HELIPLAT®: Structural Analysis of High Altitude Very-Long Endurance Solar Powered platform for telecommunication and Earth Observation Applications

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Abstract

Research is at present being carried out at the Turin Polytechnic University with the aim of designing the HAVE/UAV (High Altitude Very-long Endurance/ Unmanned Air Vehicle) HELIPLAT® (HELIos PLATform). The vehicle should climb to 17-20 km by mainly taking advantage of direct sun radiation and thereafter maintaining a level flight; during the night, a fuel cells energy storage system would be used. A first configuration was worked out, following a preliminary parametric study. The platform is a monoplane with 8 brushless motors, a twin-boom tail type with a long horizontal stabiliser and two rudders. A preliminary structural design of a scale-sized technological demonstrator was completed with the aim of manufacturing a proof-of-concept structure of HELIPLAT® and perform static test on it. A computer program has been developed for designing the anisotropic wing box, lay-up and thicknesses, leading to a maximum tip deflection of about 1.5m. A wide use of high modulus CFRP has been made in designing the structure in order to minimise the airframe weight. A main preliminary wing box structure, two C-spar and two sandwich panels, was manufactured in order to experimentally verify the numerical results. Each of the three pieces, 7.5m long was made by using a graphite/epoxy prepreg tape and autoclave cured; some CFRP ribs were bonded to the panels, front and rear half-webs were riveted along the neutral axis. Finally, the three boxes are bolted together in a single 21.5m long wing-box. A FEM analysis was also carried by using the Msc/Patran/Nastran code to verify the static and dynamic behaviour of the UAV structure. The classical hydraulic loading rig was designed and realised for applying the ultimate shear-bending-torsion load to the structure. The analytical and experimental results, show extremely good correlation.

Nomenclature

b, c	Wing span and chord
C_D, C_L	Drag and lift coefficients
e	Oswald's efficiency factor
n	Limit load factor
P_{req}	Required power for the horizontal flight
S_{ht}, S_w	Horizontal tail and wing area
V	Platform airspeed
W_{af}, W_{tot}	Airframe and total platform weight
Z	Altitude
η_{fc}, η_{sc}	Fuel cells and solar cells efficiency
η_{prop}	Propulsion system efficiency
λ	Aspect ratio

1. Introduction

There is nowadays a great request for automatic high altitude (17-25 km), flying platforms capable of remaining aloft for very long periods of time [HAVE/UAV]. They could play the role of artificial satellites, with the advantage of being much cheaper, closer to the ground and more flexible. They could in fact be self-launched and be easily recovered for maintenance, whenever necessary and could be moved to cover different regions if necessary. They allow a more detailed land vision due to their relative closeness to the land and at cost much less than $200-300 million for a real satellite. The missions of such platforms would cover a very large spread of applications: atmospheric pollution control and meteorological monitoring, real-time monitoring of

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seismic-risk areas, coastal surveillance, telecommunications services such as cellular - telephones networks, video-surveillance, photogrammetry, hydrographyc monitoring system, agriculture monitoring and so on. From a flying altitude of 17 km, an area of about 300 km in diameter would be covered for communication transmission if the onboard antenna irradiation diagram is properly chosen. Just 4-5 platforms could cover the whole of Italy from North to South. 7-8 platforms could cover the entire south Mediterranean Sea, from Spain to Israel. The vehicle should climb to 17-20 km by mainly taking advantage of direct sun radiation and thereafter maintaining a level flight. Any electric energy not required for the propulsion and payload operations is pumped back into the fuel cells energy storage system and, during the night, the platform would maintain altitude thanks to the stored (solar) energy; the geo-stationary position would be maintained by a level turning flight [1-8]. Several types of high altitude solar powered platforms (HASP) were designed in the past [9-14]. Aerostatics platforms (Sky Station and ESA-Hale) have been proposed as possible UAVs [15]. At the end of 1994, NASA started the ERAST (Environmental Research Aircraft and Sensor Technology) program (solar platform Pathfinder exceeded 24 km of altitude in a 15 hour flight). In the summer of 2001, the Helios solar-powered platform sets a new world record of 29350 metres, aiming at a flight of several days in year 2003.

A research was carried out at our Technical University, thanks to the financial support of the Italian Space Agency (ASI), with the aim of designing a HAVE-UAV Solar-powered Platform and manufacturing a scale-sized solar-powered prototype. Because of the limited financial support, only a small part of the research has been completed; nevertheless a great amount of experience has been gained in this field [1-8].

