REPLICA 55 PROJECT: A WOOD SEAPLANE IN THE ERA OF COMPOSITE MATERIALS

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Abstract

The Savoia Marchetti S55 seaplane is a symbol of the remarkable aeronautical know how reached in Italy during the '20s and' 30s, confirmed by a series of long-range record flights. Although about 250 aircraft were manufactured, to date not one flying example exists. Currently the only one remaining and preserved is exhibited in the TAM aeronautical museum in Brazil. In 2015 a group of competent and enthusiastic professionals of the aeronautics sector started the "Replica55 project" with the aim of designing, building and flying a replica of the S55 aircraft.

1. Introduction

In 1924 a peculiar machine made its first flight. It was a catamaran seaplane, equipped with twin engines, one pulling, one pushing. Three rudders surmounted a tailplane linked to the fuselage by wooden beams. The aircraft, Savoia Marchetti S55, was of wooden construction: a choice grounded in economic considerations, since the designer, Alessandro Marchetti, estimated the price of a metal equivalent at thrice as much, in a time in which the normal service life of an aircraft model was quite less than five years.
The S55 was meant to be a torpedo bomber, the 800 Kg weapon suspended in the middle of the central wing section. The torpedo could be replaced by bombs. A manned flexible mount 7.7 mm machine gun was at each end of the two nacelles, making for what at the time was a very respectable defensive armament.
The hulls had a concave shape in lieu of the usual convex one; this was done in an effort to decrease hydrodynamic drag during take off, accepting the subsequent penalty in terms of water landing impact resistance. Another attempt at favoring take off was in the inclination of the engines' axis, canted upwards. The unusual catamaran configuration choice had its reasons in the search for high stability in the water and rapid take off at the time it was thought possible for a torpedo bomber to wait long hours in ambush floating in strategic sea locations, and take off with the heavy weight from the torpedo was not to take for granted with the limited engine power available. The aircraft was initially refused by Regia Aeronautica (Italian Air Force), but later the decision was reversed and the type entered service in 1926. It would be retained as a front line aircraft well into the Spanish Civil War, where four S55 briefly saw action bombing Republican vessels.
Some S55 served in civilian airlines, but the aircraft's fame would come from its participation to several long distance raids.
The main accomplishements were:

- 1926: 14 category records for speed, endurance and altitude.
- 1927: Five continents raid (42.000 Km) by De Pinedo-Del Prete, including two way Atlantic crossing.
- 1928: Italy-Brazil flight by De Barros-Braga.
- 1928: First mass Mediterranean Cruise by 61 aircrafts, including 8 S55, 2800 Km.
- 1929: Second mass Mediterranean Cruise by 37 S55, 4800 Km.
- 1930: Formation flight Italy Brazil, by 12 S55.

- 1933 “Crociera del Decennale dell’Aeronautica” (Ten Years Air Force Anniversary Cruise), 24 S55 from Orbetello, Italy to New York, USA.

The “Crociera del Decennale” especially contributed to estabilish the image of Italy as a power player in the aviation technology game, as up to that moment only isolated aircrafts had attempted the transatlantic crossing.

2. Designing a Replica

Let us start from a definition: “replica” means something resembling in a more or less broad manner the original design and structure; it could be very close in looks but not necessarily as close in terms of structures and technologies (Figure 1).

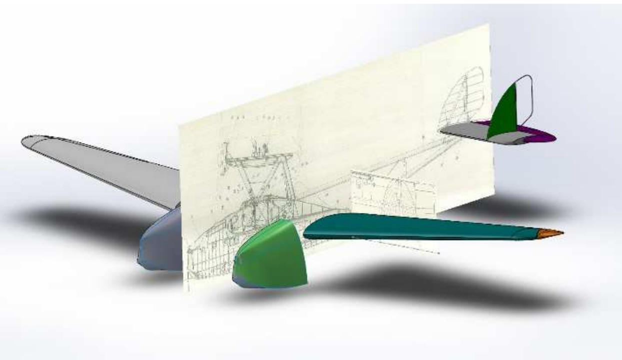

Figure 1 Definition of “Replica”

“Reproduction” is a construction exactly reproposing the original drawings, structure and technology (Fig 2,3). Our mission is to design a flying replica of the S-55X seaplane as close as possible to the original one but engineered in such a way that most of the components can be made through an extensive use of CNC machining, in order to contain time and costs of the realization (Fig 4). The extra weight of some machined parts compared to the original solution will be more than compensated by the lighter installation of engine and accessories and modern construction technology (i.e. structural glues instead of screws, nails and bolts on structural parts).

