The human powered aircraft Velair Design details and result of structural, prop and flight tests

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Abstract

The human powered aircraft Velair, (an acronym for velo = bicycle and air) has been designed in 1986, built in 1987 and has been flown since 1988 in Germany and France (Paris Air Show 1989, Paris Air Follies 1990, airport Miinchen II).
Many tests for fabrication procedures, material and structural behaviour and flight test gave confidence in the new software design tools written for aeroelastic wing design, prop design and performance prediction. These results could be a valuable basis for similar applications so that the most revealing of them will be presented here.
In spite of the constraints of a hobby project (small financial and time budget) it was possible to put together a practible and robust aircraft that is still in 'service' today. In the winter 88/89 the aircraft was subject to an optimization round (referred to as the '89' version). With a new cantilevered wing, a new rudder and some other details, the empty weight has been reduced to ~ 30.5 kg, also aerodynamics could be refined a bit. Velair is a relatively small HPA and had to fit into workshop, transportation, and budget constraints. The cantilever wing makes it quick and easy to assemble.
A brief review of some design features, wing spar layout, fabrication and test, prop design and test, and flight test results are presented (partly on slides).

1 Wing and spar design

1.1 The '88' wing

After many months of research on wing structure layout, load assumptions, preliminary designs and sizing, aeroelastic analysis, coupon testing, the I-beam spar with sandwich nose and ribs structure type was selected with an ultimate design load of 3 g.
The structural layout was then quickly calculated and the fabrication of the wing began. The D-spar only (spar, front ribs, shell, in plane load struts, root ribs and fuselage connector) was tested to minimize time and money loss in case of a failure. Well: it failed, at about 1.2 g ! The reason was that no trailing edge was taking the inplane loads (at high angle of attack) that now were compressing the soft shell in the nose. The good news was, only the shell buckled so that the spar could be reused. The shell was replaced partially and extended to the trailing edge to form a second cell to increase torsional stiffness. This was not planned originally because of unattractive weight prediction, but now it was more important to get into the air. The extra weight was doubled by repair patches and the later insertion of shell panels. This wing was tested to 1.3 g and flown with no further problems for 2 years. It is now being recycled for a solar powered aircraft. Because of higher loads it has even been retested with a load of 170 kg with no damage ! During the fabrication of the caps a few layers were added 'to be safe': the result was a stiff and solid wing.

1.2 The '89' wing

After Velair's first flight season there was time for a wing redesign effort to search for improvements. The spar options were reconsidered and the decision to build a tube spar type wing was based on the good experience with the tube spars in the tail surfaces and the drive

shaft.
The spars are thin carbon prepreg tubes with 45 degree layup reinforced by 0 degree caps in the bending plane. Because no theoretical prediction method for buckling of the cap reinforced tube was available, all the spars were tested to failure.
The methods used for the test of the tail surface spar and the outer wing panel were 3-point and 4-point bending in a testing machine, whereas a 6.50 m long section of the centre wing spar was mounted with the original fuselage attach to the ground. For simplicity this spar was loaded with a single force instead of the real shear force distribution, but this error was acceptable as the spar failed at 3.34 g. This appears to be plenty of safety but the dominant design parameter in this case is stiffness and not strength. The spar was designed to have a tip deflection smaller than 2 m, and the very desirable HM- (high modulus) fibre prepregs could not be afforded. Table 4 shows a summary of these tests.
Loads, strains and displacements were recorded during the tests. Figure 1 shows the deflection at the connector and at the end in function of the end load. The deflection at failure of the spar was high. The extrapolation to full span would give an ultimate wing tip deflection of more than 6.5 m. The failure load corresponds exactly to prediction but conservative assumptions for the allowables (Qc = 600 MPa) had been made because of the smaller diameter of intermediate modulus fibers what apparently gives lower compression strength as compared to the standard T300 fiber, and also because of the interaction between the 0 and the 45 degree layers. Another goal of the test was to validate the calculation model for structural flexibility. A couple of coupon tests (tension an d 'Celanese' compression) showed that a lower than catalog value would have to be expected. 150 GPa turned out to be the right figure for the T800 prepreg and our fab methods. The flexible model was later compared to in flight deflection and showed good agreement in bending (diagram 1). The wing tip deflection of 1.95 m did not raise buckling problems on the upper wing side for the nose shell or the skin. Of course wrinkles have absolutely to be avoided to maintain laminar flow as long as possible along the airfoil cord.
A survey of the two wings is given in table 3.

