Man Powered Aircraft Group

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The Philosophy of Man-Powered Flight

by T. Nonweiler

It is a special privilege to be asked to provide the Keystone paper, and one which I feel I do not merit, except that the occasion allows me to celebrate a personal anniversary.

It must be, give or take a month or two, about 20 years since Beverley Shenstone awoke my own active interest in the subject of man-powered flight, and therefore it is as appropriate a time as any, perhaps, for me to take a view of the scene today. I am too open to challenge as some false prophet to take the seat of a Daniel come to judgment, and too long disconnected from active participation in the work to feel (as I used to do) the undeniable strength of my own opinions. So far as a detached view can be revealing, let me take that stance; so far as one or two particular lines of research have stemmed from my earlier interests, let me report on them; and then have done.

First and foremost in my mind is a pleasure in what has been achieved in these 20 years, considerably attenuated by a disappointment that progress has not been more rapid. I do not need to be reminded that the problems involved are not easy of solution. If one short reminiscence may be permitted, I well remember (many years ago in Belfast) asking a very-important-person, connected with the purvey of a very-well-known Irish beverage, for £2000 to make a man-powered aircraft. We arranged the wording of a suitable slogan to be emblazoned on the side of the machine, and he pulled out his gold fountain pen and cheque book. "Oh, by the way," he said, with no tinge of doubt in his voice, "it will work, won't it?" Now, of course, the whole interest (from my own point of view) was that it just might not "work"; or rather, if it did fly, then what a clever fellow I would have been shown to be. Moreover, as a professional scientist, I am if nothing else, trained to be ruthlessly honest. He never did sign that cheque.

This anecdote I feel is very revealing: not only of my view of the technical difficulties, or of the financial hazards of any enterprise, but of a quite different impediment - human vanity. I'm sure the idea which used to be current in the early days of the man-powered aircraft committee, that the interests and assistance of people all over the country should be enlisted and concentrated on one single project, was (and still is) the best hope of real progress and success. But it was probably an unrealistic ideal - except in so far as it has since been given valuable but limited expression by the Society and by events such as this present symposium. Yet, there has been, and there still remains, too much uncoordinated and unrelated activity too much self-expression and sometimes even too little careful engineering. "Have you not heard of Haessler and Villinger?" Someone will be bound to ask, "or of Bossi and Bonomi or of....." Yes, of course, and I am aware, too, that it is a fact that the problems involved are attractive and stimulate interest simply because they hold out the largely illusory promise of being overcome by a small isolated group, given skill and a little luck. That does not temper the grief I have felt for the effort wasted on one or two particularly ill-conceived and misdirected projects, nor my chagrin that one particular aircraft which flew had less effort put into its stability and control characteristics (during the design stage) than that regarded by any self-respecting aero-modeller as mandatory.

What more, the cynic within me strains to enquire, can be expected of an interest that suffered an upsurge of quite unprecedented proportions when the Kremer Prize was first announced? Here I must make one or two matters crystal clear. I was personally associated with the committee when the prize was first offered and the terms of the competition were first propounded; my appreciation of the donor's generosity, and admiration for this token of his support, are second to none. Yet it has not been (in my opinion) an unmitigated benefit. It has caused a lot of competitive "secrecy", and provided (for some groups at least) the wrong kind of motivation. I fear, too, that it could provoke more resentment than pleasure in its final distribution among a winning team. On the other hand, it has undeniably been the one act which has caused the most interest and publicity, and this cannot be bad.

If competition for a prize is an obviously effective but (in my view) inappropriate motivation, what then it might be asked, is the right one? The answer is self-evident for some, incomprehensible for others: that is a sufficient answer. Moreover, I am disdainful of over-strenuous attempts to justify an interest. In the short term, there is a didactic purpose which can be adduced; particularly where a project can be promoted by a group of students - the Southampton enterprise being an early and notable example of this - and the term "student" can be given its widest connotation. In the midterm, a sporting application can be foreseen, and this is where the Kremer Prize seems admirably placed. In the long-term, a link with gliding may emerge, though if this were other than in the distant future, the activity would have emerged directly out of that sport already. But for me at least these are all subsidiary motivations, and if they all were denied, it would reduce my interest not one jot.

I am well used by now to the tolerant and kindly, if sometimes patronising, response such an attitude provokes. I do not really believe many people see a Prize as a way of getting rich quick; if they did do so, they would be sadly mistaken. Given, then, the presence of all these human pressures in a real world, and the very real difficulties of constructing any machine, perhaps my disappointment is misplaced. The years have seen some small triumphs and no doubt generated moments of elation and fulfilment. But can it be doubted that a fraction of the total effort, for a fraction of the time involved, could have produced more, if the work could have somehow been coordinated, or to coin a term, contracted out? Maybe it could be doubted: maybe it is difficult enough to mount a local exercise, let alone a sort of nationalised enterprise, on a partly amateur basis. If that is so then I remain disappointed.

Turning attention to the more detailed technical aspects of the accomplishments of these years, two particular achievements would contend in my mind for special mention: the construction of the Puffin wing, and the Perkins inflatable structure, both in their different ways, quite brilliant. But to place a brickbat on the floral tribute, it seems a great pity that so many design teams overlook the essential snag of a single-man aircraft that, although a man might be able to produce brute energy and make delicate adjustments, his control mechanism is not well suited to doing both things at the same time. How many relay races have been lost when the baton was fumbled? Or, if that doesn't convince, try drinking a cup of tea during a 100m sprint and see what happens. I believe it is the existence of this human failing which provides the two-man machine with an overwhelming advantage, overriding theoretical considerations of other kinds, though it is difficult to quantify the effect I have in mind. But perhaps the main reason why the single-man aircraft has been usually preferred is simply that it costs only about half the expense in time, constructional effort and cash?

Another area where I feel it is too easy to overlook the limitations of the human machine is in the selection of operating (height/span) ratio. It is easy to show the advantage of reducing this from say 0.2 to 0.1, and difficult to quantify what added difficulty there may be in this for the pilot in any lateral manoeuvre. It is easy to work out that this allows (on paper) adequate tip clearance for a banked turn, but difficult to predict the consequent rise in blood pressure. The latter will certainly depend on the lateral handling characteristics of the aircraft, and even if the stability characteristics have been estimated, and (for example) the right amount of dihedral included after making proper allowance for wing flexure and so on, how confident is the designer in the validity of his estimates? I do not question his ability to do arithmetic: setting aside the hazards of prediction, and there are many, does anyone yet know, with these rather unusual machines, whether (like other aircraft) it matters if they have a gentle spiral instability? I suspect that what is gentle in midair becomes disconcerting, if not alarming, close to the ground. The origin of my implied criticism here is that it is easy to be led astray by one's optimisation studies: the great advantage of an optimum is that it is flat, so design on that side of all optima if that would seem to make the pilot's task easier. Look after him, and maybe he'll be better able to look after the machine.

I speak here as one who must at one time have spent more time in optimisation than most: time that I don't begrudge as wasted. A larger part of my energies of recent years has been directed towards the design of low drag wing sections, particularly those of high camber and thickness. This work derived from dissatisfaction during my earlier work on man-powered aircraft with the NACA series based, as their listed ordinates are, on linearised theory. The work was supported by the SRC for a number of years, help I gladly and freely acknowledge, as its value in relation to man-powered flight was adduced as one of the reasons for mounting the effort. With the advent of the latest range of computers, we were able to take this study full circle and recalculate the ordinates of the NACA series to their This work has been reported elsewhere (1) and a listing of the revised ordinates is available. The sections have been used under water, and on racing cars, but not yet (to my knowledge) in the air, let alone on a man-powered aircraft.

Our more recent work has been directed towards the original specification, by use of exact theory. Understanding of ground effect in the extreme condition where the (height/chord) ratio is no longer a large number. This work was instituted in relation to certain problems associated with ground vehicles. What one might call "two-dimensional" ground-effect takes the form of an increased lift curve slope, along with an increase (for a cambered wing) in zero lift incidence, so that, at fixed incidence, lift might be either lost or gained as the ground is approached. Likewise there are associated changes of pitching moment, but the effects are only considerable when the height becomes comparable with the thickness and concern with that kind of circumstance in relation to a man-powered aircraft could only be interpreted as pedantry. Contrary to my earlier expectations, at heights of about half a wing chord or more above the ground, these effects are very slight, and completely obscured by the dominating modification of the trailing vortex system: yet if one undertook research when one was certain of the outcome, one would be ill-employed.

In that reflection I find I have completed another full circle, and am repeating myself: I happily give way to those who have a more positive contribution to make, and I wish them, and all those who assail the problems of man-powered flight the fruits of success; the sweetest fruits grow on the tallest trees.

Reference

1. Nonweiler, T.R.F. Revised calculations of the NACA 6-series of low drag aerofoils. The Aeronautical Journal of the Royal Aeronautical Society, April 1973.

Structural Design Considerations of Man-Powered Aircraft

by

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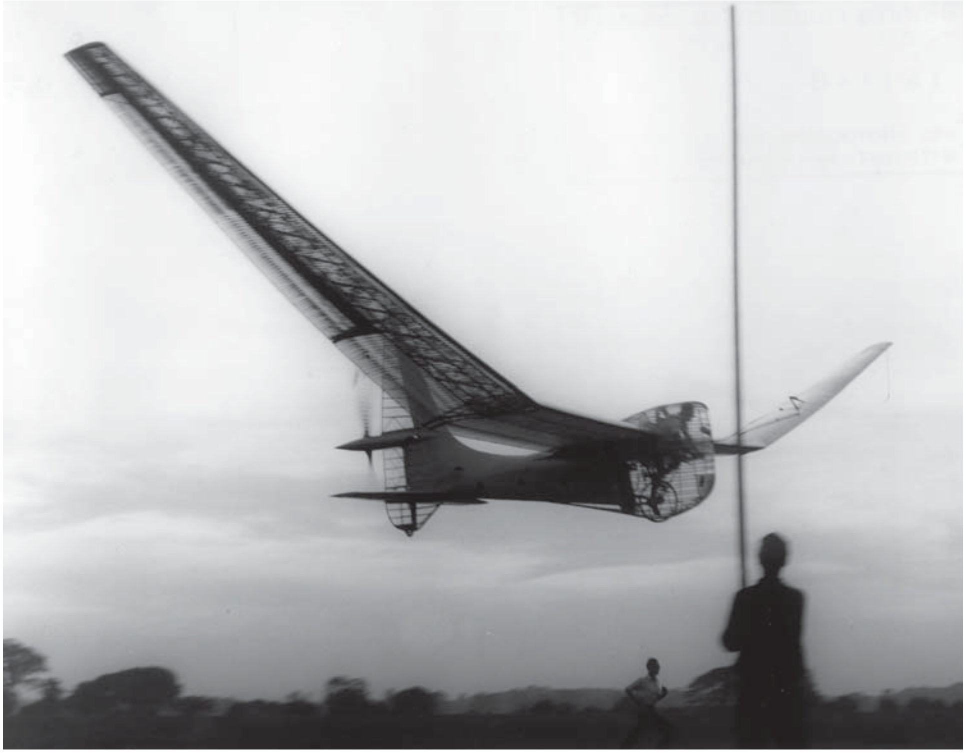

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CONTENTS

Page No.