The research project HELINET (Network of stratospheric platforms for traffic monitoring, environmental surveillance and broadband services, Co-ordinator: Politecnico di Torino) has been financed, since January 2000, by the European Commission, within the 5th Framework Program in the Information Societies Technology Action, to develop a European project in the field of stratospheric platform. The HELINET project, carried out by several European universities and partner companies, is based on the HAVE-UAV HELIPLAT®. The main objectives of the 3-year project, from the aeronautical point of view, are:

1. To design an automatic HAVE-UAV that is capable of remaining aloft for very long periods of time (about 9 months) thanks to a solar-powered and fuel cells system.
2. To gain a thorough understanding of the feasibility of a near-term aerodynamic HAVE concept, especially concerning low-Reynolds profiles and propellers.
3. To design the entire advanced composite wing (about 75 m long), payload housing, booms and tail structures.
4. To verify the production cost of each platform.
5. To manufacture a 1:3 scale-sized technological demonstrator and perform static tests on it.
6. To assess the safety and regulatory aspects of the platform.

The fuel cells system and the brushless motor and solar cell system are being designed by the Dept. of Energy and Dept of Electric Eng. of our University, respectively.

Three pilot applications in strategic areas such as positioning, environmental surveillance and broadband communications are being studied by the other partners of the Consortium, in order to demonstrate the usefulness of HeliNet as an integrated infrastructure that is able to yield several services in a cost effective and sustainable manner.

The preliminary structural design and analysis of the platform is the main scope of the present paper. A specific computer program was developed in order to define an efficient anisotropic structure feasible for HELIPLAT® application. Following the standard airworthiness regulations, the limit loads was identified and a specific structure was designed. A preliminary design of a scale-sized technological demonstrator was completed with the aim of obtaining a proof-of-concept solar-powered airplane [16, 17]. The static and dynamic behaviour of the scaled prototype was investigated by FEM analysis as introductory activity before the testing phase. It would be manufactured to verify the several disciplines involved in the project: the aerodynamics of low-Reynolds numbers, minimum mass/high stiffness optimised CFRP structures, solar cells power production, high efficiency and high reliability of brushless electric motors, high efficiency blades, automatic power and electronic control. The final project of the platform will be carried out and built from the many results expected from these tests.

A preliminary investigation was performed on a testing reference structure just designed in order to define a proof-of-concept test rig for the project. A specific wing box has been designed ,manufactured and analysed. The experimental static shear-bending test was performed on it . A good correlation with the FEM results is shown.

2. Platform design and configuration

A first configuration of HELIPLAT was worked out, as a result of a preliminary parametric study. The hard sun-powered level flight can be achieved only by means of a suitable design and an accurate integration of the best standard achievable for each technological item involved such as the structural weight optimisation, the aerodynamic, the solar cells, the fuels cells, the propulsion efficiency and the electronic devices. The design procedure, summarised here (more details in [2, 5-6]), is based on the energy balance equilibrium between the available solar power and the required power, the former being dependent on the solar cells area installed on the wing and stabiliser, the latter depending on the velocity and total drag of the platform. The endurance parameter has in particular to be fulfilled to minimise the power required for a horizontal flight. This means minimising the parameter $C_D/C_L^{3/2}$. The total coefficient drag is obtained from the sum of the wing and tails profile drag, wing and tails induced drag and parasite drag (fuselage, booms, interaction with wing and tails). Reynolds numbers of less than 700,000 should be considered. An airframe mass estimation of the platform is initially necessary to complete the power equilibrium. Based on previous papers on man-powered aeroplanes, high-altitude aeroplanes or ultra-light cantilever twin-boom tails, the following expression has been derived as a function of aspect ratio λ, limit load factor n (maximum value of 3.1) and wing platform area S_w, for the airframe weight:

$$W_{airframe} = 8.75\, n^{0.311}\, \lambda^{0.4665}\, S_w^{0.7775}$$

The total platform weight, per wing area, is determined by adding the weight of the propulsion (32 N/kW), the solar cells (6.9 N/m^2 of covered area), avionics and payload to the airframe; the weight of the propulsion system includes brush-less motors, inverter, conditioning system and propellers. As a result of the previous parametric study, a specific configuration of HELIPLAT® (Fig. 3) was worked out. The platform is a monoplane with eight brush-less motors, a twin-boom tail type with a long horizontal stabiliser and two rudders. The main characteristics for a nine months flight (starting 1st Feb) at 38°N latitude and design altitude of 17 km, carrying a payload of 981 N, are: W_{tot} = 7100N; P_{req} = 6000W; $P_{payload}$ = 800W; n_{max}: 3.1; V_c = 71 km/h (TAS); η_{sc}=0.21; η_{fc}=0.6; η_{prop}=0.81; S_w= 176.5m^2; b_w = 73m; $c_{w\ root}$ = 2.97m; λ_w = 30.2; Taper ratio = 0.32; S_{ht} = 28 m^2; b_{ht} =17.5 m; c_{ht} = 1.6m; λ_{ht} = 11.

