On the Weight of Sailplanes as a Function of their Main Geometric Parameters

By Dr. Ing. PIERO MORELLI

Presented at the 7th OSTIV Congress, Leszno, Poland, June 1958

The data on sailplane weights, geometric characteristics, load factors, etc., recently published by OSTIV [1], allow a study to be made on the correlation between the weight of sailplanes and their main geometric parameters.

The OSTIV Data Sheets show a great variety of sailplanes: remarkable differences are found in the type of structure, construction material, undercarriages (retractable or not), flaps, airbrakes, etc.

All these items, which have undoubtedly their own influence on sailplane weight, may mask the effect that the geometric parameters exert on the weight itself.

It is possible, however, to select a sufficient number of comparable sailplanes.

The type of weight-geometry correlation that is intended to be shown here is for sailplanes of similar structure and made of the same material.

In other words, an answer to the following question is sought: What is the weight variation to be expected with a prefixed type of structure and material, varying the sailplane geometric parameters, such as the wing span and aspect ratio? What is the corresponding wing loading variation?

Such a question is quite a different one from that to which an answer has been given by other authors.

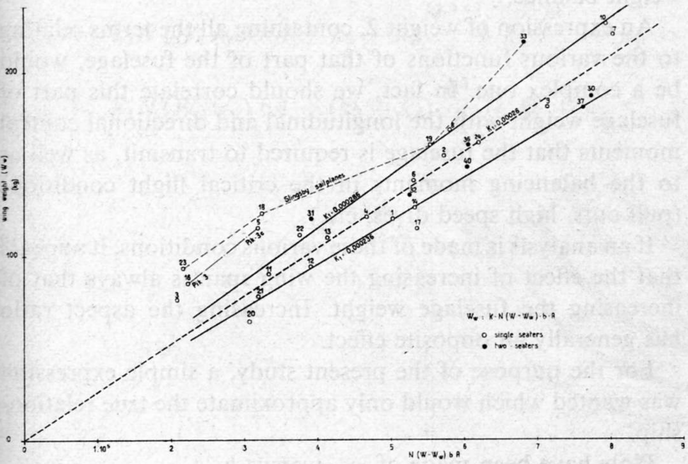

Fig. 1

In fact, in the remarkable works of K. G. Wilkinson [2] and W. Stender [3] a study has been made on the correlation between weight and geometry, on a statistical base, disregarding the differences in construction method of the various sailplanes. In other words, the fact that in a larger span sailplane, for instance, more developed structural methods and possibly different materials are employed, is accepted as a normal trend of the designer.[1]

It is believed, however, that it is a matter of interest to the designer to know what are the weight variations to be expected, varying some geometric parameters of the sailplane (as considerations on its aerodynamic performance, for instance, might require) *in the case that*, for reasons of cost, production, repair facilities and others, *he has made the choice of a certain type of structure and material.*

Wing weight

Considering separately the various sailplane components, our attention can be drawn first to the wing weight, that is the most important element in the weight breakdown of a sailplane.

A simple formula that G. Gabrielli [5 and 6] has given for the weight evaluation of metallic cantilever motorplane wings has been tried in our case:

$$w_W = k_1 \, N \, W \, b \, A$$

in which: w_W = is the wing weight,
k_1 = a coefficient depending on the material, on its degree of utilisation, on the type of structure,
N = ultimate load factor,
W = aircraft gross weight,
b = wing span,
A = wing aspect ratio.

In the case of sailplanes it is not possible to neglect the alleviating load due to wing weight that is too great a part of the total weight. Consequently, $W - w_W$ is put in the place of W:

$$w_W = k_1 N \, (W - w_W) \, b \, A \tag{1}$$

This formula has been checked in the case of sailplane wings of classical architecture and type of structure: cantilever wings of wooden construction, root thickness-chord ratio of 15 ÷ 18 %, taper ratio of 0.3 ÷ 0.5.

The plot of w_W versus $N\,(W - w_W)\,bA$ is given in figure 1, for single-seater and two-seater wings. The numbers correspond to the sailplanes listed in table 1.