1.3 Fabrication time

Fabrication time for the two wings is presented in table 5 (The figures do not include time to get materials and stuff, prepare tools and devices which also adds up when done for the first time). The second wing was so much faster and easier to make, besides a steep gradient in the learning curve it was more a 'plug and play' type construction and the following manpower consuming task types were eliminated:

- laminating of big sandwich panels
- application of vacuum (bagging, tightening)
- adjusting work (caps on web, wing connectors, ribs on web, shell)

1.4 Fabrication methods

For the '88' ribs trapezoidal styrofoam blocks between aluminium airfoil templates were hot wired, then reinforced with a layer of carbon fabric as cap and finally band sawed to the desired thickness.
The I-beam caps were laid up in one shot (3 people working 25 hours with one break for a midnight soup and another for the sunrise celebration, the schedule for the booked autoclave run at MBB/Donauw6rth beeing firm).
The webs were vacuumed Rohacell/glass strips bonded to the caps with angle layers and accurately adjusted at the wing breaks.
The '89' ribs were cut on a numeric-controlled water jet machine which also allowed to cut the hole for the circular spar and an offset for the shell very easily. The accuracy was perfect and the styrofoam block for each rib set was cut in only 60 seconds. The catch was the prehistoric control computer that took 14 minutes to zoom the data set to the required cord (fortunately it was not running on punched cards).
The prepregs for the tube spars were cut to strips of exact required width and wrapped

around or along an aluminum tube mandrel. The filament winding machine we used to wind the mandrel was intended for 5 m tube length, but after some ‘minor’ modifications to the workshop wall it could handle 8 m long tubes. After some practice we were able to build one spar per day including the cure in a self made, heat gun fired oven (also 8 m long). The use of prepregs meant a new quality of work, no more mess with resins, clean and accurate. The only catch is the required storage temperature of -18 degrees C if they are not delivered just in time. Both systems were easy to use and had good tack, even the conventional 175 degrees C (Fiberite) system.
The trailing edge was a triangle shape Rohacell strip sandwiched between carbon or Kevlar UD’s, and the shell was again the 3 mm polystyrene foam, but this time without any glass faces. The pressure side was covered 8 % and the suction side 70 %.

2 Weights

As shown in table 3 the difference in weight was considerable. The reasons for the weight saving in the second wing in spite of a thinner airfoil, higher aspect ratio, a non optimal structure (cylindric tube versus I-beam) are the following:

1. the construction was much more precise with very thin bondings, tight fits, no gaps to fill, no divided ribs, no blind bonding.
2. the stress level was higher, no more ‘chicken’ layers.
3. no repairs, no design changes (1 cell -+2 cell).
4. the use of a prepreg with a stiffer fibre (T800 vs T300).

The weight of Velair 89 was actually overpredicted with the theoretical model by 1.9 kg (obviously a rare event in 1994 Intemational Human Powered Flight Symposium l it has been replaced meanwhile

aircraft design history) which was the result of constant weight chasing and balancing of optimization, and time and cost required. The

wing	15.960
fuselage	8.082
landing gear	0.763
propulsion	2.986
controls	1.328
rudder	0.531
elevator	0.909
instruments	0.108
total empty weight	30.667 kg

Table 1: Weight summary for Velair 89

aircraft weights are summarized in table 12. There is still some weight saving potential because not everything could be optimized in the time available. This might be done if one of these days some time is left.

3 Roll control

Roll control via conventional aileron on the ‘88’ version worked fine but it was felt that the rotating wing tip had more advantages: clean airfoil, no torsional load with deflected aileron, easier to fabricate at lower weight. The disadvantage is the gap with associated lift loss and increased (induced, turbulence, separation) drag. In terms of flying quality the aileron version revealed to be slightly more reactive what is specially apparent at the begin of the take off run at low speed.
No aileron at all is impossible when the aircraft is to be operated from airfields (of finite width), bad experience was gained with the two Pelargos aircraft that did not have ailerons and were difficult to control during cross wind take off.