The choice of eight motors has been considered as a good compromise between the redundancy and mass; 5000 W of surplus power for 2 hours has been considered as the power required for the system since it would have to give power when the highest wind speed jets are blowing. The boom tail configuration has been chosen to install the oxygen and hydrogen tanks. The airframe (weight 3555 N) is about 44% of the total weight, the solar cells (1250 N) is 16% , the fuel cells (1550 N) is 19% , the propulsive system (710 N) is about 10% .

Solar cells and fuels cells are, till today, the weakest element of the project. Very thin, light, high efficiency crystalline silicon cells are today available; 21% efficiency could be considered very useful for our purpose although, in this case, the cost would increase incredibly. Fuel Cells are of great interest for storing energy in various space applications. An energy storage system, based on dedicated electrolyses and fuel cells (solid polymer type), gives an energy density of 400-600 Wh/kg. Present day cell system efficiency is about 55% and its production cost is of a few hundred thousands dollars. The parametric studies have shown how fuel cells and solar cells efficiency and mass have the most influence on the platform dimensions[18].

3. Scaled size prototype structural design

A preliminary design of a scale-sized technological demonstrator was completed with the aim of obtaining a proof-of-concept solar-powered airplane [16, 17]. It would be manufactured to verify the several disciplines involved in the project: the aerodynamics of low-Reynolds numbers, minimum mass/high stiffness optimised CFRP structures, solar cells power production, high efficiency and high reliability of brush-less electric motors, high efficiency blades, automatic power and electronic control. The final project of the platform will be carried out and built from the many results expected from these tests.

The HELIPLAT® configuration is considered as a reference point in the design of the scaled prototype. The wing span and the tail span are reduced to 1/3 of the real HELIPLAT dimensions; the chord wise dimensions are reduced to about 1/2 of the real ones; the thickness and the layout of the different elements are maintained as the real configuration. The overall airplane architecture and some particular sections of the wing, horizontal tail and booms are plotted in Figure 2. The actual HELIPLAT® applied loads (resultant bending and torsion moments and resultant shear) are calculated taking into account the effective aerodynamic and mass distributions according to the JAR-23 airworthiness requirements; they are used to determine the structural stiffness of each structural element (wing box, tail spars and booms). As an example, at the limit load condition, a maximum bending moment of 38.5 kNm and a shear load of 2.1 kN were induced at the wing root section, with a maximum strain of about 1100 $\mu\varepsilon$. The load distribution in the prototype has been modified in order to apply the same maximum strain like the full scale HELIPLAT®. This strain level would guarantee the integrity of the structure up to the ultimate loads. By means of the preliminary structural design program, the cross-section of the wing is defined in detail and plotted in figure 2. The CFRP main tubular spar will carry all the shear/ bending/ torsion loads applied to the wing, while the leading and trailing ribs have, in most cases, a profile shape function and would be manufactured with rigid foam bonded to the box. The leading edge between the two booms will be a light sandwich panel. The solar cells are encapsulated between Mylar plastic films and bonded over foam panels that are positioned around the shape ribs and structural ribs. The subdivision of the scaled wing structure consists in a 11.2m long constant chord inner wing and two 6.57m long tapered chord outer wings, one for each side. Two inner wing elements, each 4.18m long, are connected to a 4.2m centre wing box to make the constant chord wing tubular spar.