Structural Design Considerations of Man-Powered Aircraft

1. INTRODUCTION

The purpose of this paper is to record the structural design experience obtained during the construction of the Puffin aircraft. The paper starts with some fundamental considerations, follows by outlining the specific solutions adopted on the Mk; I and Mk; II versions of the Puffin, and concludes with some comments on future structural development possibilities.

2. STRUCTURAL DESIGN REQUIREMENTS

2.1 The fundamental requirement

The dominant problem of man-powered aircraft design is to reduce the required horsepower to that available from the average fit man.

Now Horsepower required is proportional to Drag x Speed
And in steady flight Lift = Weight, so

HPr is proportional to Weight / (Lift/Drag) x Speed

The weight of a man is fixed within fairly narrow limits and to a first approximation the lift drag ratio may be regarded as fixed by the current state of art, so speed is left as the prime term at the designer's disposal. Simple calculations show that this speed must be low, in the region of 20 mph or less. Hence in order to support the aircraft weight a large wing is required and furthermore, to reduce the induced drag to lowest possible values, this wing must have a fairly high aspect ratio. Taking a typical aspect ratio of 20, it is interesting to note that even were it possible to produce a zero airframe weight, then an aircraft of 40 ft span would be needed to support the weight of the man alone at these speeds.

The airframe weight standard typical of first generation man-powered aircraft leads to actual aircraft spans in the region of 80 ft for a single man design. The prime structural design problem is then to support a man weighing say 150 lbs on a beam of total span around 80 ft for the minimum possible weight and to clothe this beam with the lightest possible aerofoil surfaces shaped to achieve a high L/D.

2.2 Stressing requirements

2.2.1 Load factor

Conventional manoeuvring and gust load requirements are unsuitable for man-powered aircraft. For example, at a cruising speed of 18 mph and a load factor of 2.5 (i.e. 1.5 g increment) the radius of turn in pitch is 14.4 ft which is less than the length of the aircraft. In terms of useful manoeuvres the g requirements are remarkably low because of the low cruising speeds; for example, if the minimum turn radius is 250 ft to enable the aircraft to follow a typical perimeter track, the incremental g required is only 0.004, and the angle of bank a mere 5°, (see Fig. 1). Similarly, a step gust of only 10 ft per second would produce an incremental g of 0.8 and pitch the aircraft through 13° in 1/2 sec; flight in such conditions is therefore ruled out on handling, rather than strength considerations. Flight experience confirms these theoretical considerations, only very gentle turns are needed, and handling difficulties preclude flight in other than light wind and therefore low gust conditions

Actual flight loads will therefore vary little from the datum 1 g steady flight condition, and might be covered by a purely nominal load factor of at most 1.2, which, with a conventional factor of safety of 1.5 would lead to an ultimate design g of + 1.8. It was considered however that it would be unwise to design to these low values as there would be no margin for unpredictable effects in such a wholly novel type of aircraft, or for ground handling loads, or for the application on every flight of a load approaching the design limit load. It was also probable that an aircraft of such low ultimate strength and large size might be too flexible. It was therefore decided arbitrarily to design to a maximum positive load factor of 2.0, which with a factor of safety of 1.5 gave an ultimate positive load of 3.0 g.

In the light of actual experience it is certain that these factors could be reduced, and a plausible basis for a second generation aircraft could be a load factor of 1.5, corresponding to an ultimate positive load of 2.25 g. Such a design basis would necessitate a very thorough detail stressing and strength testing programme, and careful examination of aeroelastic effects.

The undercarriage design landing case was based on considerations of the maximum likely descent velocity. The natural rate of descent, power off, was 0. 66 ft/sec. A phughoid excited by sudden cessation of pedalling could double this descent rate temporarily, and the extreme manoeuvrability in pitch could cause a further doubling.

This would lead to a touch down vertical velocity of 2.64 fps with an associated descent angle of 5.7°. This should be readily perceivable by the pilot so in round terms a limit of 5° descent angle need not be exceeded, and the corresponding design vertical velocity of 2.3 fps was covered. A separate case of 2 fps sideways velocity at touch down was also covered.

2.2.2 Aeroelastic requirements

The need for these may not be immediately apparent, but first order calculations quickly indicate that considerable attention has to be paid to aeroelastic matters. Accordingly the Puffin was designed to meet the conventional stiffness requirements as set out in the then BCAR requirements (Ref. 1). These criteria provide cover against control reversal, divergence and flutter phenomenon. Calculations made on the wing characteristics in terms of these specific phenomena confirmed that the orders of stiffness demanded by the criterion were in fact needed for control reversal and divergence phenomenon.

In addition special checks were made on the effects of aircraft flexibility on the stability and control characteristics. For example, wing dihedral is greatly affected by the bending deflection of the wing. Wing torsion deflection can significantly affect the span-wise load grading and hence the induced drag factor, and also affect longitudinal static stability.

2.2.3 Design speeds and flight envelope

Two design speeds were covered, a cruising speed corresponding to the design performance condition, and a dive speed based on the maximum speed that could be reached in descending from the design cruising height of 10 ft to ground level.

The V - g design cases for the Mk; I and Mk; II aircraft were:-

Aircraft	Speed	Normal acceleration Design Load Factor	Fully Factored Load
MK: 1	Cruise 18 mph	+ 2.0 g	+ 3.0 g
	Dive 25 mph	+ 2.0 g	+ 3.0 g
	Dive 25 mph	- 0.5 g	
Mk: II	Cruise 16 mph	+ 2.0 g	+ 3.0 g
	Dive 20 mph	+ 2.0 g	+ 3.0 g
	Dive 20 mph	- 0.5 g	

3. MATERIALS AVAILABLE

Many parts of the structure of a man-powered aircraft are very lightly loaded, so it is useful to consider materials under high and low loading situations separately.

3.1 High loading situations

These occur in the wing main spars and in a few other localised areas such as pilot's support structure, wheel and wheel attachments, and root fittings of tailplane to fuselage and fuselage to wing attachments. A survey of the materials available at the time on a conventional basis of specific strength and specific stiffness indicated that the commonly accepted aeronautical materials, viz: spruce, light alloy were comparable regarding these properties (see Figs. 2 and 3). Choices could therefore be made using conventional stressing methods with the loading index determining where metal or wood was most appropriate. Magnesium is useful for smaller parts of medium strength requirement but complex shape.

3.2 Low loading situations

In practice these have a greater influence on the total weight of a man-powered aircraft because of the extremely low structural densities involved in areas outside the main spars (see Table I, weight analysis). This led to consideration of a range of materials including balsa wood, low density plastic foams, and paper honeycombs, but it was found that of these balsa wood had the best specific strength and stiffness properties. It is interesting to note that balsa wood has closely comparable specific properties to normal high grade aeronautical materials providing allowance is made for the actual density of the balsa wood being used (see Figs. 2 and 3). Unlike other timbers its density can range widely from a minimum of about 4. 5 lbs per cubit foot to a maximum of 17 lbs per cubic foot. It was found that the material was quite satisfactory and consistent above a density of about 6 lbs per cubic foot and the density used could be tailored to the particular loading index. Below 6 lbs per cubic foot properties become more variable, there was a far greater likelihood of compression shakes being present and by 4. 5 lbs per cubic foot the wood becomes very brittle. It was only used therefore at the lowest densities in very minor applications.

The plastic foams were considered but suffer from rather low specific strengths and because of their particular cellular structure a very low specific stiffness. Some experimental work on plastic foam ribs using polystyrene foam at 1 lb per cubic foot density with, and without, balsa capping indicated an inferior capability to a built up structure in low density balsa (5 lbs per cubic foot). Thus balsa at 5 lbs per cubic foot density can be used in very low loading situations, such as wing ribs, with an efficiency comparable with the much lower density foams. If however it were possible to invent a material of the same specific properties as balsa but at much lower density a useful weight benefit could be obtained.

An important material question arises in the best covering for the aircraft, particularly on the wing with its very large area. Originally tissue was considered but by far the best material emerged as being Melinex which is a form of terylene and available in extremely low thicknesses. In fact, all the Puffin aircraft were covered in this material at a thickness of 0.00035 ins and a weight of 1/25 oz per square foot of single surface. The covering weight for the whole wing was only 2 lbs. Besides having an extremely low weight this material can be shrunk by moderate heating to a very smooth surface possessing excellent local strength.

4. PUFFIN MK: I SPECIFIC DESIGN

4.1 Wing

It is obvious that the minimum bending weight will be obtained with a single spar placed at the maximum thickness position along the wing cord. Such a spar was designed with a conventional twin compression boom and twin tension boom sandwiching a Warren girder shear web. The spar booms and shear struts were of spruce, and the shear struts were attached to the spar booms using thin ply wood gussets and beetle glue. Incidentally one mysterious problem encountered during construction taught us the forgotten lesson that one must not be over zealous in mixing such glue as air bubbles can be formed with disastrous effects on the joint shear strength. Towards the wing tip the spar boom cross sections became very small; this would have caused problems of buckling stability but these were averted owing to the stabilising effect of the balsa skin.

The torsion structure was a double box of a 1/ 16 in low density balsa (5. 5 lbs per cubic foot) supported on light internal balsa ribs. This gave the required torsional stiffness for minimum weight. A subsidiary rear spar of balsa was also provided. Fig. 4 shows the essential features of the construction on the Mk: I test specimen. One major problem on the balsa box was to avoid excessive pick-up of tension strain on the lower skin as, although no contribution to the bending strength was attributed to the balsa, failures in the skin would reduce the wing torsional stiffness. To lessen this problem the main spar was constructed with a droop corresponding to a half g down load. For joining to the balsa skins the wing spar was forced to a straight-position in a massive jig as shown in Fig. 5 such that when the wing was carrying 1 g load in flight in the spar the skin was This arrangement worked quite satisfactorily in practice but accounted for the curious anhedral appearance of the outer wing on the ground effectively only loaded to 1/2 g.

4.2 Tail plane and elevator

The tailplane was designed on similar principles to the wing except that no spar pre-load was necessary; also balsa spar booms were used towards the tip owing to the quite nominal bending loading there. The elevator was constructed entirely from low density balsa using a D nose with built up ribs.

4.3 Fuselage

Primary structure is confined to the rear fuselage. Examination of the design cases indicated that the torque reaction from the propeller gear box which was mounted in the fin was a major design case. Bending loads were of some consideration but only became critical towards the wing attachments, where a tapered spruce longeron was fitted to collect the loads. Clearly the most efficient torsion box is provided by material at the outside periphery and this led to the use of a balsa monocoque, this also solving the problem of providing a smooth streamlined surface. A test specimen of this was constructed with a 3/32" thick low density balsa skin (see Fig. 6), and satisfactorily met the allowable design stresses which were based in turn on systematic testing of a number of balsa wood specimens for shear strength and stiffness. Fig. 7 shows the actual fuselage frame- work, with balsa frames and mixed spruce/balsa longerons.