4 Propeller layout

The prop was designed using the methods of Larabee [1] (later compared to Adkins and Liebeck [2], which gave similar results for the low loading). Some data are shown in table 2. A static prop test with an electric motor was not too difficult to perform for a first glance at the prop static thrust (which is not a design

prop diameter	2.80 m
prop speed	190 rpm
aircraft speed	8.4 m/s
absorbed power	300 W
advance ratio	0.94
C_p	0.048
C_T	0.046
thrust	33 N
torque	16 Nm
calculated efficiency	89%
activity factor	46 / blade
airfoil	FX 60-100
beta 75	28.7
prop weight	713 g
hub	aluminum, ground adjust
construction	molded carbon shell + spar

Table 2: Design data for the Velair prop

goal but still a useful figure to find out if a self powered take off is possible at all with no. prop pitch control) and structural integrity for the required torque and rpm range.
But to validate the design software for the advance ratio of interest it was of course necessary either to use a wind tunnel or to measure the moving prop. As a wind tunnel was not available at affordable costs we decided to mount a measurement jig on top of a car and record the data with our datalogger. Team member Martin Hubner built a sophisticated device with self made load cells to measure torque and thrust. The prop was driven by an old two stroke lawn mower engine coupled to the prop via belt drive. The data recorded were: shaft torque, thrust, calibrated air speed, rpm and temperature.
The results were nice for the absorbed power, but disappointing (in terms of data quality) for the evaluation of thrust and efficiency: the thrust measurements were not accurate enough because of the bumpy runway that induced oscillations that were transmitted and amplified by the huge lever arm as they reached the thrust measurement element (to avoid interference with the car the propeller axle was positioned in a height of approx. 4.50 m above ground level). This uncertainty in the thrust data lead to the wide scatter in the efficiency results so that a conclusive result was not possible (see the confusion in diagram 3 and 5). Also the prop had to be operated in the wake of the spaceframe and the engine. The use of the two stroke engine revealed to be better than expected, the belt drive worked fine and torque measurements and thus the absorbed power measurements gave smooth figures.

5 Pilot

At the beginning of the project a couple of ergometer tests were run at the University of Tiibingen3 to get figures about the actual available pilot power. These were fully instrumented bicycle-ergometer rides with monitoring of heart rate, blood pressure, breath flow, and continuous breath gas and blood analysis. During these tests power was increased by steps of 50 Watt every 3 minutes until complete exhaustion. One of the results was the specific oxygen consumption that allows a good evaluation of the combustion efficiency. Such results were also published by Daedalus team members Bussolari & Nadel [3] and have been used for a comparison. One of their results was that a pilot is able of operating for 4 hours at 70 % of his maximum oxygen uptake.
The multitude of candidate pilots examined for the Daedalus team lead to a simple approximation for the available power in function of time that is shown in figure 6. The own results are recalculated from short distance hill races. It is safe to say the levels of exhaustion achieved there are way too high considering that simultaneously a fragile aircraft has to be controlled safely. Anyway the numbers give an absolute upper limit. The design power of Velair is 3.75 W/kg (pilot weight) resulting in an absolute power of 225 W for a 60 kg pilot. This power level should be maintainable for 2 hours, what has not been demonstrated yet (the ergometer

tests were done in a time of best shape, which was never again available after this aircraft was ready!).

6 Flight test

Since August 1988 approx. 110 flights have been completed on several airfields. The first time was dedicated to increase reliability, and to simplify the drive train (twisted chain). Since 1990 there was not one single problem left, the aeroplane was just flying and didn't see the workshop since.
In the fall of 1989 the first sensors were ready for flight data acquisition, specially the heart rate monitor that was a tricky piece of work. Some results are shown here for heart rate (figure 9) and aircraft speed (figure 10,11). Flying in windy and turbulent weather conditions is usually unpopular for HPA's and figure 11 shows a flight with a slightly turbulent wind of about 7 kn. Given a stall speed of ~ 27 km/h (15 kn) we see that the flight speed could drop quickly for a few km/h's and deccelerate uncomfortably close to stall. The maximum wind speed Velair has ever seen was 12 kn (during the Paris Air Show in 1989). But the wind was standing exactly on the nose and not too turbulent so that there were no problems with it. In general the pilot workload becomes much more intense with strong wind and a lot of aileron and rudder corrections increase the required power and make flying uncomfortable. Figure 10 shows conditions where there was almost no wind and we see that it was much easier to maintain the best speed of 31 km/h. In these conditions the plane flies on its own and requires only smallest control inputs.