A satisfactory agreement has been found with actual data. Two straight lines may be drawn, corresponding to values of $k_1 = 0.000236$ and $k_1 = 0.000286$, a mean value being $k_1 = 0.00026$. The lower value applies to single spar wings with a plywood covered torsion resisting leading edge and fabric covered in the remaining part (the Weihe wing, as an example). The higher value applies to plywood covered wings, with a close rib spacing, as those aiming at much laminar flow (the Eolo and Veltro wings, for instance).

The wings under consideration may differ in several details which obviously have an influence on their weight and partially justify the scattering of points in figure 1: the type of airbrakes, to have or not flaps, the type of wing junction (two-piece, three-piece, one-piece wing), and others.

The *thickness-chord ratio* (t) of the wing sections is not accounted for by formula (1). In current formulas [6] wing

[1] Interesting remarks on these weight-geometry correlations have been made by B. S. Shenstone [4]

weight, in general, is claimed to be inversely proportional to t. A plot has been made of w_W against $N(W - w_W)\, bA\, 1/t$, but the scattering of points was not at all reduced with respect to figure 1. This would suggest that, in our case, the weight reduction of bending resisting material due to an increase of t, is approximately compensated by the weight increase of plywood skin and spar webs (the thickness of which cannot be reduced below a certain limit), of the ribs and other minor items. In any case, it is believed that t has not a major effect on the weight of sailplane wings, unless possibly in the case of extreme values of t, as points 20 and 21 in figure 1, relating to D-34 and D-34b sailplanes (having a 21 % thick wing over the whole span) would suggest.

Three *ultimate load factors* (N) can usually be distinguished on a single sailplane, at a given gross weight:

1. the ULF on which structural calculations are based,
2. the ULF by which compliance with the regulations is demonstrated,
3. the effective ULF, as resulting, for instance, from rupture static tests.

The last value is generally unknown, sailplane structures being rarely subjected to rupture tests.

In some cases, there is a remarkable difference between values 1 and 2: In fact, the strength requirements represent a minimum, and higher values of load factors than those specified are chosen sometimes, depending on the designer's personal judgement and experience.

A difference, moreover, certainly exists between the effective and calculated ULF, depending on the assumptions on which the calculations are based and on the limitations of calculation methods.

Of these three values of N, undoubtedly No. 2 is the less significant and, consequently, the less suitable to be introduced in formula (1); it is, however, the only one usually known.

It should be realized that the difference between calculated and effective ULF may vary considerably from one design to another; in figure 1 this results apparently in a scattering of points in a direction parallel to the abscissae.

A check on the validity of formula (1) is offered by the points corresponding to sailplanes of the same designer, it being reasonable to suppose in this case that the difference between the effective and certificated ULF is a constant. Thus, the points should lie on a straight line parallel to that corresponding to formula (1). This is approximately verified in the case of Slingsby sailplanes (points 23–18–19–33).