4.4 Aeroelastic considerations

Detailed calculations were made on wing divergence and aileron reversal speed and confirmed that the stiffness demanded by the BCAR criteria gave a reasonable but not excessive margin against these phenomenon. More particular calculations were made on the longitudinal static stability and it was found that due to the large camber of the wing there was a powerful de-stabilising term by the time the diving speed was reached. However it was estimated that at realistic speeds of flight which were thought unlikely to exceed 20 mph the problem was of minor magnitude and acceptable. The increase of wing dihedral due to wing bending at 1 g was estimated to be 5°, this, in fact, is an advantage as man-powered aircraft always tend to have negative spiral stability and increased dihedral alleviates this problem. The estimated upward deflection of the wing from zero g to 1 g flight was 3 1/2 ft at the tip. As a man-powered aircraft is continually excited by the cyclic loads from the foot on the pedals considerable attention was paid to the possible vibration characteristics of the aircraft in flight. The fundamental frequencies of various components were estimated as follows:

Wing bending	1.2 cps
Fuselage torsion	4.0 cps
Propeller on drive shaft	4.2 cps

These frequencies compared with a pedalling excitation expected to occur at about 2.4 cps. This appeared to be a reasonable margin but did cause some anxiety until the aircraft was flown when there was in fact found to be no real problem, vibration did occur but it was not excessive. The problem was probably alleviated by the high aerodynamic damping which occurs naturally on aircraft with such low structural densities.

4.5 Pilot support structure

Alternatives appeared few here and an early decision was made to construct this of welded magnesium tube of 0.75 ins overall diameter and 17 gauge. (See Fig. 8). This proved entirely satisfactory in practice and under the somewhat cossetted conditions of man- powered aircraft no corrosion problems were encountered.

4.6 Wheel

It was considered that the extensive development which had gone in over many decades into the lightweight bicycle wheel could probably not be bettered and accordingly such a wheel was purchased. Tests showed the wheel with its 1.25" tyre to be capable of absorbing 35 ft. lb of Kinetic Energy before permanent distortion, and this gave a safety factor of 1.65 on the design case of section 2.2.1. The design proved to be very satisfactory in practice with no wheel or supporting structure damage ever being reported due to normal flying although some damage did occur to the tail wheel due to accidental encounter with holes, etc. in the runway.

4.7 Transmission

It was felt on an intuitive basis that it would be most efficient to drive the propeller by a torque shaft and to transfer the pedal motion into this shaft as near to the source of power as possible. A very compact gear box of conventional construction was designed to accomplish this using steel gears in a magnesium casing. The gearbox performed with complete satisfaction throughout the whole project's history. Fig. 9 shows the pedals, wheels, gearbox and propeller support shaft. The propeller was mounted on the fin to avoid the need of an extra special mounting surface and a light transmission shaft appeared feasible using a high stiffness construction with a large diameter balsa wood shaft (see Fig. 10). This was made from three cross-ply laminations of 1/32" balsa and weighed 2.3 lbs. It was subjected to a ground strength test, flew satisfactorily for a number of flights but finally failed on a reverse loading case which had not been covered in the design. It was then replaced with a slightly heavier, and smaller diameter, etched light alloy shaft which performed satisfactorily for all of the remaining flying, at a small weight penalty.

4.8 Propeller

The need to obtain a good profile combined with a reasonable strength quickly led to the choice of a laminated balsa blade with local spruce reinforcing near the root to meet the bending requirements (see Fig. 11). This construction worked well with no problems.

4.9 Controls

Stick forces were estimated to be relatively trivial and the maximum control cable load was 25 lbs. The smallest diameter of woven steel cable available was used, with complete satisfaction. Pulleys and fairleads were of conventional form and fabricated in magnesium.

4.10 Front fuselage fairing and canopy

Fig. 12 shows an early experiment at building this up from 1" thick polystyrene foam sheet. This was abandoned in favour of the lighter structure fabricated from low density balsa (Fig. 13).

5. PUFFIN Mk. II

5.1 Optimum aspect ratio and t/c ratio

The optimum overall wing geometry to give the lowest horse-power requirement was examined in considerable detail for the Mk II design. It is interesting to note that the substantial variation of profile drag coefficient with Reynolds Number and thickness chord ratio, which occurs at the low RN of man-powered aircraft, leads to overall optimum aspect ratio and t/c ratio which are lower than would be the case were C_{D0} independent of these parameters. Fig. 14 shows some early estimates of theoretical optima, and shows the effect of varying compared with constant C_{D0}. Extreme bias towards high aspect ratio and high t/c ratio is not required. (The actual aspect ratio selected for the Mk; II aircraft was higher than the optimum shown on these basic curves owing to a special trim drag constraint arising from a desire to use the Mk; I tailplane with the larger Mk: II wing. A fairly low t/c of 13.7% was actually used to ensure good aerofoil performance.)

5.2 Specific design

This version of the aircraft was designed to embody the best features of the Mk: I design, but to overcome deficiencies wherever possible. In broad terms this meant a complete redesign of the wing torsion resisting structure, some secondary improvements in the wing rib structure, and virtually no change in the rest of the aircraft. The main deficiency of the Mk: I wing lay in the tendency for the balsa skin to crack, not due to flight loading but due to shrinkage. This was accentuated by the conditions of low humidity which were frequently encountered in the hanger and was offset to some extent by the expedient of internally steaming the wing prior to flight. This was essentially a nuisance rather than a fundamental problem. To avoid this however meant complete reconsideration of the form of torsion structure. The previous and successful spar construction was transmuted into a two-spar form but with discrete cross-bracing interconnecting the spars to provide the torsional resistance. This cross-bracing was provided entirely by massive balsa struts which concentrated the material which had previously been dispersed in the skin of the Mk: I aircraft. A substantial amount of testing was done on the strut specimens to identify the preferred density of balsa to provide maximum stability in the struts under compressive loading, this being a dominant design case. The form of construction is shown in Fig. 15, where it is seen that the cross-bracing struts were fastened to the spruce spars using large plywood gussets. These balsa cross-bracing struts were quite massive, 0.875" x 0.875" at the wing root, but being made of 10 lb per cubic foot balsa they all only contributed 15 lb to wing weight. It was still felt unwise to allow the balsa struts to pick up any of the end loads due to wing bending and for this reason main box ribs were effectively omitted in so far as no major constraint was provided between the front and the rear spar. Thus, under up-load on the wing the compression in the top booms caused the upper booms to move slightly away from each other, with the balsa diagonals moving in a slight 'scissor' fashion. Conversely, on the lower surface, under elongation due to tension the bottom booms moved slightly towards each other and by this means, sensibly, no end loads due to bending were transmitted to the balsa torsion struts. This arrangement seemed to work quite satisfactorily in practice, clearly a nominal amount of spar interconnection strength was in fact provided by the alternate rib diagonals shown in Fig. 16 and by the light weight superimposed balsa ribs.

The external rib shape was provided as before by a light balsa structure which was stressed for the normal flight envelope and in fact required a small measure of compression stabilisation in the upper boom of the rib by the fitting of a span-wise nylon thread. The ribs were pitched very closely (1. 25" at the wing tip) to provide a high quality aerofoil profile (Fig. 17).

Some problems were encountered in the design of the booms when in compression on the outer wing as their section was then very small, typically 0.2" width x 0.4" depth for each boom element. Local balsa strips were fitted to mutually join and stabilise the adjacent front and rear parts of the boom. Owing to the increased span and the problems encountered in transporting the Mk; I aircraft it was decided to fit a joint at one-third semi-span in the Mk; II wing. The joint design was relatively conventional, a 10 g light alloy plate being sandwiched between the spar booms with conventional hollow steel pins to effect the joint. Details may be seen on Fig. 18.

Aeroelastic calculations were made on this wing in some detail. The outer wing was essentially designed by the torsional stiffness requirements. Furthermore, the datum twist to which the wing was built allowed for in-flight torsional deflection, while a small component of bending deflection coupled with the small sweep was of some significance in building up the desired total load grading.

This was aimed at a satisfactory stall pattern with negligible penalty on the theoretical minimum induced drag factor. The wing was proof- loaded to 2 g, a somewhat agonising experience mentally but one which was completed successfully. The in-flight bending deflection of the wing was measured by taking a photograph from the rear. The upward tip deflection was found to agree exactly with that predicted from the theoretical load grading and the ground measured bending stiffness from which it was concluded that the air load distribution was as predicted. In turn this meant that the outer wing was working satisfactorily in aerodynamic terms and therefore offering the best chance of a minimum drag flow. This result was felt to justify the provision of the very large number of ribs. On the Mk: I aircraft the flight measured tip deflection was significantly less than predicted and it was suspected that the outer wing airflow was unsatisfactory, with laminar separations associated with the low tip Reynolds number probably accounting for a double penalty of increased local profile drag and increased drag due to a poor span-wise load distribution.

A final problem on aeroelastics arose from the aileron design. The aileron had its hinge near the upper surface in order to allow a continuous Melinex covering on the upper surface, thus avoiding any gap and risk of spoiling airflow in this sensitive low Reynolds number regime. This hinge position made much down aileron movement impractical, but the large up movement consequently required fitted the need to minimise adverse aileron yaw. The aileron chord was large, partly to offset the loss in control power due to limited down-ward movement, and also to enable the hinge to be mounted near the main rear spar, thus eliminating any subsidiary rear spar. Fig. 19 shows in cross section the aileron and rear spar design. This design led however to high loads in the aileron operating cables due to the strong tendency of each aileron to float up under 1 g conditions, and to twist due to the limited torsional stiffness available from the triangular balsa torsion box below the aileron hinge (Fig. 19). The operating cable was therefore replaced with stiff 16 gauge piano wire, which greatly augmented the torsional stiffness of the aileron via aileron operating lever connections provided at three points along the aileron span.

These measures, together with a small preset deflection in the aileron led to zero aileron angle and twist in 1 g flight.

The grain in the aileron's torsion box was set at 45° to maximise torsional stiffness and also to allow the aileron to accept the bending deflections of the main box without failure. The latter effect was made possible because the failing strain of balsa in tension across the grain is double that along the grain.

A further minor problem on the wing design lay in one tendency for the wing trailing edge member to pick up excessive bending load owing to its large displacement from the neutral axis. This was averted by cutting the trailing edge member at 3 or 4 places across the span.

The form of construction for the Mk II wing was very satisfactory and occasioned no problems whatever during all flights of the aircraft.

6. FUTURE POSSIBILITIES

The wing structure of the Mk II Puffin was very satisfactory in meeting the aerodynamic and structural requirements, and can be used as a datum from which to assess the effect of possible improvements.

The weight analysis in Table I suggests some lines of approach. Unfortunately there is a greater percentage of airframe weight contributed by lightly loaded parts and no radically new approaches are evident here; improvement can mainly come on a modest scale by spending a lot of time on detail design and strength testing.

The highly loaded parts offer much more scope for weight reduction, by use of advanced new materials, and by reduction of manoeuvring load factor. Figs. 2 and 3 indicate the strength and stiffness increases available from unidirectional fibre composites, and suggest that a carefully selected use of glass fibre and carbon fibre in both high strength and high stiffness forms could give considerable advantages, especially by tailoring the particular fibre usage to local loading and stiffness needs. The application would be most effective in elements such as the wing spar booms where the loads are sensibly unidirectional, and a detail design study would be necessary to obtain any reliable estimate of the lightest possible structure.