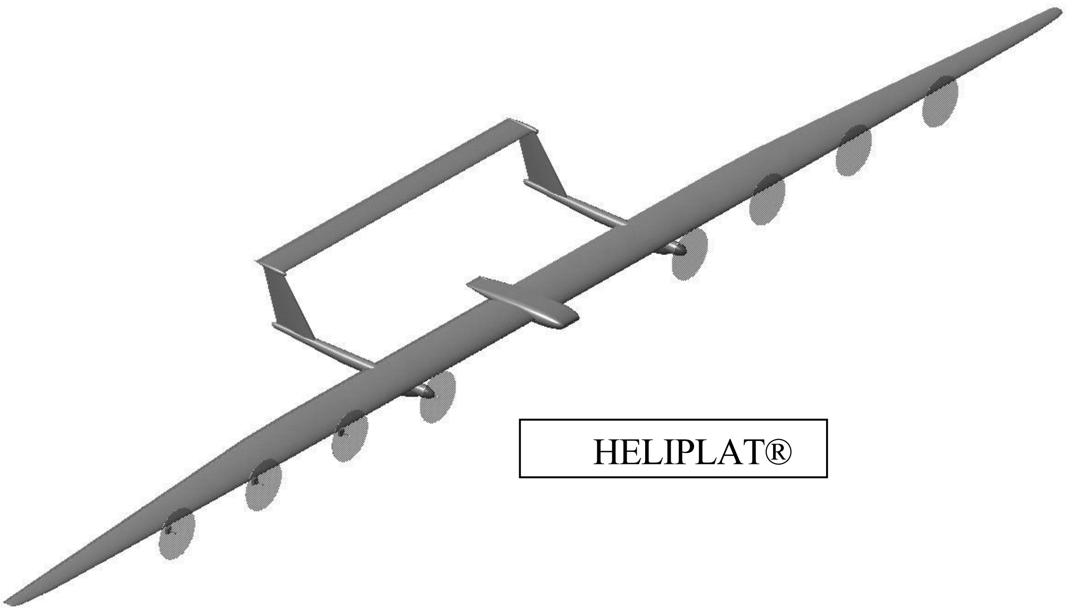

Figure 1

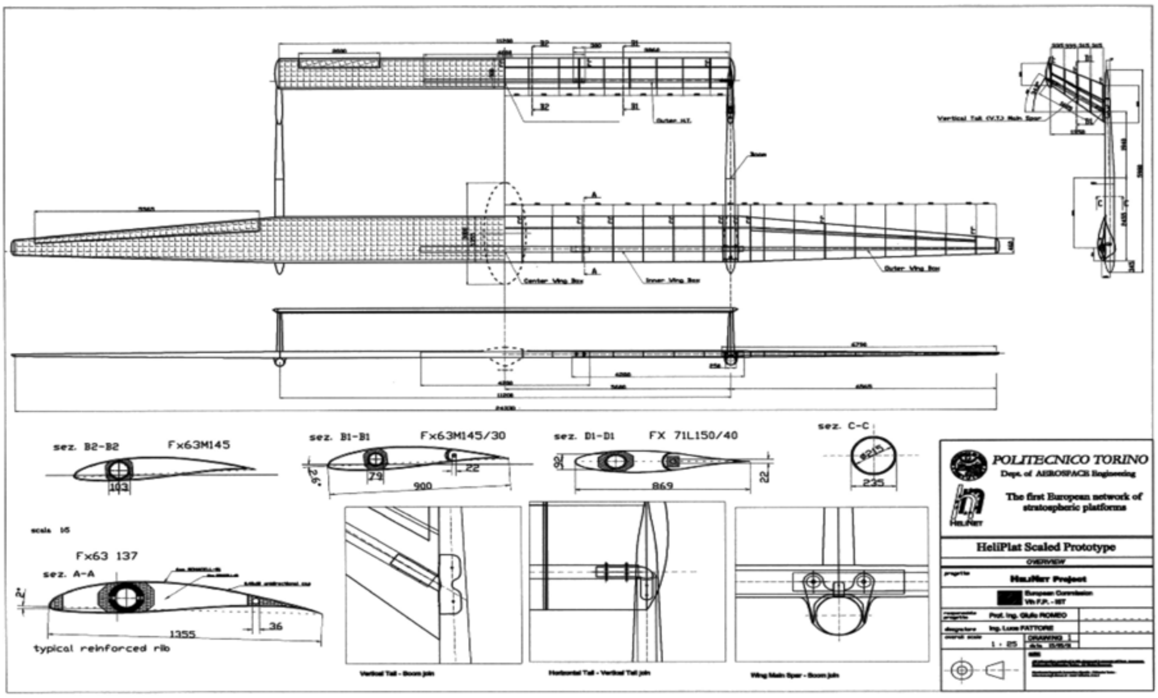

Figure 2

The inner wing boxes enter the centre one for a distance of 0.44m and two pairs of bolts (one on the front and one on the rear web) join them. Two 6.79m long parts make up the tapered parts and they are connected in a similar way. The CFRP main spar is composed of sandwich reinforced tubes made of M55J graphite/epoxy pre-preg tape and Korex, or Nomex, honeycomb materials. Each tubular structure should be autoclave cured, at 120°C and 0.3 MPa pressure, in a single-cure cycle. Some ribs should be bonded to the tubular spars in the indicated positions and particularly in correspondence to the fittings and engine mounts. A special bolt system was developed to increase the bearing strength of the composite fitting. The pin junctions consist of a 28 mm diameter titanium-reinforced hole to reach a final pin hole of 20 mm. The distance between the two front and rear bolts is calculated in order to obtain the design limit load for each bolt. Carbon fibre reinforced foam ribs should be manufactured and mounted on to some sections as plotted by "rr" in figure 2. Two or three layers of CFRP are used to reinforce the foam rib. Special CFRP honeycomb ribs should be manufactured and mounted in correspondence to the fittings between the several wing spars and, above all, in correspondence to the booms. All the ribs will then bonded by a micro-sphere-reinforced glass-epoxy to the spars. The M55J graphite fibres have been chosen as graphite/epoxy pre-preg tape to manufacture each CFRP wing-box. The main mechanical properties of the laminae used to design the wing-boxes, as supplied by CASA Space as A-Basis values, are:
E_1 =279.3 GPa; E_2 =5.84 GPa; G_{12} =4.05 GPa, ν_{12} =0.36; . σ_{1R}^{t} = 1036 MPa; σ_{1R}^{c} = -381 MPa; ε_{1R}^{t} = 0.37%; ρ = 1.58 kg/dm^3.
It is worthy to note that an effective reduction in weight could be obtained if a higher performance material were available. By introducing the previously mentioned mechanical properties into the structural design computer program, the lay-up of each portion of the single tube was chosen and indicated in the corresponding drawing. Fig.3 represent the distribution of the unidirectional laminae in the tubular spar caps along the span. An high number of UD0 plies are present. The preliminary strain behaviour in the tubular spar caps are reported in fig.4. The comparison with the FEM results shows a good correspondence. Slight differences are due to the necessary simplifications introduced into the analytical design program while the FEM calculation take into consideration the effective distribution of masses and the effective strain concentration as in the real case. A maximum

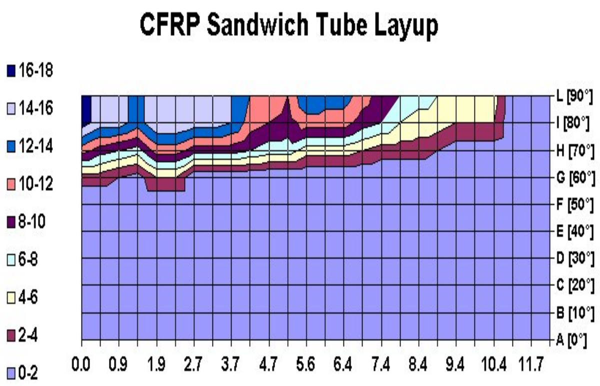

Figure 3

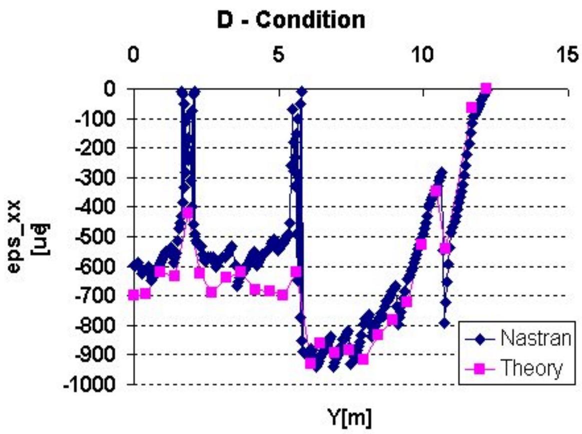