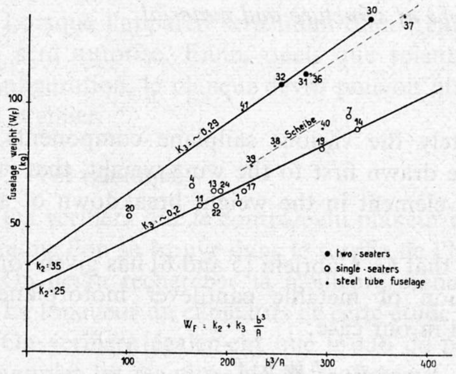

Fig. 2

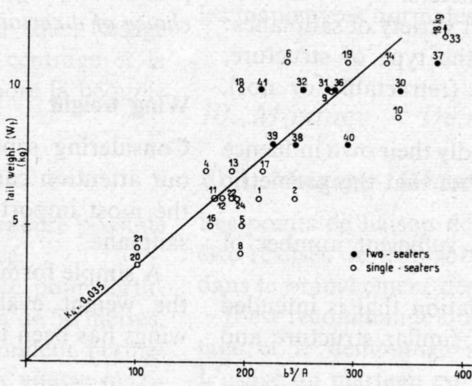

Fig. 3

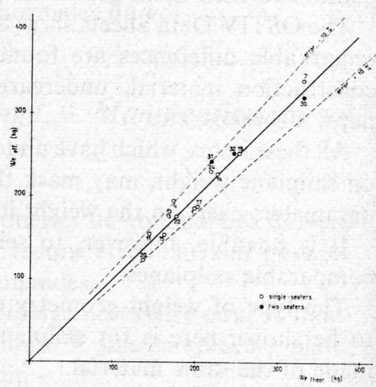
Fig. 4

Fuselage weight

The fuselage weight may be considered the sum of:

1. a constant term (relating to the part of the fuselage containing the pilot: cockpit, canopy, cockpit controls, etc.),
2. a term depending on the wing geometry (mainly the span and the aspect ratio),
3. a term depending on the sailplane gross weight (undercarriage).

The evaluation of the first term has been made by a graphical extrapolation (figure 2), as it will be shown later.

The weight corresponding to the second term is relating to the tail boom that must be long enough to supply the required balance and control moments but, to a certain extent, also to the fuselage front portion that must be as much longer or heavier as it is the rear part, for reasons of weight balance.

An expression of weight 2, containing all the terms relating to the various functions of that part of the fuselage, would be a complex one. In fact, we should correlate this part of fuselage weight with the longitudinal and directional control moments that the fuselage is required to transmit, as well as to the balancing moments in the critical flight conditions (pull outs, high speed dives, etc.).

If an analysis is made of these various conditions, it appears that the effect of increasing the wing span is always that of increasing the fuselage weight. Increasing the aspect ratio has generally an opposite effect.

For the purpose of the present study, a simple expression was wanted which would only approximate the true relationship.

Plots have been made of w_{fus} versus b,

$$\frac{b^2}{A}\ (= S),\quad \frac{b^4}{A^2}\ (= S^2),\quad \frac{b^3}{A}$$

A little dispersion of points has been found in the plots versus

$$\frac{b^4}{A^2} \text{ and } \frac{b^3}{A} \cdot \quad \frac{b^3}{A}$$

has been retained as a more suitable parameter (figure 2).

Undercarriage weight (part 3) is a small part of fuselage weight and is not considered separately here. It results therefore included in the other two items, this being considered permissible in a general study of this kind.

Data on vertical tail weight are not available. This weight is therefore to be considered as included in part 2 of fuselage weight.

Figure 2 shows that, according to our assumptions, it is fairly approximate to express the fuselage weight as:

$$w_{fus} = k_2 + k_3 \frac{b^3}{A} \text{ (kg)} \tag{2}$$

where: $k_2 = 25$ for single-seaters,
$= 35$ for two-seaters,
$k_3 = 0.2$ for single-seaters,
$= 0.29$ for two-seaters.

Numbers in figure 2 refer to sailplanes listed in table 1. Only fuselages of fairly comparable structures have been considered in figure 2.

Horizontal tail weight

A plot of horizontal tail weight (w_t) versus b^3/A (figure 3) has shown that a straight line, corresponding to the equation

$$w_t = k_4 \frac{b^3}{A} \tag{3}$$

($k_4 = 0.035$), may be traced through the points, representing a great number of sailplane wooden horizontal tails (table 1).

Useful load

The weight of the pilot(s) plus parachute(s) and instruments is considered a constant:

$$w_p = 100 \text{ kg (single-seaters)} \tag{4}$$
$$w_p = 180 \text{ kg (two-seaters)}$$

Empty and gross weight

The sailplane gross weight *(W)* is finally written, summing up expressions (1), (2), (3), and (4):

$$(5)\ W = W_e + w_p = (w_w + w_{fus} + w_t) + w_p =$$
$$= k_1 N (W - w_w)\, bA + k_2 + k_3 \frac{b^3}{A} + k_4 \frac{b^3}{A} + w_p =$$
$$= k_1 N (W - w_w)\, bA + (k_3 + k_4) \frac{b^3}{A} + k_2 + w_p$$