However for purposes of estimating the order of possible improvements some plausible assumptions may be made as follows:-

Wing spar booms and web

a) Design to ultimate g factor of 2.25 instead of 3.0

b) Fabricate in carbon fibre, taking intermediate strength grade of same stiffness/strength ratio as spruce. This corresponds to a tensile specific strength of 4.5 x spruce.

Problems of compression boom stability will prevent full exploitation of this specific strength improvement, but a usable improvement of 3 x spruce is assumed.

Overall weight reduction factor = 1/3 x 2.25/3 = 0.25

Spar weight reduction = 35.4 (1-0.25) = 26.5 lb.

Remaining highly loaded parts of airframe

Here the loading cases will probably be more multidirectional and this, together with problems of load transfer from the highly stressed fibres, will dilute the advantages of the composite materials. An overall advantage of 2 x specific strength is assumed, on the remaining highly loaded parts listed in Table I.

Overall weight reduction factor = 1/2 = 0.5
Weight reduction of highly stressed parts = 23.1 (1-0.5) = 11.5 lb

Total benefit

Total weight saving = 38 lb.
New airframe weight = 97.5 lb (72%)
New all up weight = 247.5 lb (86.7%)

This saving may be exploited either as a reduction in aircraft size with the same HPr, or a reduction of HPr at the same aircraft size.

The span reduction would be from 93' to about 78.5', with some allowance for the escalating effect of weight saving as area is reduced.

The horsepower reduction at 93' span would be about 20%, reducing a typical HPr of 0.35 to 0.28.

Either of these improvements is very worthwhile, and lend encouragement to a detailed design study of the best ways of exploiting the potential of high strength composite materials. Their usage on a man-powered aircraft would be relatively uninhibited by the high material cost, and there should be scope for exploiting the ability to fashion continuous structural elements in complex directions to suit local geometric and load path requirements.

7. ACKNOWLEDGMENTS

The author would like to acknowledge the major part taken in the structural design of the Puffin aircraft by Messrs. F. W. Vann and F. T. Watts, both members of the Hatfield Man-Powered Aircraft Club.

8. REFERENCES

1. British Civil Airworthiness Requirements Civil Aviation Authority London.

9. LIST OF SYMBOLS

g	Acceleration due to gravity
HPr	Horsepower required
V	True air speed
L	Lift
D	Drag
C_{D0}	Profile drag coefficient
t/c	Thickness/chord ratio
RN	Reynolds number
CL	Lift coefficient
E	Modulus of elasticity.

10. LIST OF FIGURES

TABLE 1

WEIGHT ANALYSIS OF PUFFIN MK II

Component	Total Weight (lb)	Weight Makeup (lb) Highly loaded parts	Lightly loaded parts
Wing			
Centre section box	30.9	21.6*	9.3+
Two outer boxes	24.4	13.7*	10.7+
Ribs, LE & TE, controls and covering	28.7	0	28.7
Sub Total	84.0	35.3	48.7
Fuselage			
Rear fuselage structure	9.2	1.0	8.2
Nose structure & canopy	3.0	0	3.0
Tailplane & Elevator	6.3	1.0	5.3
Upper fin & Rudder	2.0	0	2.0
Pilot Support Structure	8.6	7.0	1.6
Pedals, Wheels, Gearbox	6.1	5.1	1.0
Propeller & Bearing	2.7	1.0	1.7
Prop: Transmission Shaft (with bearings, gear etc.)	7.6	5.0	2.6
Control Systems	6.0	3.0	3.0
Sub Total	51.5	23.1	28.4
Total Airframe	135.5	58.4	77.1
Pilot	150		
Total All Up Weight	285.5		

* Spruce spar booms, web, joint fittings.
+ Massive balsa torsion and other bracing struts and gussetts.

MK: II Wing Geometry

Area	393 square feet
Taper ratio	3:1
Inner 1/3 span parallel chord)	
Span	93 ft
Aspect Ratio	22
Thickness /chord ratio, Inner 1/3 span	13.7%
Thickness /chord ratio, tip	11.0%

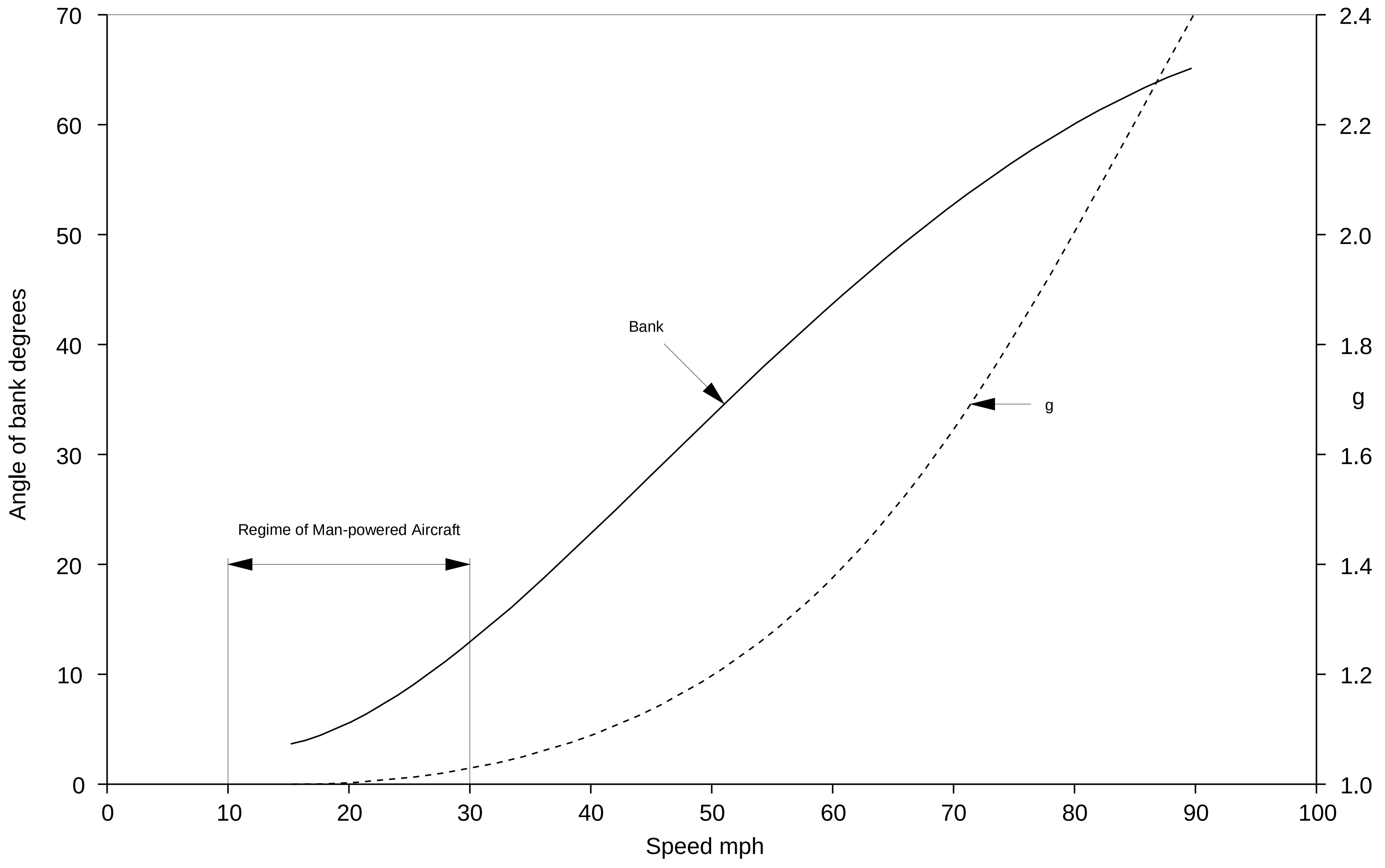

Fig 1: Bank angle and normal acceleration for a steady turn of 250’ radius

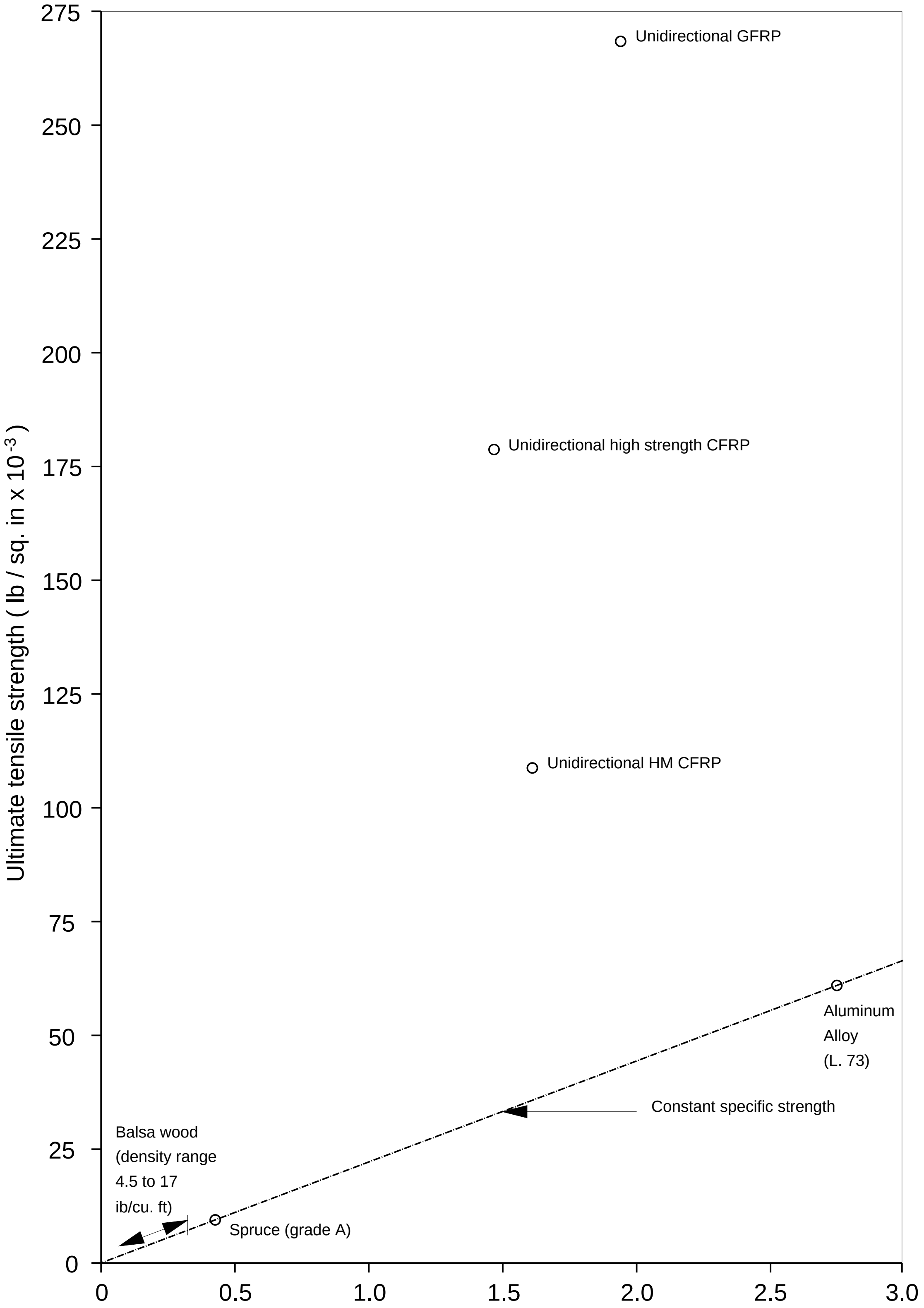

Fig 2: Ultimate tensile strength vs specific gravity of materials suitable for Man-powered aircraft