Figure 4

deflection of about 1.5m was determined in the wing tip at the maximum applied limit load condition (manoeuvring). A successful result from the testing activity on the scaled prototype could give an important assessment to the new light structure. The scaled horizontal tail (HT) structure consists of a constant chord element 11.2m long. It will be manufactured in three pieces: the inner part will be 4.0m long, and two outer parts, each 3.9m long. The cross-section consists of a main CFRP sandwich tubular spar that will carry all the shear/ bending/ torsion loads that are applied to the horizontal tail. A secondary CFRP rear spar is positioned aft from the main one to have a suitable structural support for the elevator systems. The leading and trailing ribs would be manufactured in rigid foam bonded to the box. The scaled double vertical tail (VT) structure consists of a 1.685m long tubular spar for each tail, with a circular cross-section of 0.088m external diameter. The two spars are made of CFRP sandwich construction, using M55J graphite/epoxy pre-preg tape and Nomex honeycomb. The lay-up is arranged in order to reach the expected stiffness as in the other structural elements. The scaled boom-structure consists of a 5.98m long tapered tubular member, with a circular 0.235m diameter cross-section near the wing box and 0.15m diameter at the vertical tail junction. The 0.235m diameter is maintained up to 2.55m from the wing box. The two booms are made of CFRP sandwich construction, using M55J graphite/epoxy pre-preg tape and Nomex honeycomb. The lay-up is arranged in order to reach the expected stiffness. A special connection between the boom and wing box, based on the introduction of a structural rib, has been designed. The junction (Fig. 5) is composed of three elements; the first in correspondence to the wing box spar is made of a specific shaped plate; the second positioned at 0.7m aft the wing box spar is made of a pin-bolted connection and the third positioned in correspondence to the rear spar. A finite element numerical analysis is also being carried out, using the MSc/Patran/Nastran FEM code, to predict the static and dynamic behaviour of the whole structure (Fig.6). The static FEM model is composed of 70.000 elements. QUAD4 elements were used to model the CFRP spar laminates; solid HEX8 elements were used to model the adhesive tape and the steel bush stuck to the CFRP, in order to verify the maximum shear stresses in the adhesive tape (it should be less than 10 MPa). A special mesh procedure is carried out in order to permit an exact definition of the geometry of each single ply. The aerodynamic loads are applied to the several surfaces and are in equilibrium with the inertia loads. The highest loads arise on the wing due to the effect of the horizontal tail manoeuvring at design dive speed.