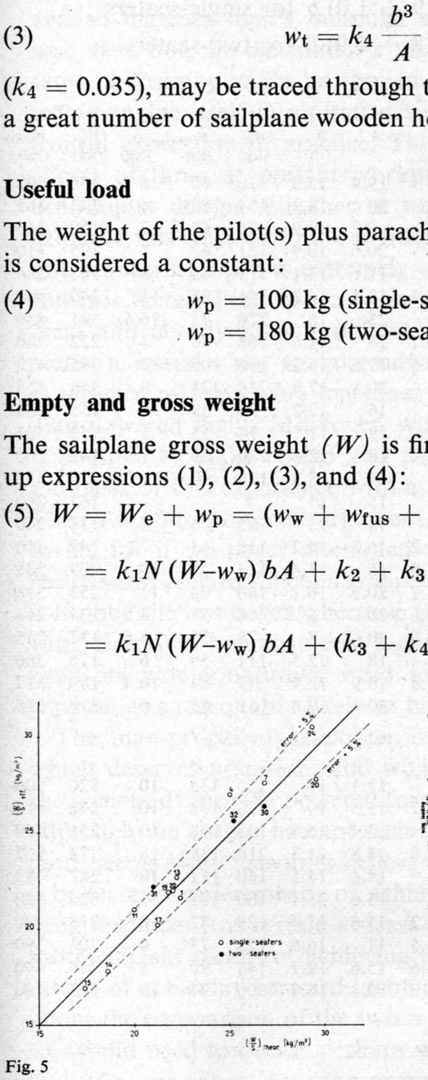

Fig. 5

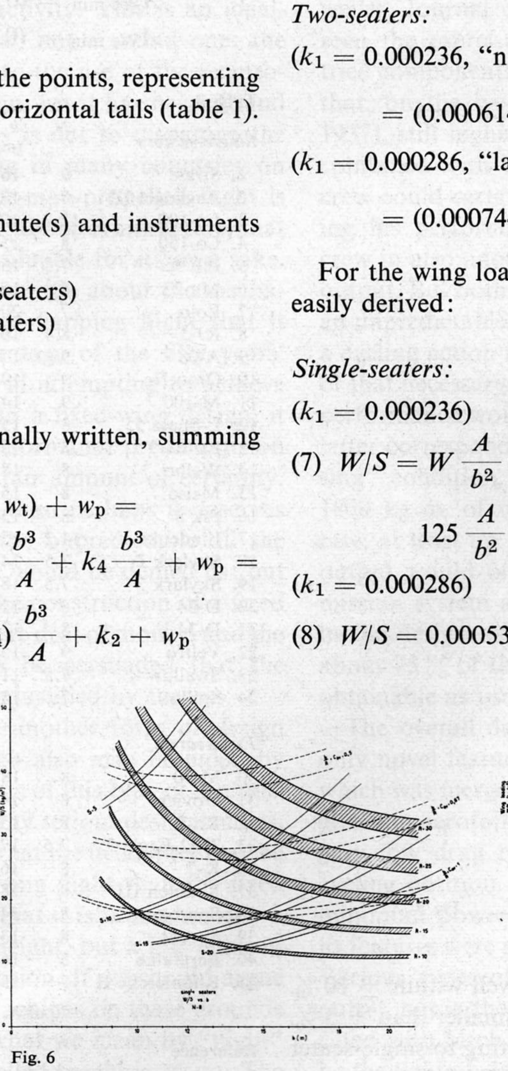

Fig. 6

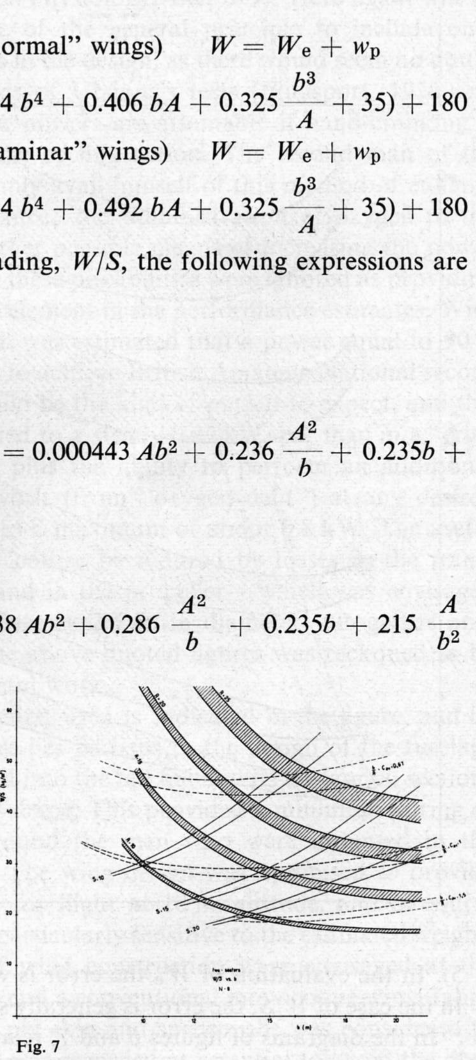

Fig. 7

It is, evidently:

$$W - w_w = (k_3 + k_4) \frac{b^3}{A} + k_2 + w_p$$

Expression (5) therefore becomes:

$$(6)\ W = k_1 N \left[(k_3 + k_4) \frac{b^3}{A} + k_2 + w_p \right] bA + (k_3 + k_4) \frac{b^3}{A}$$
$$+ k_2 + w_p = k_1 (k_3 + k_4) N b^4 + k_1 (k_2 + w_p) N bA +$$
$$(k_3 + k_4) \frac{b^3}{A} + k_2 + w_p$$

In the case of the wooden sailplanes considered in figures 1, 2, 3, the k coefficients assume the values already indicated.

The coefficient k_1 assumes the values 0.000236 and 0.000286 for "normal" and "laminar" wings respectively (see paragraph on wing weight and [7].

Correspondingly, the sailplane (empty, W_e, and) gross weight, W, may be expressed as follows (for $N = 8$):

Single-seaters:

($k_1 = 0.000236$, "normal" wings) $\quad W = W_e + w_p$

$$= (0.000443\, b^4 + 0.236\, bA + 0.235 \frac{b^3}{A} + 25) + 100$$

