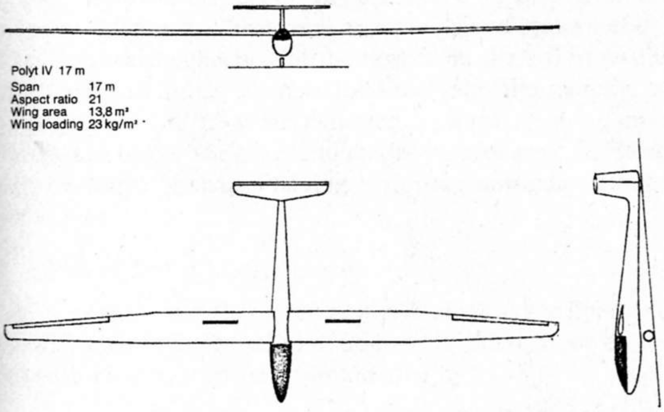


Fig. 16. Polyt IV

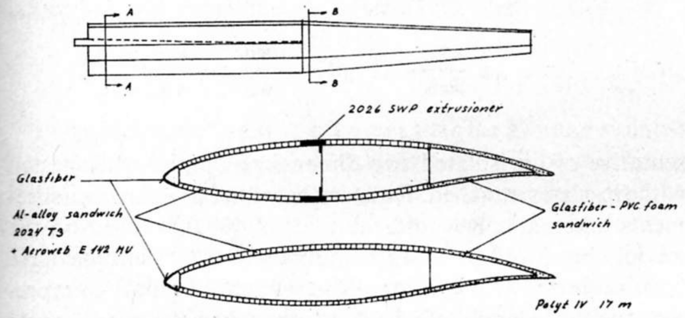


Fig. 17. Polyt IV details, wing

edge. The vertical webs are bonded to this with a coldsetting adhesive, and blindriveted. The rivets are designed to carry the full static load, the bonding serves only to increase the fatique life. The angle bonded to the web and the extrusion is making the joint peel — eave hyphen in proof.

B shows the middle section of the sandwich panel and its joint to the middle web. The panel is in two parts riveted together. This serves two purposes. If the wing is damaged, it is very difficult to repair. A divided panel makes it possible to replace only the damaged part. The divided panel also makes it possible to bond and rivet the middle web to the panel.

Leading and trailing edges, made in fiberglass and foam, are bonded into position.

We are presently building a testwing in order to find out whether it is possible to use the method. The form for the central wing has been built, and will be used for this test-wing. It is built in aluminium, in order to take care of the heat expansion, and has been built with an overall acuracy better than 0,1 mm. Testpieces bonded in it with coldsetting adhesives are also within these dimensions, and shows a

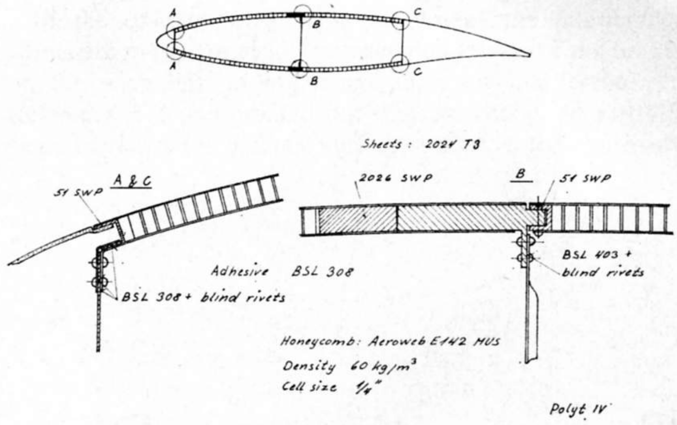


Fig. 18. Polyt IV details, wing

wavyness of less than 0,05 mm. We have not yet made any bonds with hotcuring adhesives in this form, but have made modeltests giving good results. All the auxiliary tools such as chemical vats and oven have been built, so at present we only wait for delivery of the adhesive. We have done so since february.

A probably not too optimistic weight analysis gives a weight of a wing of 60 kg for a 17 m glider with AR 21 and an airfoilthickness of 15%. The glider has been designed in accordance with the OSTIV specifications for standardclass gliders.

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