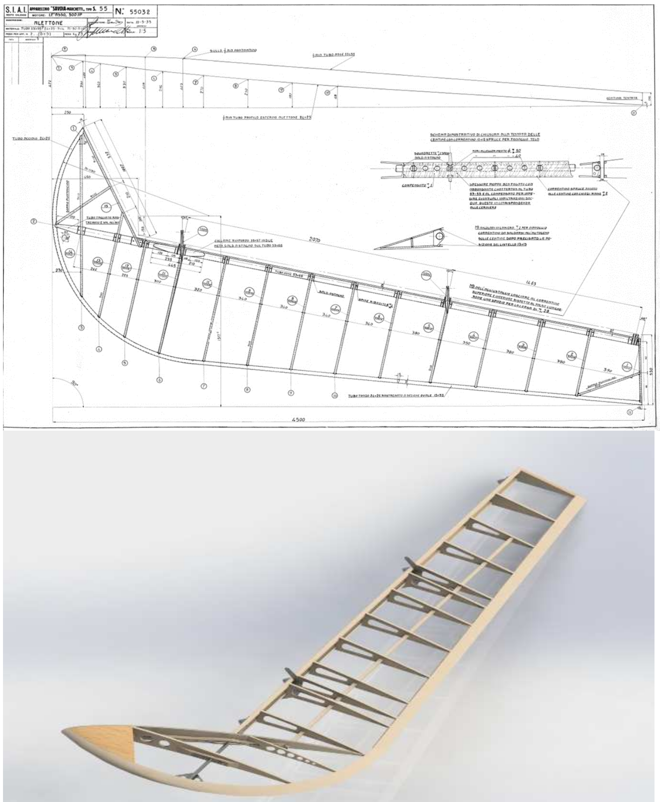

Figure 2 aileron detail – original drawing & “Replica” CAD model

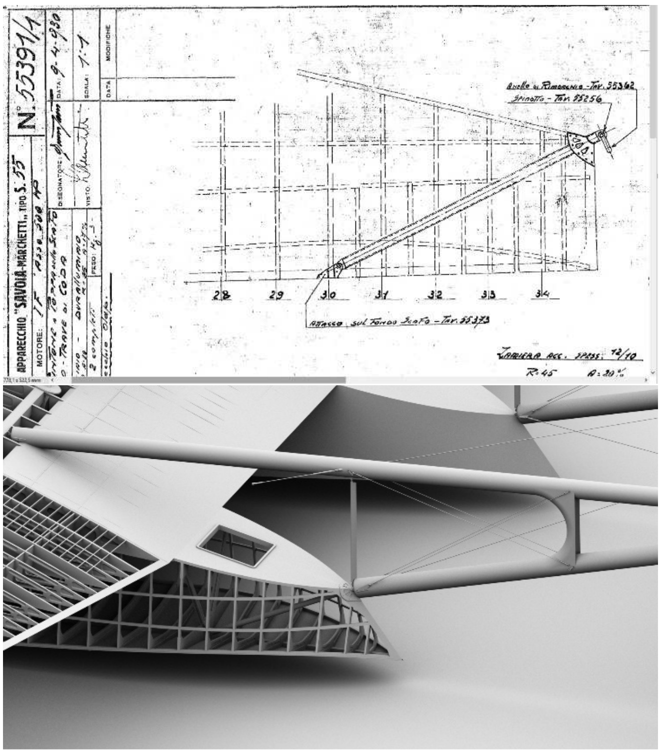

Figure 3 Hull–boom joint detail – original drawing & “Replica” CAD model

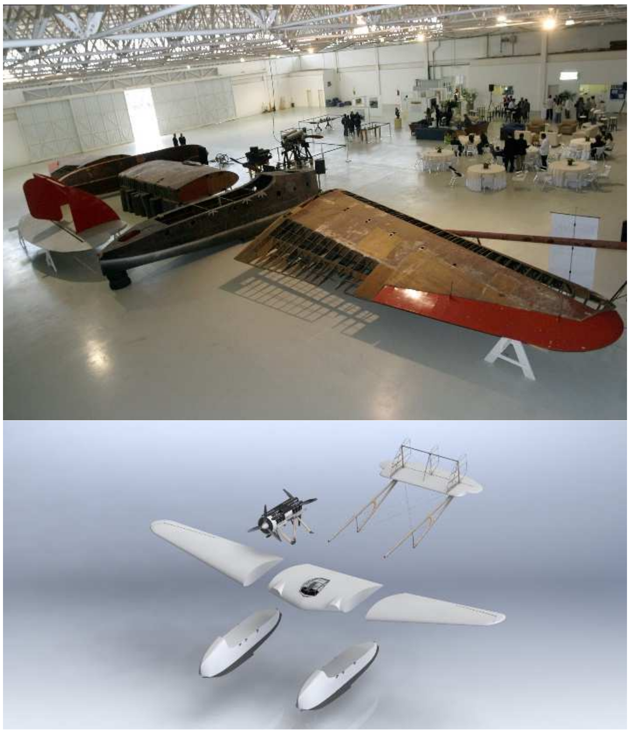

Figure 4 Flying Replica concept

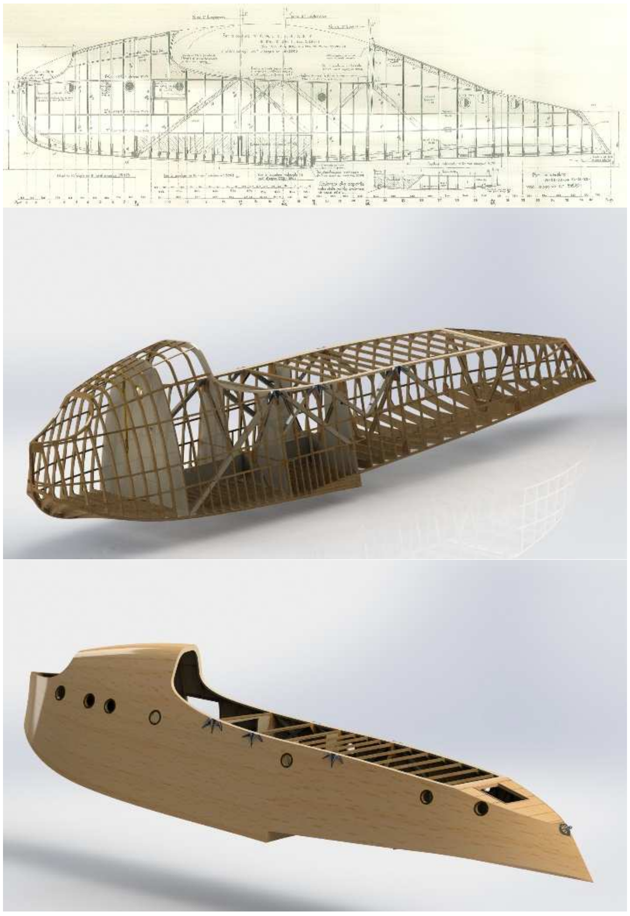

Figure 5 Hull – original drawing & "Replica" CAD model

Designing a replica, even if in full scale, poses nevertheless several issues not always easy to solve; let us talk about some we encountered during our work (Fig 5).