7 Conclusion

Some test results found during the development of Velair have been presented. It could be demonstrated that the prediction of structure behaviour, strength and performances are in good agreement with the realized aircraft. Unfortunately lack of time prevented from a good intense training effort and this could never be improved: the aircraft projects that followed on were too fascinating and demanding allowing no more than a hobbyist training pace, some 3000 km/year, compared to the 16000 km/year (as an active amateur bike racer) when Musculair 2 was flight tested.
But the experience gained could be applied directly to the development of a serie of manned and unmanned high altitude aeroplanes used for atmospheric research, where light structures, low Reynolds number aerodynamics and high efficiency propeller design are required as well. A prospective analysis of the resulting opportunities for electric and solar airplanes was given in [4]. It was again Paul Mac Cready and his Aerovironment team who turned those dreams into reality and created the solar powered Pathfinder [5] which shows the radical approach of optimized solutions.

8 Acknowledgements

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Finaly my gratitude to the industry for giving this and that4, but specially to Atari Computer for the sponsorship and for having on the market in 1985 a fast and affordable computer that was and still is a very valuable tool.

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photography and videos), MBB Manching, airport Munchen II, abroport de Paris (runways), Polaroid (u.s. altimeter sensor)

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Peer Frank.

1994 International Human Powered Flight Symposium. AIAA Pacific Northwest Section and the Museum of Flight.

	D spar only	Velair 88	Velair 89
		geometry	
span [m]	21.0	21.7	23.2
area [m^2]		16.4	16.9
aspect ratio		28.7	31.8
airfoil		FX63-137 (13.7%)	PF 25 (12.9%)
drag @ C_L = 1.3		0.03327	0.02888
		structure	
spar		I-beam	tube and caps
cap material	Fiberite	HYE1048/T300	Ciba M10 /T800
web material	glass Rohacell		
ribs	Styrodur		Styrofoam
rib caps	carbon fabric		balsa strips
covering			12 micron Hostaphan
transport breaks		2	4
		weights	
spar	5.912	5.912	9.092
shell	3.97	8.471	1.526
ribs	0.665	1.710	1.526
IPL struts	0.518	0.518	0.39
TE			1.598
covering			0.698
misc.	2.43	7.153	1.17
total weight [kg]	13.5	23.794	15.960

Table 3: Realized wing designs compared

spar		elevator	outboard wing	inboard wing	inboard wing
position Y	m	0	3.5	0	2.10
inner diameter	mm	30	60	84	84
number of shere plies		4	4	8	6
nominal tube thickness	mm	0.5	0.5	1.0	0.75
number of 0 degree plies		2	9	17	11
nominal cap thickness	mm	0.25	1.25	2.125	1.375
cap width	mm	20	32-48	60	60
cap area (each side)	mm^2	5	45	127.5	82.5
material		T300/920	T800/M10	T800/M10	T800/M10
test method		3 point bending	4 point bending	3 point bending	3 point bending
ultimat bending moment [1]	Nm	213.5	1200	[2]> 6401	3923.5
e_{ult} t/c-cap	%		0.32/0.35	> 0.33 / 0.27	
$M_b R/I_c$	MPa	1423	444	> 597	566