($k_1 = 0.000286$, "laminar" wings) $\quad W = W_e + w_p$

$$= (0.000538\, b^4 + 0.286\, bA + 0.235 \frac{b^3}{A} + 25) + 100$$

Two-seaters:

($k_1 = 0.000236$, "normal" wings) $\quad W = W_e + w_p$

$$= (0.000614\, b^4 + 0.406\, bA + 0.325 \frac{b^3}{A} + 35) + 180$$

($k_1 = 0.000286$, "laminar" wings) $\quad W = W_e + w_p$

$$= (0.000744\, b^4 + 0.492\, bA + 0.325 \frac{b^3}{A} + 35) + 180$$

For the wing loading, W/S, the following expressions are easily derived:

Single-seaters:

($k_1 = 0.000236$)

$$(7)\ W/S = W \frac{A}{b^2} = 0.000443\, Ab^2 + 0.236 \frac{A^2}{b} + 0.235b + 125 \frac{A}{b^2}$$

($k_1 = 0.000286$)

$$(8)\ W/S = 0.000538\, Ab^2 + 0.286 \frac{A^2}{b} + 0.235b + 215 \frac{A}{b^2}$$

Two-seaters:

($k_1 = 0.000236$)

$$(9)\ W/S = 0.000614\, Ab^2 + 0.406 \frac{A^2}{b} + 0.325b + 215 \frac{A}{b^2}$$

($k_1 = 0.000286$)

$$(10)\ W/S = 0.000744\, Ab^2 + 0.492 \frac{A^2}{b} + 0.325b + 215 \frac{A}{b^2}$$