Materials: some of the materials (especially aluminium or steel alloys) mentioned on the original drawings are simply not available anymore; other material like caseine glue or some mechanical solutions are simply not accepted by aeronautical authorities today (Fig 6,7).

Aerodynamic: most of the early aircraft wing profiles, especially if designed before the '20s, have flight characteristics the modern pilot would define at least "brisk"; in general we may find wing profiles with unpleasant stall behaviors, marginal or even negative stability over one or more axis of the aircraft, flutter issues.

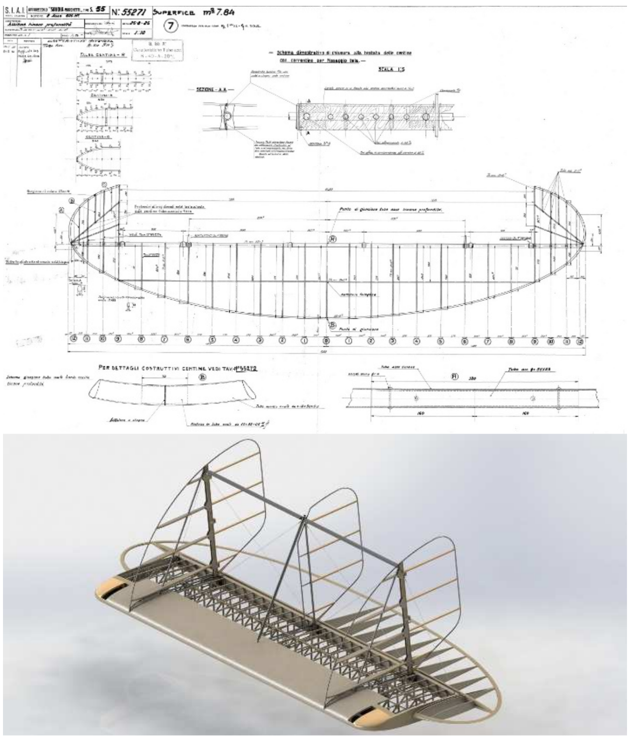

Figure 6 Horizontal Tail – original drawing & "Replica" CAD model

Propulsive Unit: the installation of a new propulsive unit (considering the unavailability of original engines) creates one of the biggest issues, because the old engines were characterized by big mass and a relatively low power-to-weight ratio; the needed power and low RPM torque needed for the big diameter propeller was achieved with generous engine displacements. Modern engines, usually available with even greater power, are generally way lighter and, together with nowadays pilots (generally heavier) create balance issues not easy to solve without deviating (sometimes quite consistently) from the external shapes of the originals.

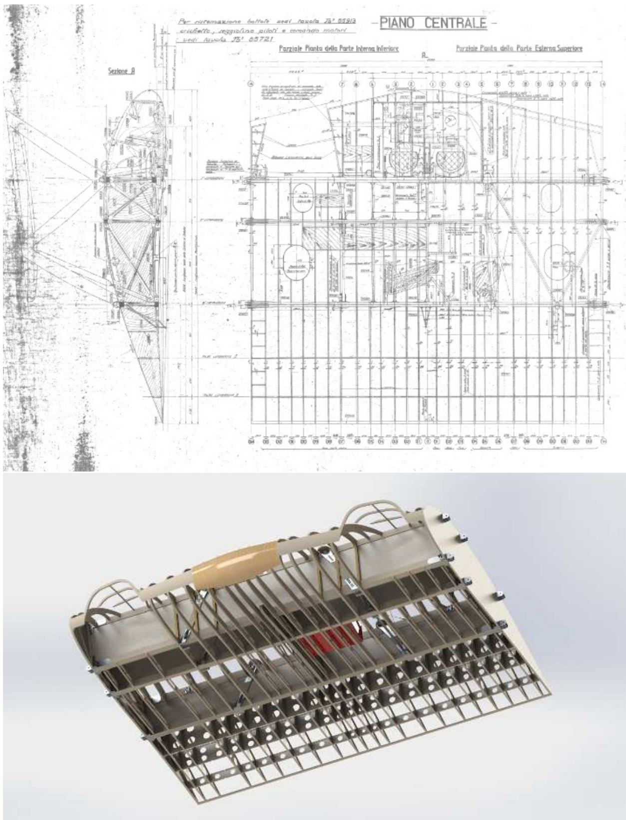

Figure 7 Wing central part – original drawing & “Replica” CAD model

It’s not unusual to see, especially at air shows, flying replicas with nose sections way longer and displaced compared to the original. Some interesting figures we encountered during our S-55X design: the weight of the original Isotta Fraschini ASSO 750 engine (the original installation) was 640 Kg (dry, without exhaust and propeller hub); a modern engine or comparable power flies around 275 Kg (Fig. 8,9). The original radiator (Fig 10), made by thousands of tin soldered copper tubes, weight 110 Kg plus 63 L of water per engine; a modern heat exchanger of comparable dissipative characteristics stays well below 40 Kg (and needs way less coolant).