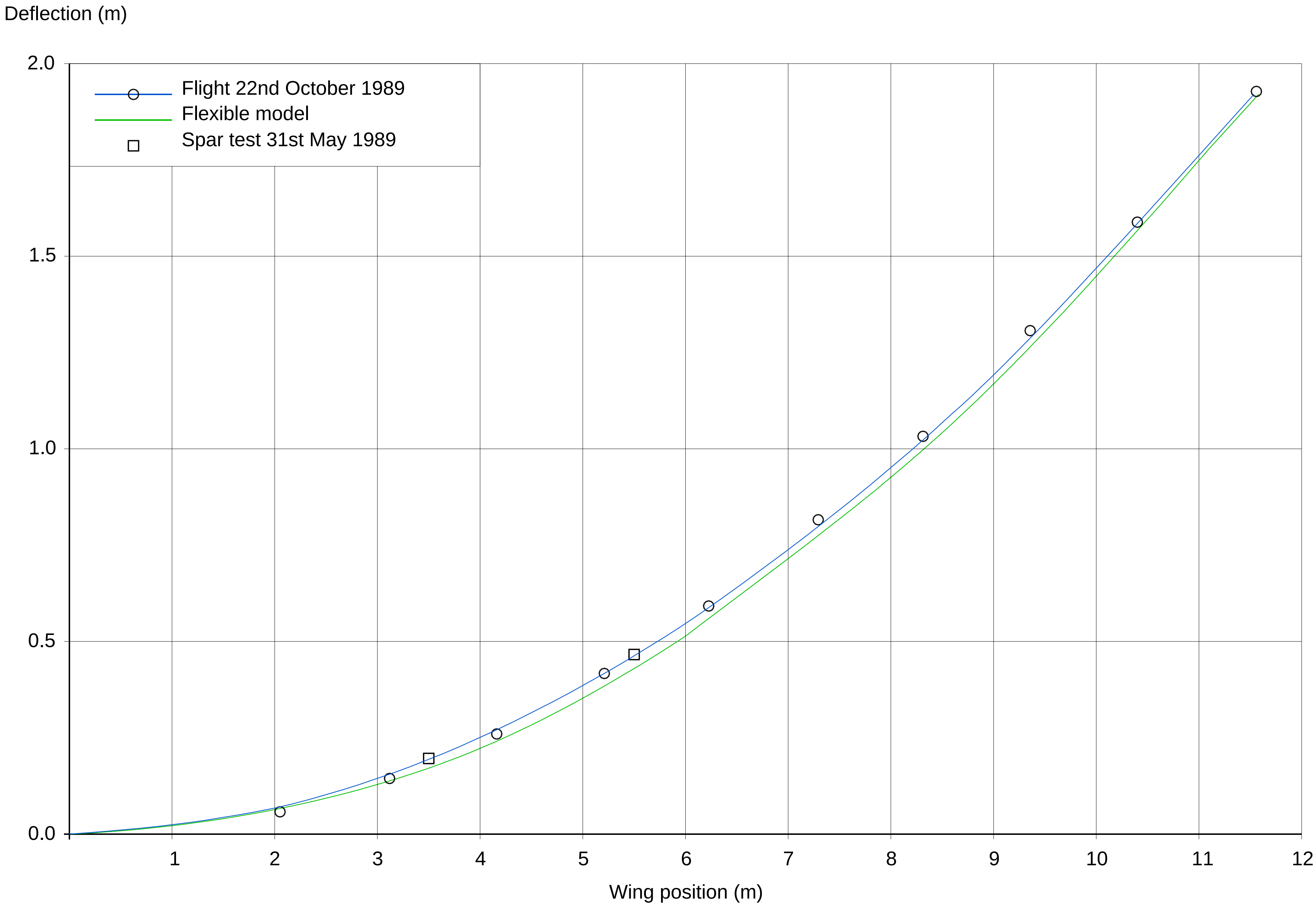
Table 4: Result summary of tube spar tests

1. It was not possible to tell if the tubes failed in compression or buckling because of the explosion failure mode.

2. No failure here, just for information

	Velair 88		Velair 89	
task	people x time	man hours	people x time	man hours
rib data sets rib templetes rib fab rib caps rib assembly	1 x 5 1 x 16 1 x 10 2 x 5 2 x 10	5 16 10 10 20	1 x 16 1 x 15 1 x 8 1 x 4	16 15 8 4
carbon inserts parts fab machined parts spar caps fab curing	1 x 20 2 x 20 3 x 35 3 x 15	20 40 75 45	1 x 10	10
webs fab spar assembly	2 x 10 2 x 21	20 42	3 x 30	90
shell fab shell bonding	4 x 24 3 x 24	96 72	1 x 5 2 x 10	5 20
TE fab TE assembly	1 x 1 -	1 -	2 x 5 2 x 10	5 20
inplane load struts fab inplane load struts assembly	1 x 15 2 x 10	15 20	1 x 20 1 x 15	20 15
airlerons airleron control instalation	1 x 25 1 x 10	25 10	2 x 5 1 x 10	10 10
wing tips	1 x 10	10	1 x 10	10
fuselage connectors wing connectors root ribs	1 x 20 1 x 15 1 x 5	20 15 5	1 x 20 1 x 15 1 x 10	20 15 10
finish	1 x 30	30	1 x 15	15
covering	-		1 x 20	20
total fab time		622		343

Table 5: Estimated fabrication time for Velair 88 and Velair 89 wings



Deflection (m)
2.0
1.5
1.0
0.5
0.0
Flight 22nd October 1989
Flexible model
Spar test 31st May 1989
1
2
3
4
5
6
7
8
9
10
11
12
Wing position (m)