A check of the above formulas has been made, comparing the real and calculated values of W_e and W/S (fig. 4 and

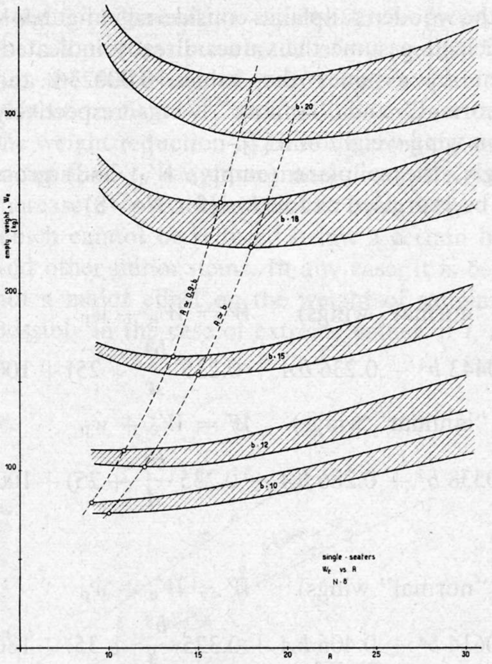

Fig. 8

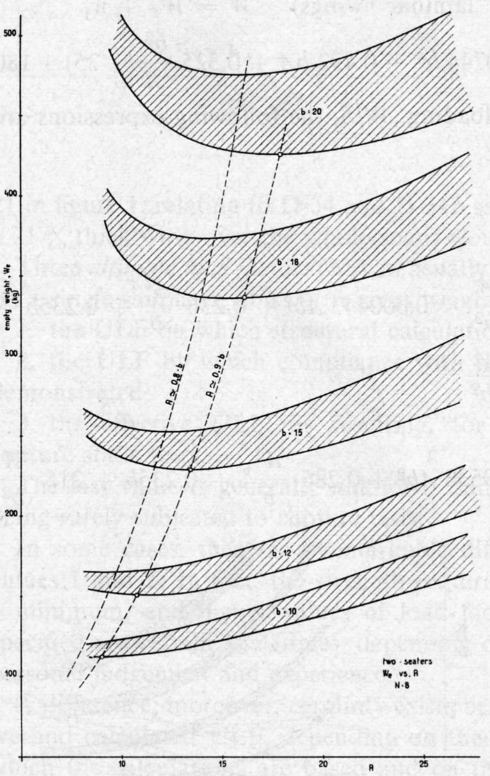

Fig. 9

5). In the evaluation of W_e the error is well within $\pm$ 10%. In the case of W/S, the error is generally smaller than $\pm$ 5%.

In the diagrams of figures 6 and 7, relating to single-seater and two-seater sailplanes respectively, W/S is plotted versus b at constant aspect ratio (A), at constant wing surface (S), and at constant mean geometric chord $(c_{av} = b/A)$. The two curves traced for each value of these geometric parameters (A or S or c_{av}), correspond to the two values of k_1, in the expression for wing weight. The two curves may then be considered to be the lower and upper limit of the weight of a great variety of sailplanes.

Two interesting remarks can be made, resulting from these diagrams:

1. The curves at constant A show a *steady decrease* of W/S with span, in the interval considered of $b = 10 \div 20$ meters. They would show a minimum value at wing spans above 20 m.

2. If the wing leading is to be maintained constant, an increase of span must be accompanied by an increase of aspect ratio. The condition of constant W/S *corresponds approximately to* c_{av} = *constant.*

Plots have also been made of W_e against A (fig. 8 and 9), at constant values of b. As in the previous diagrams, two curves have been traced for each value of b, corresponding to the two values of k_1 in the expression of wing weight.