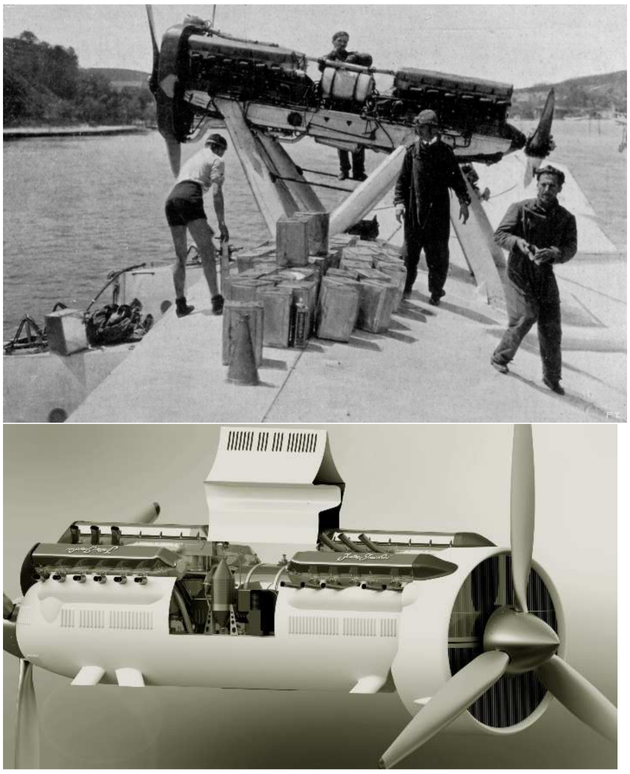

Figure 8: Old propulsion system

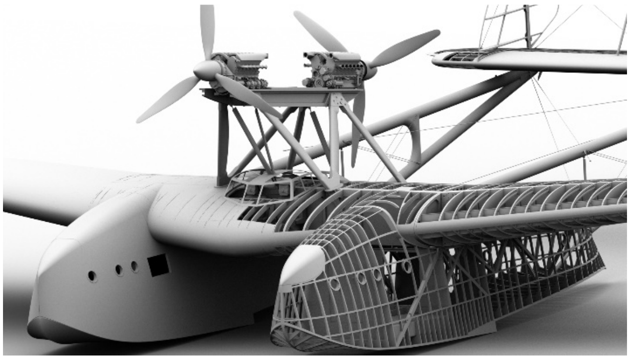

Figure 9 New propulsion system installed

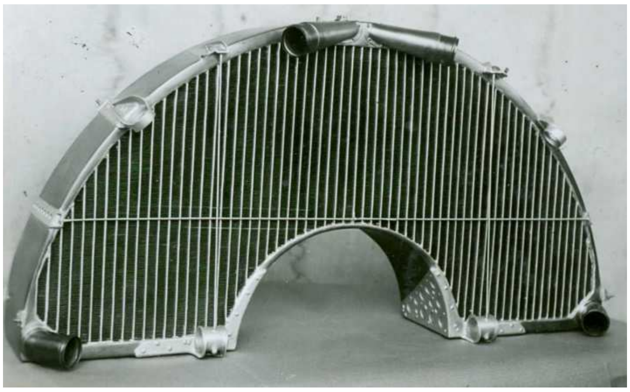

Figure 10: Original radiator

The original propeller, including the hub, weighted more than 140 Kg (Fig 8). And again, many accessories nowadays are simply unconceivable: we may talk about the 35 Kg oil tank holding 162 Kg of engine oil which adds to the 30 Kg of oil running on the hoses and engine basement; the small gas engine (two strokes) Garelli compressor for engine start-up, totaling another 25.37 Kg, the sea anchor with line for a total of 50 Kg, the radio receiver spotting its 10.52 Kg (Fig 11).

Ergonomics: not last in modern replicas design are ergonomics issues, about the pilot and, in general, all the occupant of the aircraft. The main considerations are that the standard man of the 1930 was below 165 cm and weighted less than 65 Kg; modern pilots (and passengers) are closer to 180 cm of height and 95 Kg of weight as shown in Figure 12.

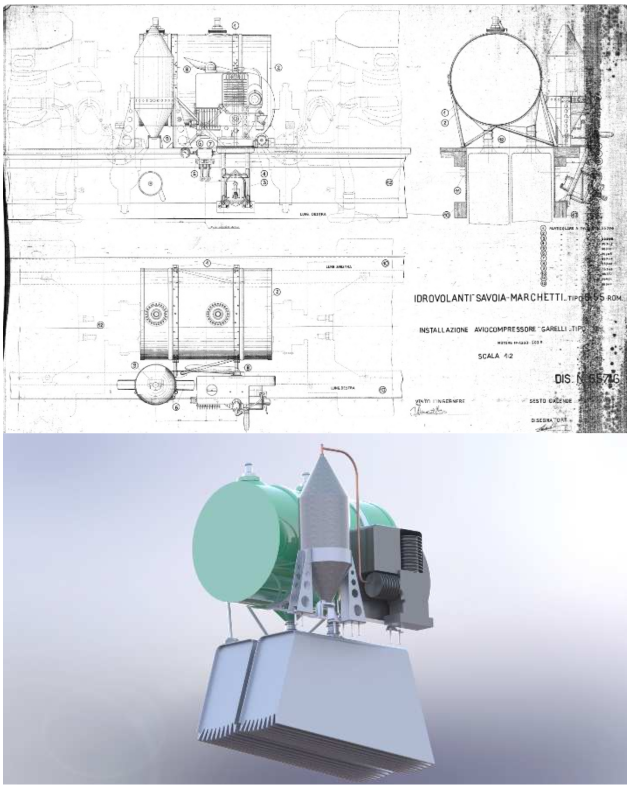

Figure 11: Garelli compressor for engine start-up

In our S-55X replica we have been able to accomodate, with some difficulty, two modern pilots with a percentile 97, corresponding according the reference tables, to a pilot with a total height of about 188 cm. Same considerations were taken for the definition of the four seats designed inside each hull plus a fifth one for an assistance crew member.

The design of the covering windows above the cockpit area has been slightly raised to allow the use of safety helmets by the crew, protection pretty unusual in the 30's.