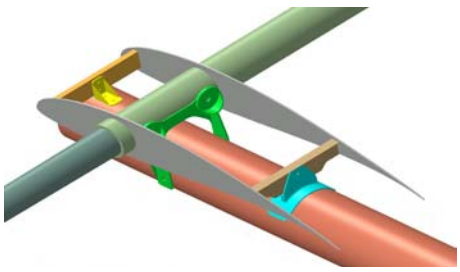

Figure 5

A dynamic analysis of the scaled prototype model has been carried out. The first bending mode is also plotted in Figure 6. The lowest eigenvalue frequency is 2.2 Hz.

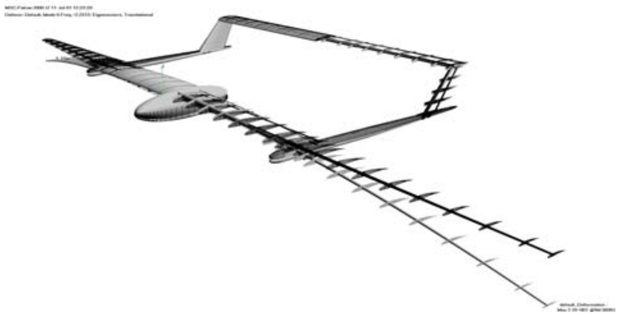

Figure 6

A preliminary classical aeroelastic analysis has been performed on the scaled prototype in order to have specific design indications useful for the subsequent flying platform design. The Fem model has been reduced to a simplified one by the use of a beam-wise approach considering a certain degree of simplification in mass and stiffness distribution. The horizontal tail is considered only as an inertial element in order to have a representative dynamic behaviour. A refined model should also consider the aerodynamic effect of the tail itself, but at this preliminary stage only the wing characteristics have been investigated. The classical V-g plot is shown in figure 7 taking into consideration the first 16 modes. A critical condition seems to be determined at a velocity of about 25 m/s that is not so much higher than the considered diving velocity according the airworthiness requirements. A successive classical flutter condition occurs at a velocity of about 56 m/s. Specific critical aeroelastic aspects have been pointed out by this simplified analysis. They have to be considered into the subsequent design activity of the platform with a more detailed investigation. A static test will be carried out on the scaled-size prototype. CASA Space - EADS, will manufacture all the single elements (spars, ribs, booms, fittings, etc.) which will then be assembled in our laboratory to produce the wing, HT, VT, Booms and then the whole scaled-size prototype. The maximum strain will be reached during the static test up to the limit load; the test will be carried out up to the ultimate load, to obtain the structural margin of safety. The mechanical equipment will be designed and manufactured to make a shear-bending-torsion test on the complete scaled-size prototype and verify the theoretical behaviour. The static test on the complete scaled model would seem to be more meaningful then several tests on each element of the structure. Several interaction effects can in fact arise when the different elements are tested while

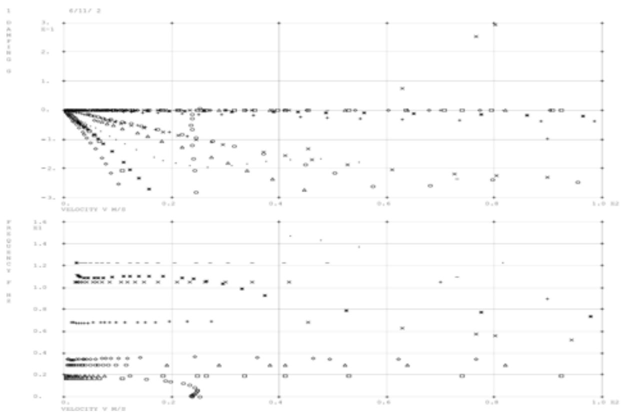

Figure 7

assembled one to another:

- Booms are simultaneously subjected to loads applied by the wing as well as by the horizontal and vertical tails. It will be very difficult to isolate the former without introducing some simplifications, which do not represent the proper boundary conditions.
- The highest loads on the wing are transmitted from the HT manoeuvring.
- The behaviour of the horizontal tail is very much influenced by the constraints to the vertical tail.