These curves show minimum values of W_e, at values of A which are easily determined equating to zero the partial derivative

$$\left(\frac{\delta W_e}{\delta A}\right) b = \text{const.}$$

of equations (7), (8), and (9), (10), thus obtaining:

$$A_{We\ min} = (0.9 \div 1.0)\, b \text{ for single-seaters,}$$

$$A_{We\ min} = (0.8 \div 0.9)\, b \text{ for two-seaters.}$$

Table 1

Single-seaters	N	b (m)	A	S (m²)	w_w (kg)	w_{fus} (kg)	w_t (kg)	W_e (kg)	W_{max} (kg)
1. Strale	9	16	19.4	13.3	120	60	6	186	300
2. Zugvogel III	8	17	20	14.5	154	83	6	243	365
3. Lo-100	12 ?	10	9.2	10.9	76	67	7	150	265
4. Lo-150	8	15	20.6	10.9	121	67	7	195	310
5. Pik 3c	7.5	15	17.1	13.1	115	45	5	165	280
6. Mg-23	8	16.4	18.5	14.2	141	88	11	240	360
7. Eolo	7	20	25	16	220	95	(16.5)	341	450
8. RJ-5	8.4	16.7	24	11.6	168	50	4	222	340
9. A-08	9	17.6	19.6	16.2	180	105	10	295	410
10. Orao IIc	9	19	20.3	17.8	226	121	9	356	455
11. M-100	9	14	16	12.2	90	59	6	155	255
12. L-Spatz 55	8	15	19	11.7	94	53	6	153	265
13. Ka-6b	8	15	18.1	12.4	110	65	7	182	300
14. Weihe	8	18	17.7	18.3	126	90	11	227	335
15. Meise	8	15	15	15				162	290
16. Pik 3	8	13	13	13	85	45	5	135	240
17. Ilindenka I	11.2	15.2	16.2	14.2	115	65	7	187	310
18. Skylark 2	7.5	14.6	16	13.4	123	76	10	209	308
19. Skylark 3	7.5	18.2	20.5	16.1	160	82	11	253	358
20. D-34	8	12.6	20	8	64	55	4.2	123	216
21. D-34 b	8	12.6	20	8	78	55	3.6	137	235
22. Veltro	9	15	18	12.5	111	59	6	176	266
23. Swallow	7.5	11.8	10.9	12.9	93	84	10.4	187	317
24. Spillo	7	18	30	10.8	161	65	6	230	325
Two-seaters									
30. M-30	8	18	17.1	19	186	134	10	320	500
31. Gövier	8	14.7	11.5	19	120	112	10	242	410
32. Ka-2	8	15	13.4	16.8	133	108	10	251	460
33. T-42 Eagle 3	7.5	17.8	14.8	21.3	216	138	18	372	562
36. K-7	8	16	14.6	17.5	160	112	10	282	485
37. Kranich III	8	18	15.6	21.1	180	135	11	326	520
38. Sperber	8	14.2	11.6	17.4	128	82	8	218	400
39. Specht	8	13.5	11	16.6	123	75	8	206	390
40. Bergfalke	8	16.6	15.6	17.7	148	90	8	246	440
41. Rhönlerche II	7	13	10.3	16.3	100	97	10	207	400

Reference

[1] "THE WORLD'S SAILPLANES", published by OSTIV and Schweizer Aero-Revue, first edition, Berne 1958.

[2] K. G. WILKINSON, "The Design of Sailplanes for High Performance", Aircraft Engineering, Sept. 1951.

[3] W. STENDER, "Entwurfsgrundlagen für Segelflugzeuge", Weltluftfahrt, Dec. 1952.

[4] B. S. SHENSTONE, "Progress in Two-seater Sailplane Design", Aircraft Engineering, Jan. 1953.

[5] G. GABRIELLI, "Note sul progetto dei velivoli", L'Ingegnere, Sept. 1949.

[6] G. GABRIELLI, "Peso teorico e peso reale delle ali a sbalzo", L'Aerotecnica, fasc. 1°, 1953, vol. XXXIII.

[7] P. MORELLI, "Study, Construction and Flight Tests of the High Performance Sailplane CVT-2 'Veltro'", Schweizer Aero-Revue, Jan. 1957, and OSTIV Publ. IV.