Safety Installations: aircraft of the 30's were generally not provided with safety equipment nowadays considered standard; safety belts, for example, were not generally installed and, when installed, they were generally two point straps. On the original S-55X design there was no safety belts provision, not for the pilots nor for the crew. Adding modern type, multi point, safety belts creates not easy to solve issues because the original structure was not designed to provide suitable attachment points, satisfying the modern safety requirements imposed by the aircraft authorities. For example the JAR-VLA requires for the crew retaining device the capability to sustain a longitudinal acceleration of 12 g's, a vertical acceleration of 4 g's and a side acceleration of 2 g's. Not easy to comply on an old wooden craft designed almost 100 years ago.

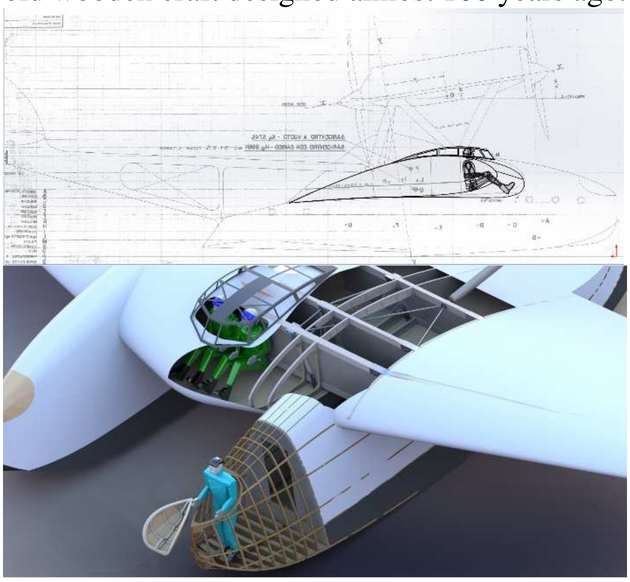

Figure 12: Ergonomics issues

3. Team S55 & structural idealization

Even if largely derived from original drawings, the engineering and manufacturing process has been rationalized, having as a reference basis the rules and criteria imposed by current EASA regulations. A group of young engineers of the Polytechnic of Turin founded on December 2017 the " TEAM S-55 " giving the opportunity to several students to achieve a significant experience about all the key aspects of the complete aeronautical design process: from the definition of aerodynamic and hydrodynamic loads to the characterization of the materials used and finally to the FEM structural modelling of the entire structure. Furthermore, all the themes of the aircraft design, i.e.: flight mechanics, propulsion, flight controls, systems installation, et caetera were also addressed.

3.1. Wood as composite material

The use of existing aeronautical composite materials can be considered as a return to the origins of aeronautical history after the period of metals. The S55 Seaplane is mainly made of wood. This material, made of cellulose fibers embedded in a lignin matrix, from the structural analysis point of view, can be considered as a composite material. Plywood and GLULAM (Structural glued-laminated timber) are currently used in aeronautical constructions. Plywood is usually available in the form of a laminate consisting of glued sheets, suitably oriented and optimized for the load application. The plywood with typical orientations at 0°, 90 °, 45° allows a random redistribution of the defects, present in the original solid wood. In this way, the material can be considered more homogeneous, localized stress concentrations are avoided and an increasing in mechanical performance is expected. As an example in figure 13 the trend of the critical compression load is reported Vs the specific stiffness. Three types of orientation, a plywood panel with all the layers oriented at 0°, a second case with layers at +-45 ° and a quasi-isotropic lamination [-45/0/+45/90]s. with different types of wood has been considered. ANC18 [6] has been used as reference for the mechanical characteristics used in calculation. In detail in figure 13 it is showed how the quasi-isotropic laminate is able to reduce the dispersion of the data present in the laminations at 0 ° and + -45°. Moreover an important activity was dedicated to the definition of the mechanical characteristics of the orthotropic sheets forming the laminates present in the aircraft and to the definition of the stratification of the different items of the aircraft. The original S55 material distribution serves as a baseline on which to intervene with the possibilities offered by current numerical controlled processes and the wide wood material choice today commercially offered.