The results that should be obtained from the several tests will enable the future development and manufacturing of the full-size flying platform, equipped with the proper avionics and ready to fly.

4.Preliminary wing box manufacturing and testing

Under the financial support of the Italian Space Agency (ASI), a 21m long wing box has already been designed, leading to a maximum tip deflection of 1.5m and angle of twist of 2°. The 24m long wing has to withstand (according to the JAR 22 Airworthiness Req.) an ultimate bending moment of 44 kNm and ultimate shear load of 6.8 kN, corresponding to an ultimate load factor of 9 (a safety factor of 2 was used in this first experience). An optimisation computer program similar to the one used for the scaled size prototype was developed for designing the anisotropic wing box, under shear - bending - torsion load, in order to choose the proper lay-up and thickness that would minimise the wing mass; the thickness of each panel sandwich face is tapered from the spar at the corner with the web (12 layers) up the middle panel (3 layers); a proper lay-up was used in all webs for improving both the crushing load as well as the bearing strength; a maximum tip deflection of 1.3m and angle of twist of 2 degrees was imposed at limit load. The Rayleigh-Ritz method was used to determine the buckling load of the sandwich panel under uniaxial compression and shear load, including the transverse shear deformation of the core. The main mechanical properties of the laminae used for manufacturing the wing-boxes are: E_l=200GPa; E_2=9GPa; σ_l=1800MPa; ε_l=1.2%; ρ=1.65kg/dm^3. As a consequence of the stiffness requirements to be satisfied, the maximum strain that would be reached in the spars is 0.003. Although a higher strain should be supported by the structure, a fatigue life greater than 10 million cycles would be obtained, in this way, without any damage propagation. The wing box was manufactured in three boxes, 7.5 m long each, and joined by 4 bolts for each side in the one meter of overlapping between two adjacent wing-boxes. Each wing-box is composed of two sandwich panels and two half-webs made by graphite/epoxy prepreg. Each upper and lower panel was cured, at 120°C, in a single-cure cycle with the two half-webs. The whole wing box mass resulted of 70 kg, including 8kg for fittings and bolts. The classical hydraulic loading rig was designed for applying the ultimate shear-bending-torsion load to the structure and to verify the theoretical behaviour. A numerical finite element analysis has also been carried out, by using the MSC/PATRAN/NASTRAN FEM code, in order to predict the static behaviour of the wing structure. The static FEM model is composed by 51000 elements: QUAD4 elements were used for CFRP laminates and solid HEX8 elements were used for adhesive tape and steel bush stuck to CFRP. A test up to failure was carried out up to a load corresponding to 4.5g. The experimental testing set up is represented in fig.8. The load is applied by means of a central jack and distributed along the wing span by several loading sections. They are defined in order to represent the actual shear and bending load condition. Several experimental and analytical results are reported in figure 9. A maximum deflection of 480mm was measured at an applied load of 5000N with a good correlation with the numerical results. The experimental measurements are reported as geometric symbol. It is noteworthy as the wing rotate around the hinge of the loading rig, producing a downward deflection in the root section and an upper deflection in the tip section. The deflection along the span is plotted for several values of the load applied in the root section; the continuous curves drawn, show the FE wing deflection obtained for the complete model by a linear calculation. The last result represent the FE deflection for the non linear reduced preliminary model showing a little effect. A more noticeable effect can be observed in fig.10 where the presence of the crushing pressure introduces a relative panels deflection with respect to the web and ribs. Some experimental strains are reported in fig.11. A crushing pressure slight effect has been observed for the increment in compressive dorsal strain of SG21 and SG30 with respect to ventral strains of SG24 and SG31 (SG stand for strain gauge) in the specific wing box section. A reduced FE model has been defined in order to investigate this non linear aspect. The model has been limited to the central part of the wing box. The load was applied as the effective case by means of concentrated forces in the pin-bolt junction together with a pressure distribution over the ventral and dorsal panels. The effect of the local junction was neglected in this phase. The investigation of this important effect has to be done developing a new detailed model that takes into consideration the actual manufacturing shape of local sides of dorsal and ventral panels near ribs and spars not included in the preliminary non linear model presented here. In these positions in fact the sandwich core is reduced obtaining a local solid laminate. A change in the local strain distribution is expected. The behaviour of the in-plane load for different section of the central wing box model is represented in fig.12 and fig. 13. The load is concentrated within the spar locations as expected. The difference between dorsal and ventral load distribution is due to different shape of the wing box and different lay-up.