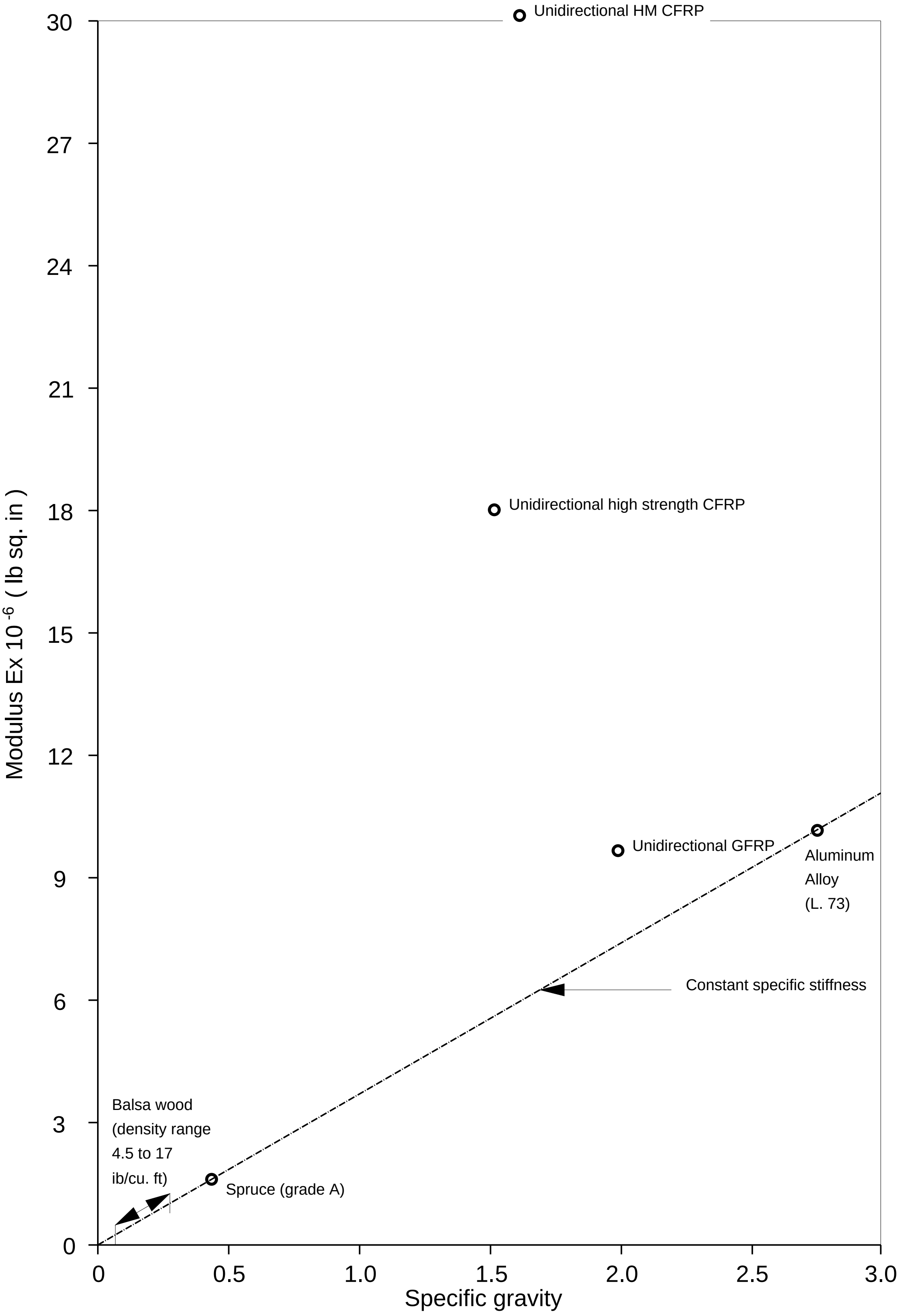

Fig 3: Modulus vs specific gravity of materials suitable for Man-powered aircraft