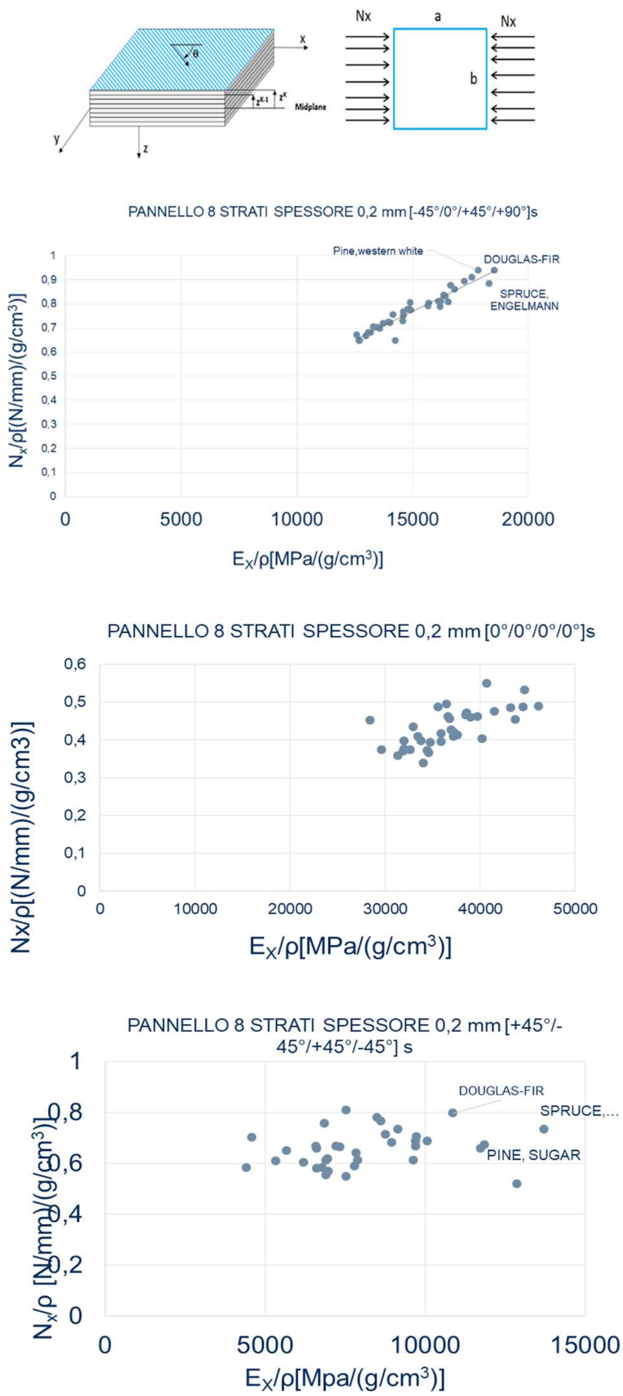

Figure 13: Unidirectional critical load of different plywood configurations

Figure 14 shows the materials adopted with attention to the different types of wood used in the various components of the aircraft. The type of wood most used in making the S55 is birch plywood (Yellow Birch). The plywood has been used extensively to make wing and empennages panels, central wing, floors, diaphrams, frames, ribs, spar webs, panels of leading and trailing edges. Plywood is also widely used in side and bottom panels of the two hulls.
Hemlock is then used in engine truss, ailerons, stiffening stringers of the horizontal empennage, while oak is used in the aileron compensation surface. Yellow poplar plywood is then used especially for the wing and empennages ribs.

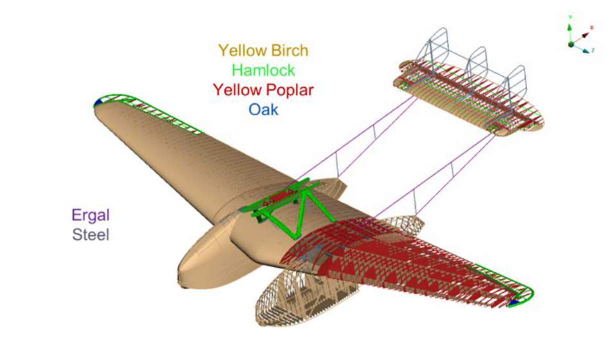

Figure 14: Typical materials in S55 aircraft

In order to avoid distortion effects due to thermal variations or moisture absorption, it is advisable that the orientations of the laminate sheets in the gluing sequence are such as to constitute a set of plies symmetrical and balanced as possible.
• Symmetrical laminate: at each plate above the mid - plane it must correspond one below of the same orientation
• Balanced laminate: each plate oriented at +θ and placed at +z must be inside the laminate a lamina oriented to -θ at -z).
In the mechanical junction zones it is preferable to have sequences consisting of many layers with different orientations (quasi-isotropic sequences), meanwhile for the shear loaded members is structurally more convenient made them with plywood oriented to -/+ 45 °. The laminates consist of a sequence of layers of orthotropic material (MAT8 in FEM material properties card) whose constitutive equation is as follows:

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

$$\begin{Bmatrix}\tau_{13}\\ \tau_{23}\end{Bmatrix}=\begin{bmatrix}G_{13} & 0\\ 0 & G_{23}\end{bmatrix}\begin{Bmatrix}\gamma_{13}\\ \gamma_{23}\end{Bmatrix} \quad (1)$$

Constants Q_{ij} are derived from the macro mechanical properties of unidirectional lamina by means E_{11}, E_{22}, ν_{12}, G_{12}, G_{13}, G_{23} using the following formulas:

$$Q_{11}=\frac{E_{11}}{1-\nu_{12}\nu_{21}}\ ;\ Q_{22}=\frac{E_{22}}{1-\nu_{12}\nu_{21}}\ ;$$
$$Q_{12}=\frac{\nu_{12}E_{22}}{1-\nu_{12}\nu_{21}}\ ;\ Q_{66}=G_{12} \quad (2)$$

Mechanical properties of orthotropic lamina of materials used in Finite Element Model are below summarized in tab. 1:

Table 1: Mechanical properties of UD lamina of wood materials used in Finite Element Model

	Unit	Hemlock	Oak	Yellow Poplar	Yellow Birch
ρ	g/cm^3	0,45	0,61	0,44	0,64
E_{11}	MPa	11300	11300	8618	12755
E_{22}	MPa	350,3	926,6	370	637,75
ν_{12}		0,423	0,448	0,392	0,45
G_{12}	MPa	361,6	915,3	594,64	867,34
G_{13}	MPa	429,4	1005,7	646,4	943,87
G_{23}	MPa	33,9	1005,7	146,5	216,8
X_C	MPa	49	45	28,27	44,82
Y_C	MPa	3,8	6,4	4,274	9,515
X_T	MPa	78	96	59,3	104,1
Y_T	MPa	2,3	-	1,723	2,69
S	MPa	8,6	13,2	6,412	11,24

The constitutive equation of the elements laminated in orthotropic material (PCOMP in FEM) is consequently obtained by taking into consideration the orientation and the thicknesses of the single layers. The link between the loads acting on the medium plane of the laminate and the related deformations / curvatures can be expressed by the relation:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} \quad (3)$$

Where A, B, D are respectively the membrane, coupling and flexural stiffness. In case of symmetrical lamination the elements of the matrix B are equal to zero and the membrane behavior will be completely separated from the bending one. If the laminate is balanced the coefficients A_{16}, A_{26}, D_{16}, D_{26} will equal zero. Fig. 15 shows as an example the lamination of the S55 upper wing panel, while Fig. 16 shows the hull with the relative laminations.