5. Conclusion

The results of the parametric study show that it could be possible to obtain a very long endurance high altitude platform for earth observation and telecommunication applications, at least for low

Figure 8

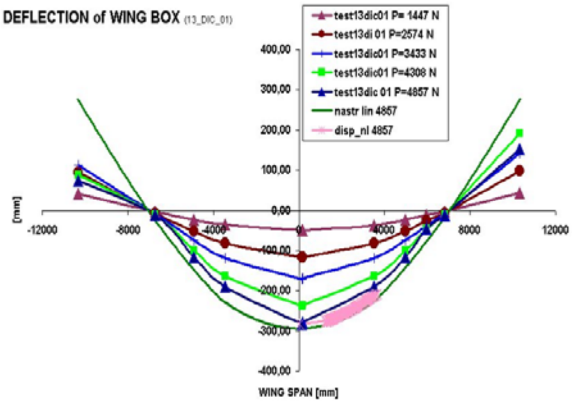

Figure 9

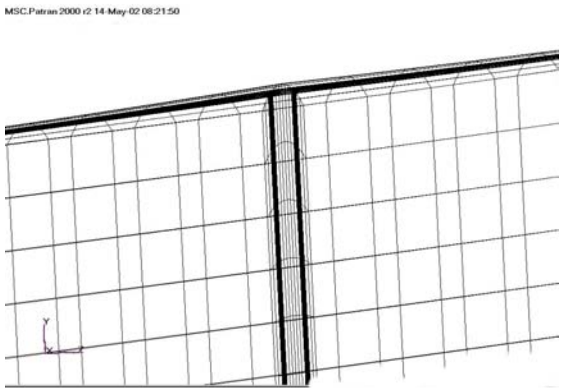

Figure 10

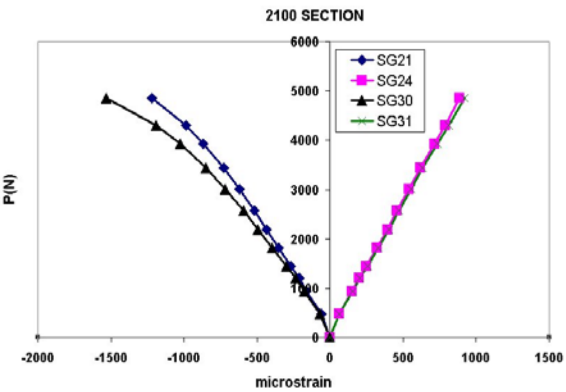

Figure 11

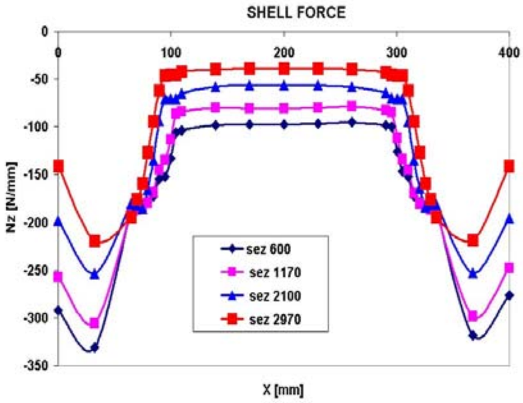

Figure 12

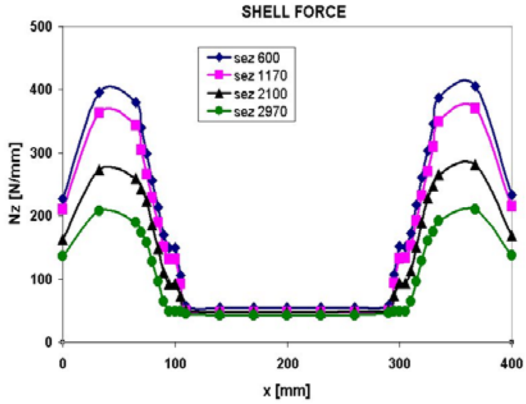

Figure 13

latitude sites in Europe and for nine months of operation. The structural preliminary design of the platform has been developed in order to verify its feasibility. A scaled size prototype was defined in order to be representative of the actual platform. The structural design has been concentrated on the definition of its structures maintaining the thickness and the maximum strain level. A good correlation between the FEM and numerical results has been obtained. The FEM numerical analysis of the scaled-size technological demonstrator shows the feasibility of the airplane withstanding the planned mass and stiffness. A good comparison is expected from the static test on the whole scaled aircraft. An good comparison has been obtained between experimental and FEM results of a 21m long CFRP wing box under shear/bending tests. It concerns the manufacturing of a preliminary CFRP wing box that was used as a proof-of-concept in the HELIPLAT design phase. Certain non linear interaction between crushing loads and in-plane loads has been pointed out for this wing box addressing the design to the chosen tubular CFRP spars. More detailed model will be developed in order to investigate this effect.

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