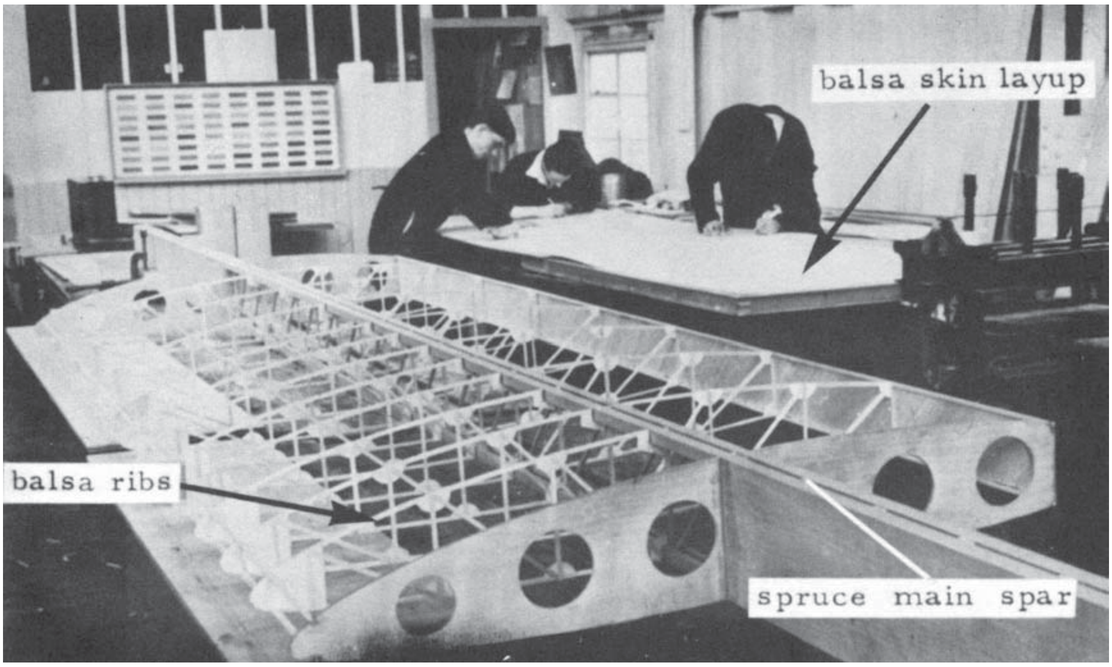

Fig 4: MK I Wing test section

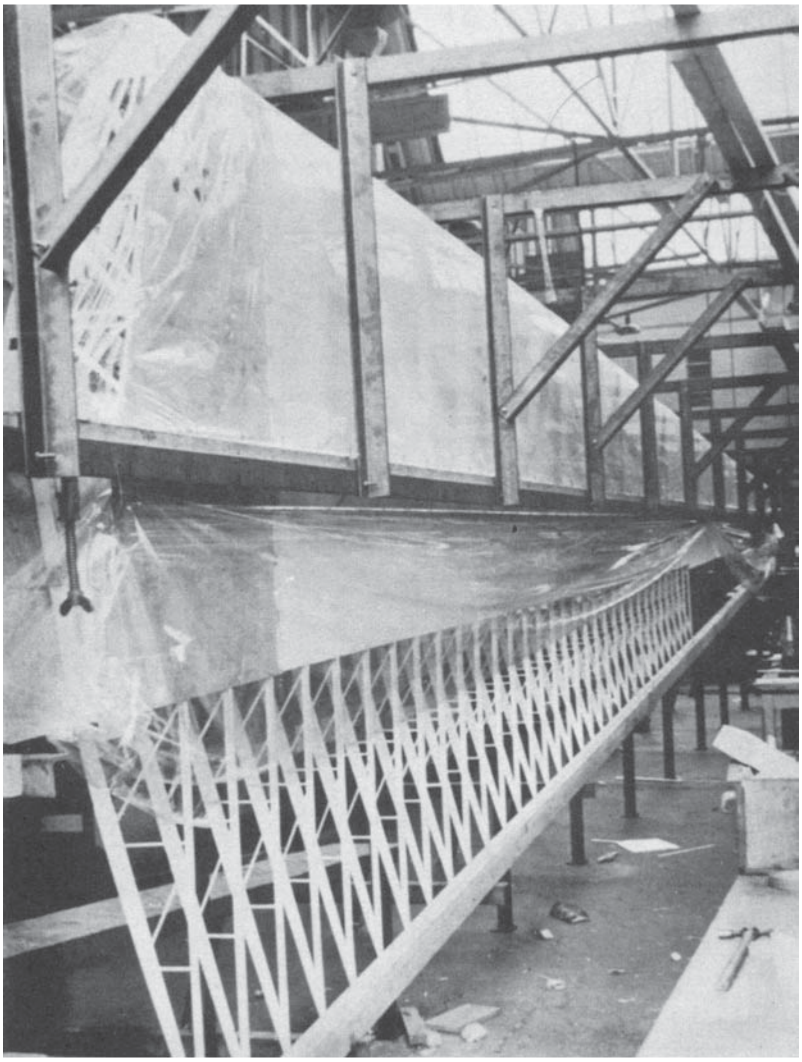

Fig 5: MK I wing in jig

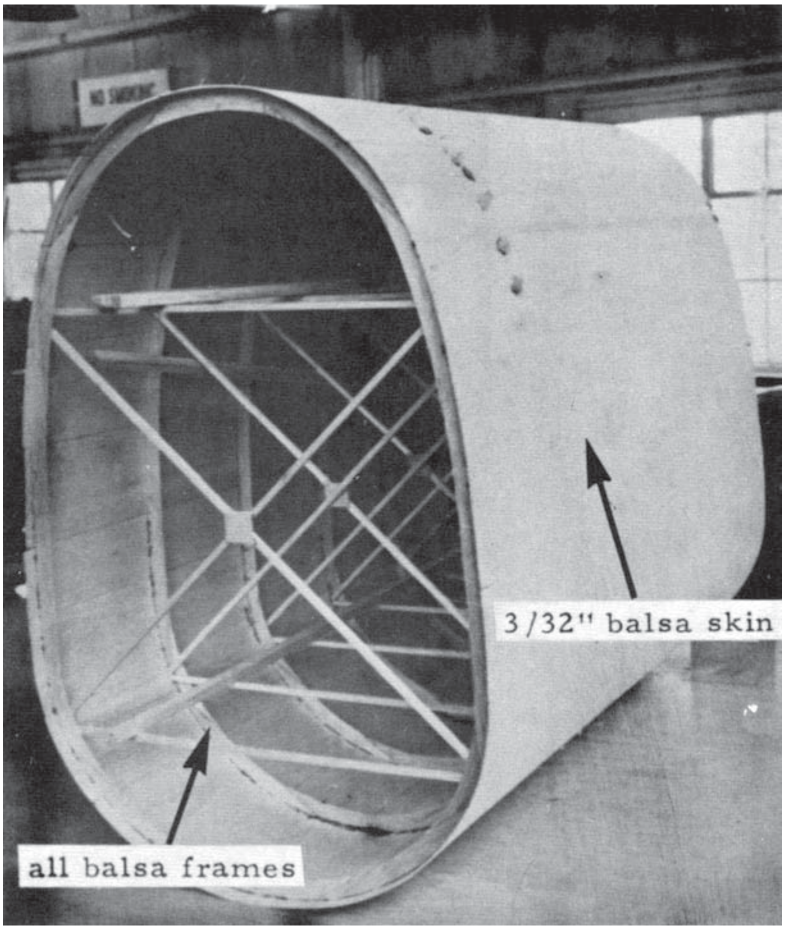

Fig 6: Fuselage test section

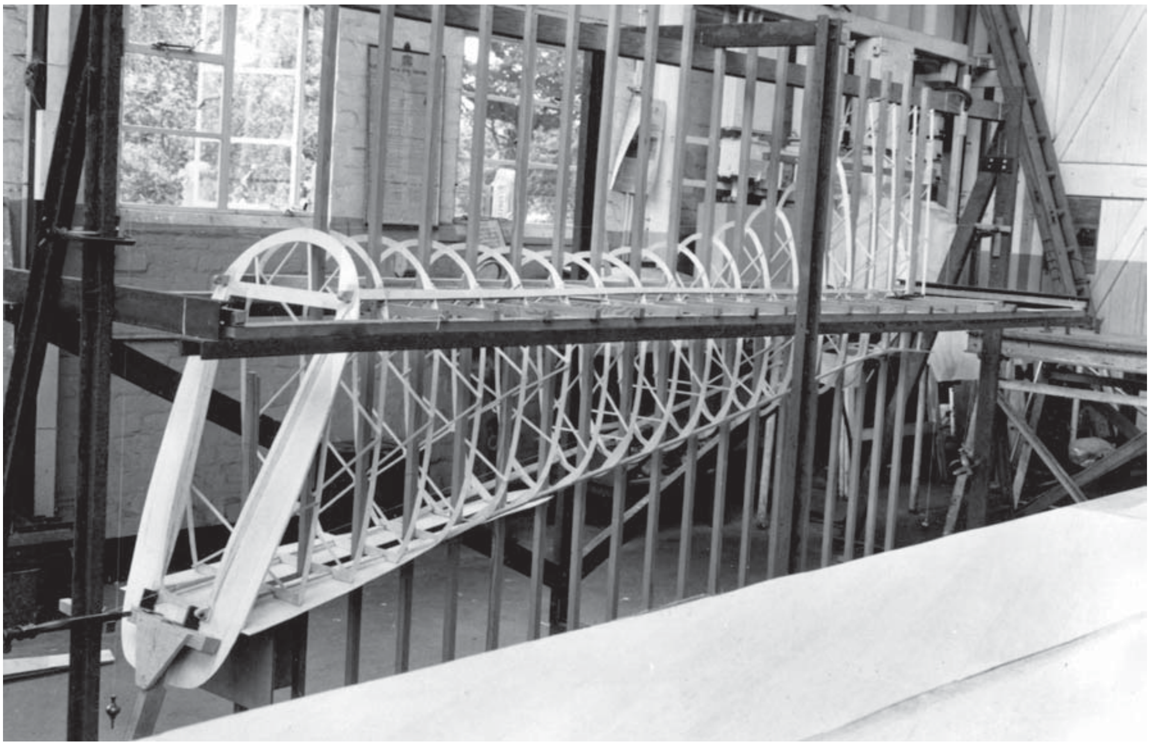

Fig 7: Fuselage prior to skinning

Fig 8: Pilot support structure

Fig 9: Transmission system components

FIG 10. Laminated Balsa propeller drive shaft.
3 x 1/32” laminations of Balsa at +- 45 degrees.