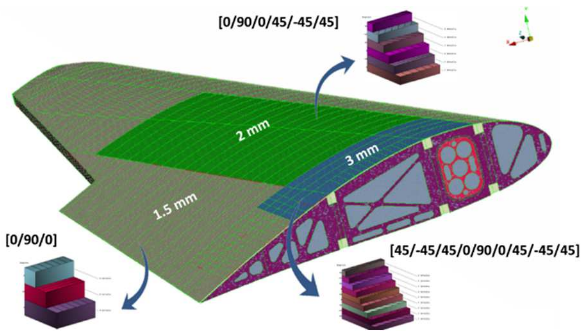

Figure 15: S-55 Wing upper panel plywood thickness and lamination

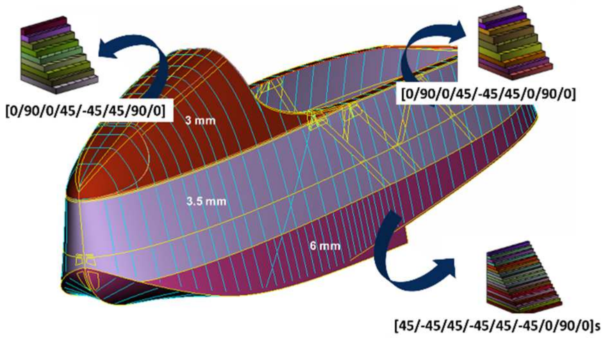

Figure 16: S-55 Hull panel plywood thickness and lamination

The wing panel has areas with three different thicknesses (3mm, 2.5mm, 1.5mm), the laminations are symmetrical except for the 2mm plywood obtained from the gluing of two 1 mm plies. The hull, made of birch plywood, shows in the top area a laminate consisting of 9 layers and a total thickness of 3mm, an intermediate area made of of 9 layers too with a thickness of 3.5 mm and an area with a maximum 6 mm thickness made with 18 layers. This thickness is required in order to withstand the high pressure loads that occurs in the S-55 hull during the ditching phase.

3.2. FE model definition

Pre and post processing phases benefited from the support of BETA CAE Systems, the main student team sponsor. The complete FEM model build up, from CAD data to ready-to-run solver input file was performed by the advanced CAE pre-processing software ANSA®. Modal and static analysis were subsequently conducted with the NASTRAN® solver. The analysis of results was finally conducted with the post processor META®. The FEM idealization and the subsequent simulations, allowed the members of Team S55, through the re-analysis of a project of the past, to acquire important skills related to the correct idealization of an aeronautical structure made of laminated composite material, as happens in the FEM simulation of a modern aircraft of the latest generation, through the use of the most modern techniques of structural simulation. Alessandro Marchetti, the original designer of the S-55 seaplane, did not have the chance to use modern simulation techniques; in spite of this he showed great ingenuity as both by young engineers and modern designers involved in the project had occasion to observe.

The first step in finite element modelling is to separate the structure into substructures – wings, hulls, ailerons, engine mount, stabilizers, etc. Then each substructure is reduced into its components - rings, ribs, spars, cover plates, etc. It is continued through as many levels as it is necessary. Then, the element type and the element size are chosen before the beginning of the finite element modelling of the S55 aircraft. The size and type of elements are adapted to the structures. The aircraft structure is modelled by shell, beam and three-dimensional finite elements. All parts of the aircraft structure are modelled separately. The masses of the different parts are modelled as the non-structural or concentrated masses. The structural parts are joined into subassemblies and then the stiffness calculation and the modal analysis are done.

Modal Analysis: The determination of natural (normal) frequencies and natural (normal) mode shapes of the structure with damping neglected is the first step in the dynamic analysis. According to natural frequencies and natural mode shapes that characterize the basic dynamic behaviour of the structure, we have the indication of how the structure will respond to dynamic loading. The natural frequencies of a structure are the frequencies at which the structure naturally tends to vibrate if subjected to a disturbance. An appropriate deformed shape of the structure at a specific natural frequency of vibration is its normal mode shape, or the normal mode of vibration. Natural frequencies and natural mode shapes depend on the structural properties and boundary conditions. Computation of natural frequencies and natural mode shapes of a structure could be of great significance. They tell us at what frequencies the structure can be excited into resonant motion. In many cases, this information is sufficient for modifying the structural design in order to reduce noise and vibration. An example of free mode shape of S55 Aileron and Hub are reported in figure17 and 18.

Static analysis is performed mainly to verify stiffness and strength of the entire structure.

Starting from composite components it is possible to determine the failure index (FI) using the values of the tensile, compressive and shear allowable values, shown in table 1, in combination with classic interactive failure criteria used for composite materials (Tsai Hill criteria):

$$FI = \frac{\sigma_1^2}{X_{t,c}^2} + \frac{\sigma_2^2}{Y_{t,c}^2} + \frac{\sigma_1\sigma_2}{X_{t,c}^2} + \frac{\tau_{12}^2}{S^2} \qquad (4)$$

Where σ_{ij} are ply stresses from the Nastran analysis and X, Y, S are ply stress tensile, compressive and shear allowable from the PCOMP bulk data entry. The failure index calculation permit the identification of the critical areas, and, where necessary, to made the adequate structural modification in order to verify the fulfilment of the strength and stability safety requirements imposed by the regulations.