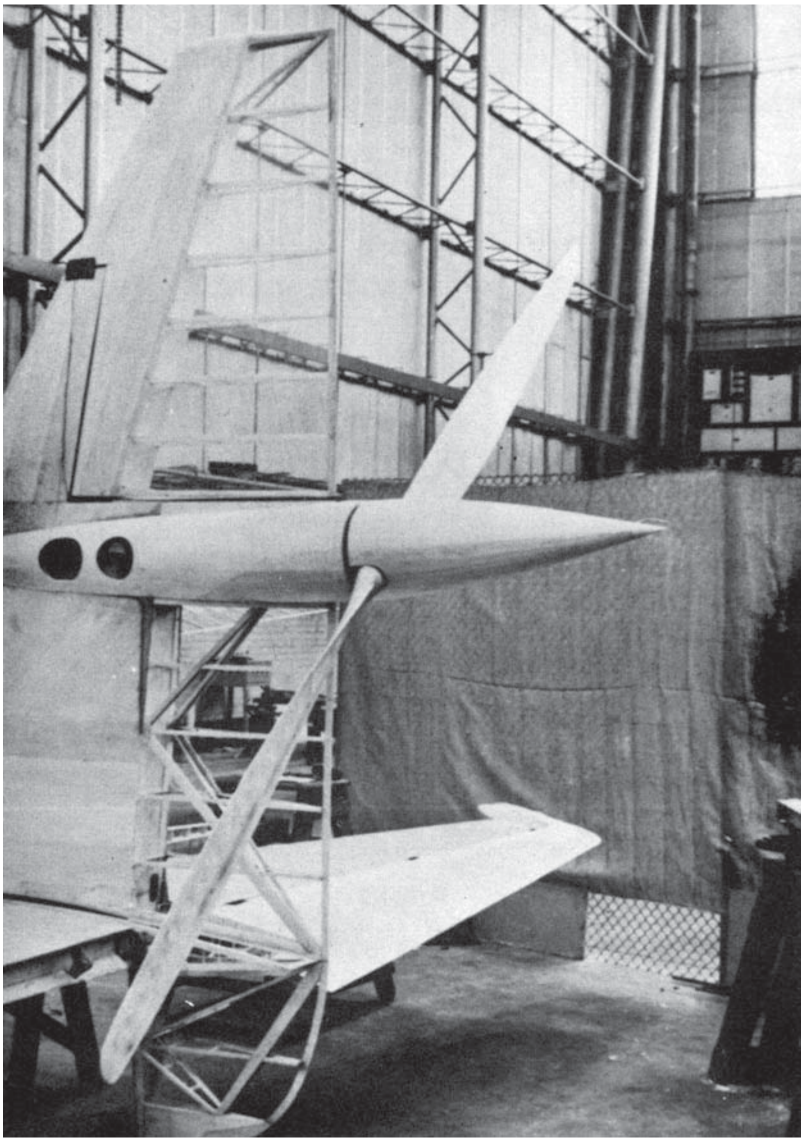

Fig 11: Propeller and empennage

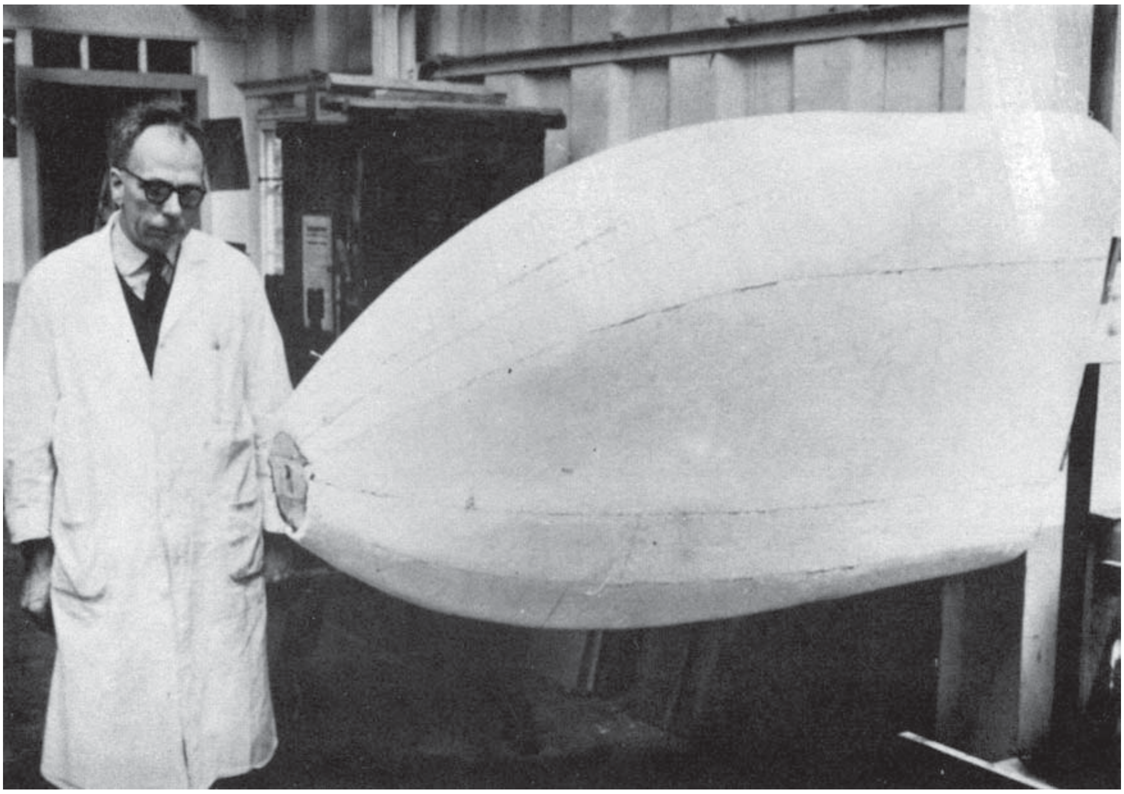

Fig 12: Experimental fuselage nose in polystrene foam

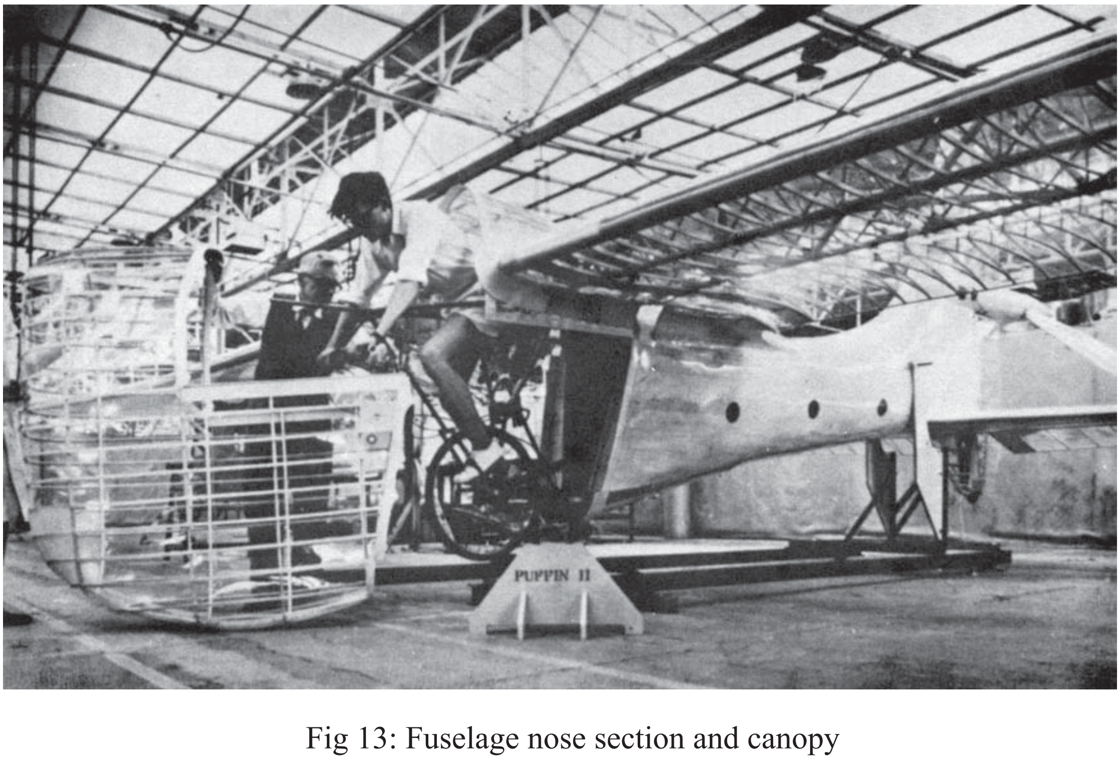

Fig 13: Fuselage nose section and canopy

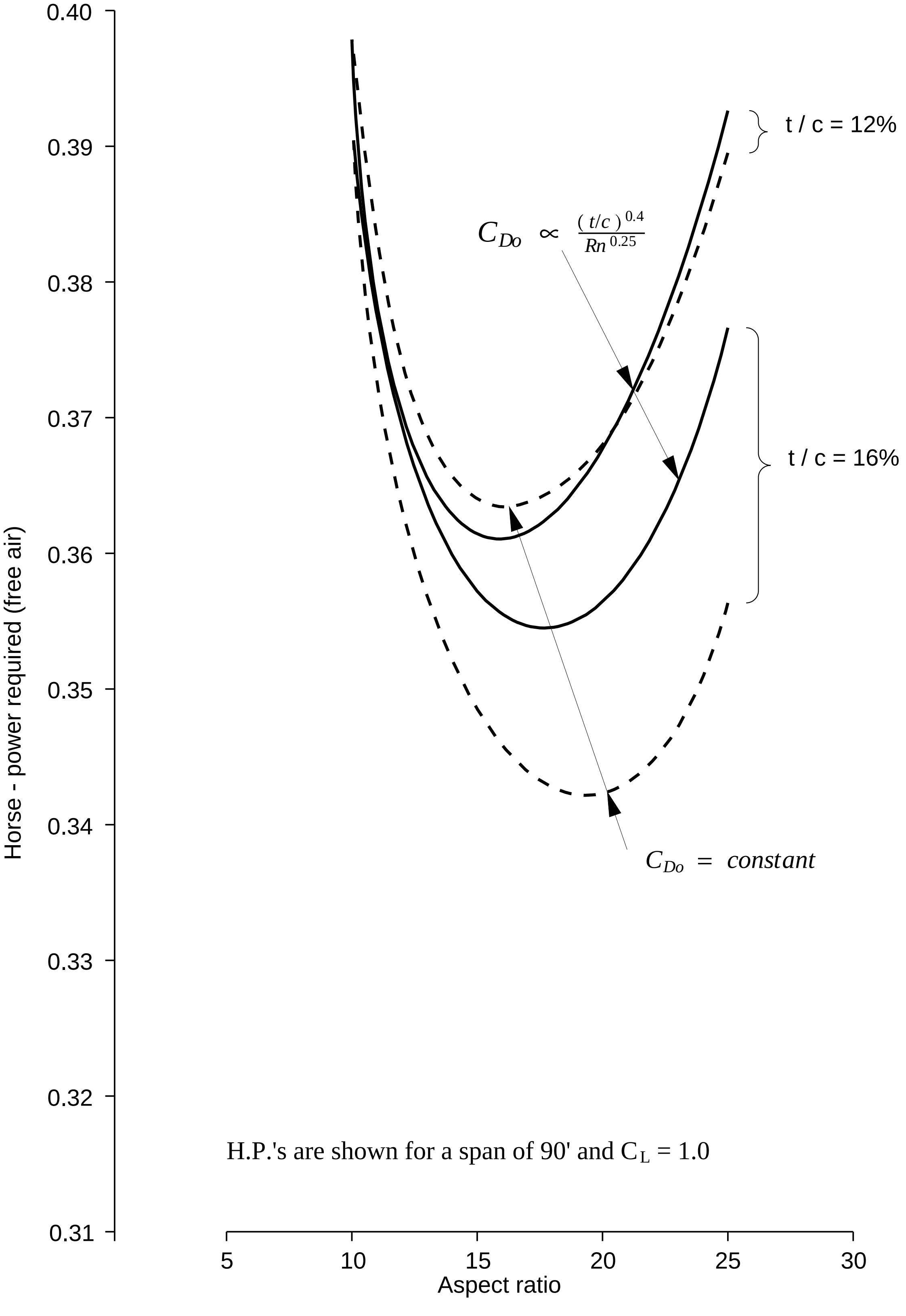

Fig 14: Effect of profile drag law on optimum structure parameters

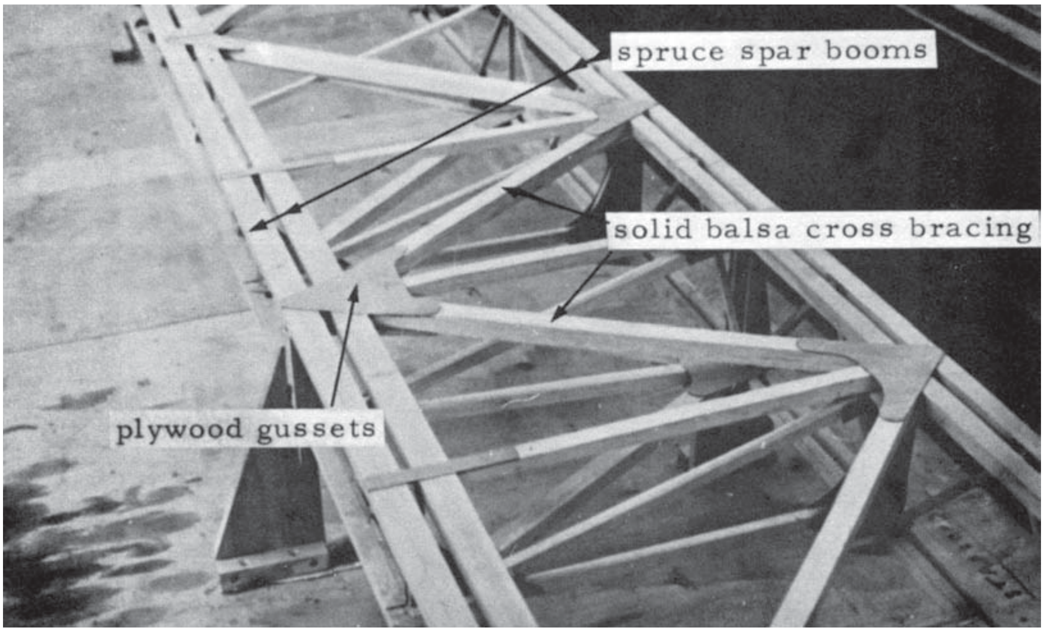

Fig 15: MK II centre section box

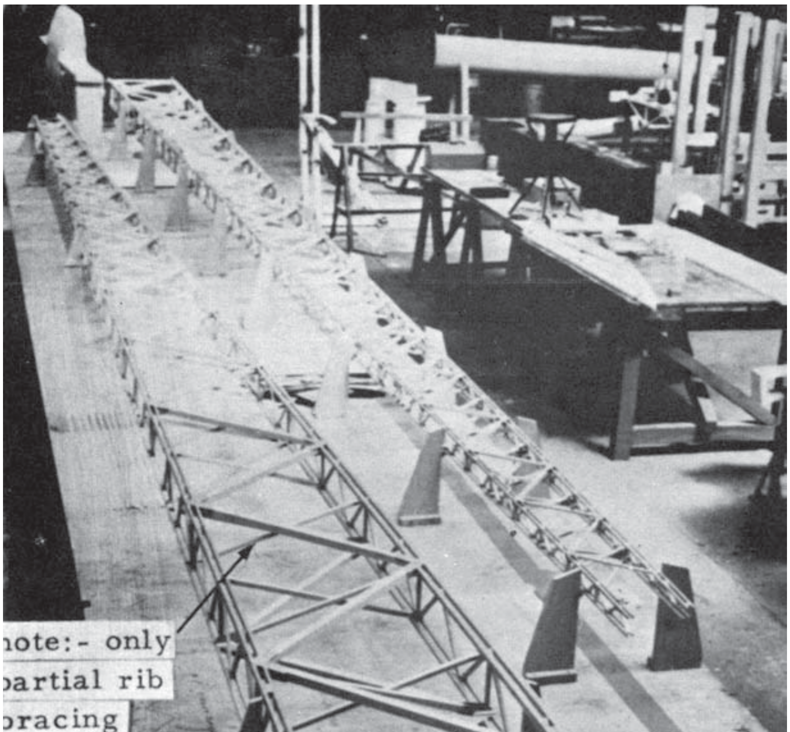

Fig 16: MKII outer wing boxes

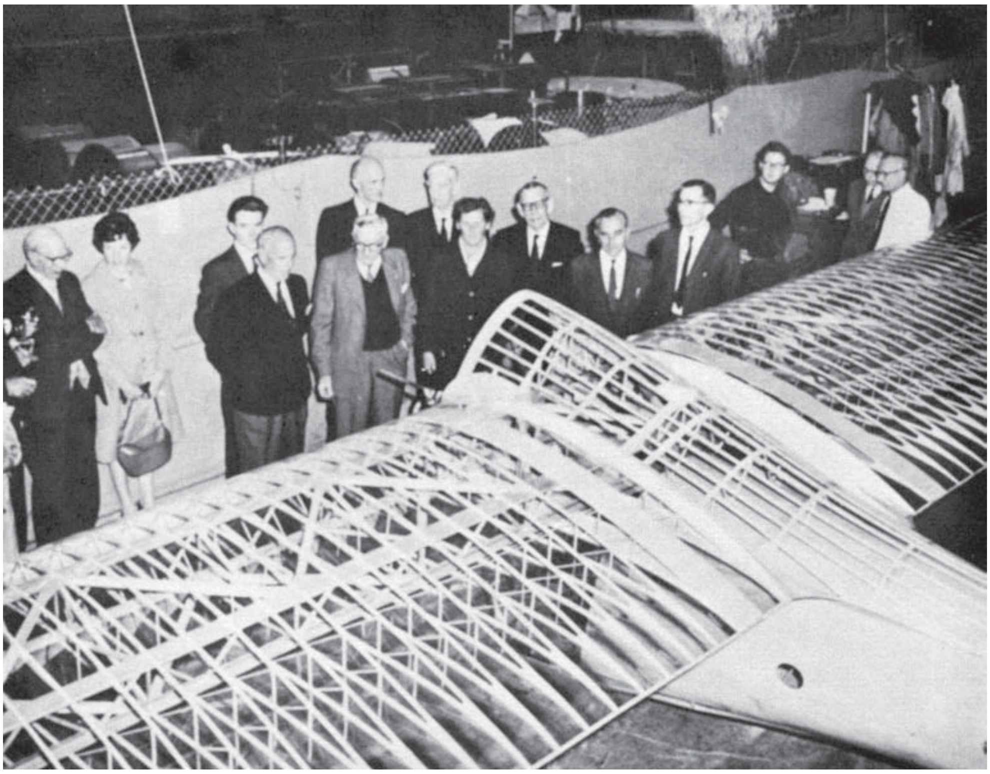

Fig 17: MK II inner wing construction

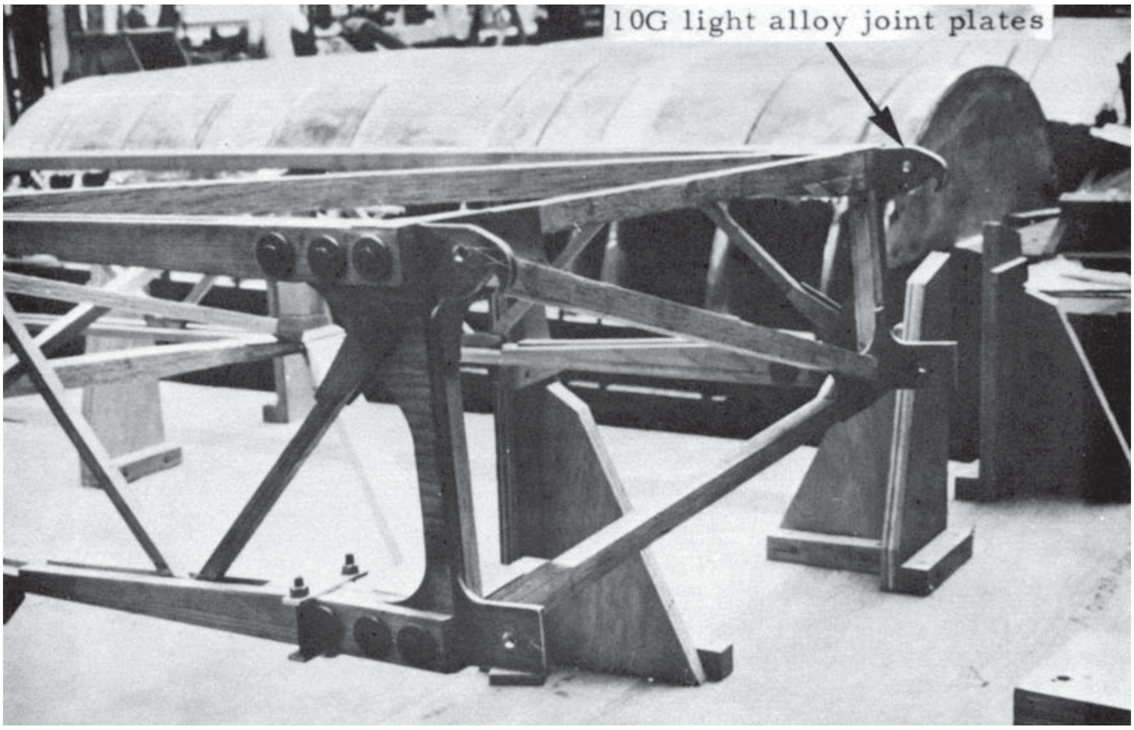

Fig 18: MK II dihedral joint fittings

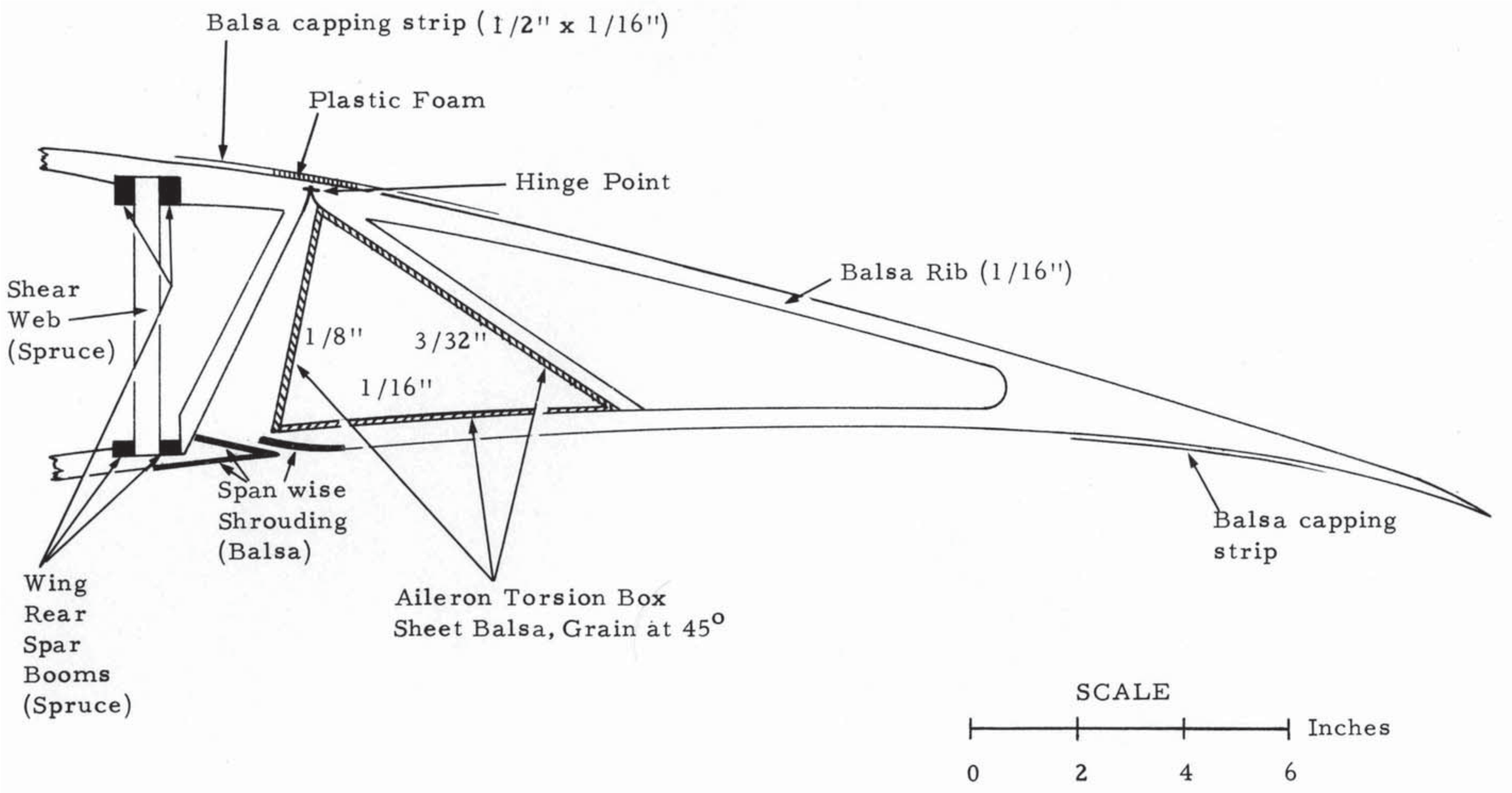

FIG 19: Aileron and rear spar cross section

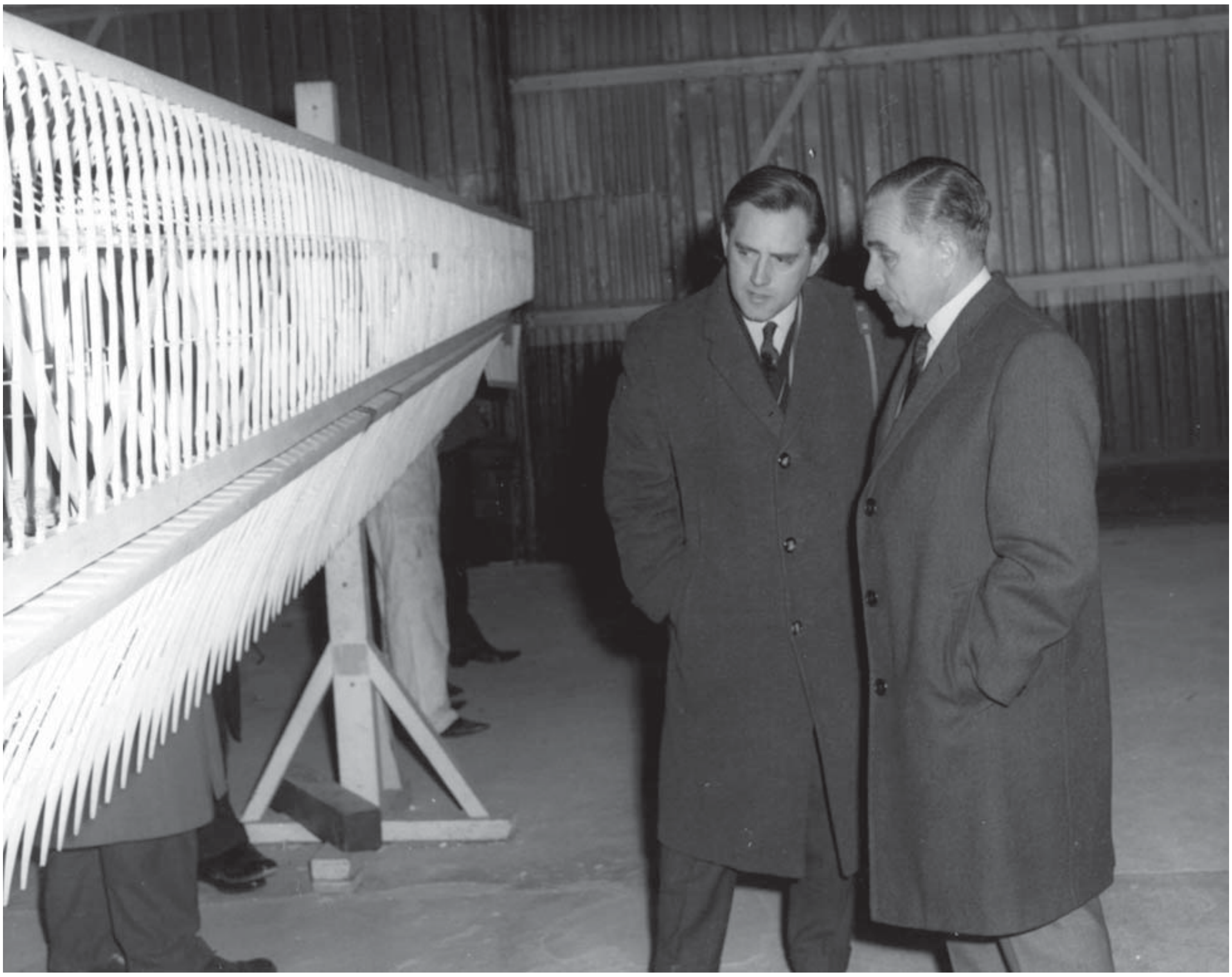

Fig 20: MK II Airleron and outer wing ribs