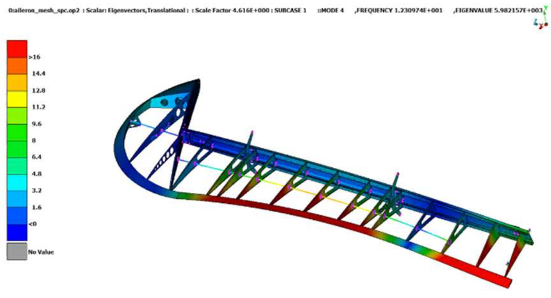

Figure 17: Aileron free mode shape (Mode 4- bending mode)

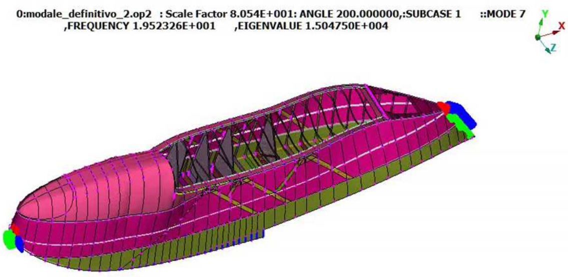

Figure 18: Hull free mode shape (Mode 7 – torsional mode)

In figure 19 and 20 is presented, as an example, the results of the static analysis in terms of displacements and stresses, performed on the S55 wing and relevant to the load case simulating the vertical max load factor of 3.17.

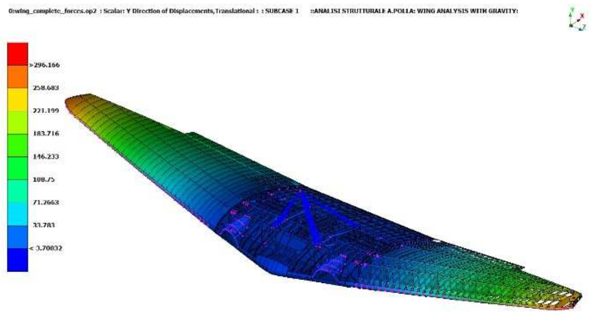

Figure 19: Static wing deflection at maximum load factor Nz=3.17

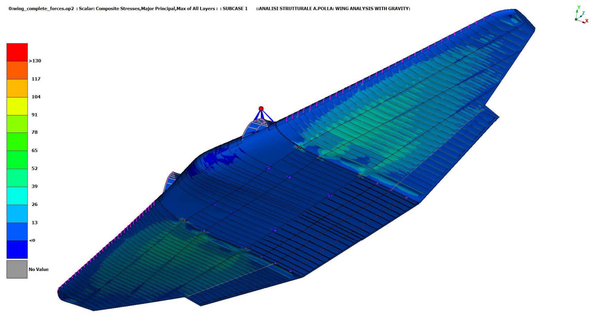

Figure 20: Stress on the bottom of the wing at maximum load factor Nz=3.17

3.3. Loads and type of analysis

According to the EASA " CS¬23 Certification Specifications the main flight load cases selected for the analysis are:

- Max speed at max/min load factor
- Min speed at max/min load factor
- Max aileron load at max deflection
- 1/3 aileron deflection associated at 2,66 max speed
- Gust Load
- Empennages cases max deflection

All the load cases are considered at minimum and maximum aircraft weight.

As far as is related to water load, the structure of S 55 seaplane Savoia Marchetti *".....must be designed for water loads developed during take-off and landing with the seaplane in any attitude likely to occur in normal operation at appropriate forward and sinking velocities under the most severe sea conditions likely to be encountered...."* (EASA " CS¬23 Certification Specifications). The EASA CS 23 suggests the use following formula to calculate the pressure at the hull bottom . (see also fig. 21).

$$p = \frac{C_4 K_2 V_{SO}^2}{tan(\beta)} \qquad (5)$$

Where VSO is the seaplane stalling speed and b is the angle of dead rise at appropriate station, C4 and K2 are coefficients calculated according to CS23.527 and CS23Appendix I.

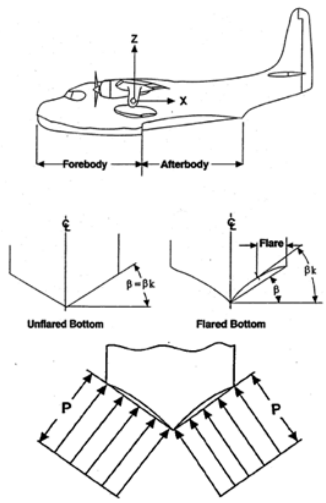

Figure 21: EASA CS23 Pressure at Hull bottom

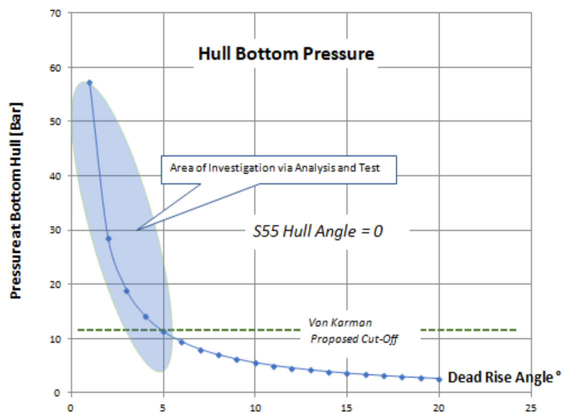

Figure 22: Hull bottom pressure computation

The formula is very similar to the one proposed by T. von Karman in a paper published in the 1929. Furthermore the interesting paper by A. G. Smith, C. H. E. Warren, D. F. Wright. (1957). is presenting the results of their investigation reviews of the work done up to 1948 on the behavior of aircraft when making a forced landing on water. The von Karman approach is discussed and is well evidenced that this formula is a useful guide, but for tangβ < 5 deg the mean pressure is not likely to be very much greater than its value for 5 deg. It can be observed in fig 22 that the pressure values can reaches values presumably not compatible with the structural strength

Moreover the theoretical approach needs to be confirmed either by numerical simulation supported by test on model. A numerical model will be prepared for the water impact simulation during landing. Furthermore it is planned to validate the theoretical approach with a test on a scaled model which similitude is based on Froude Number. The evaluation variation of the pressure vs time could be studied as well as the distribution of maximum pressure at the bottom of the hull.

4. Conclusions

To design a flying "replica" of the S-55X seaplane is, from the engineering point of view, more complicate than to "reproduce" it. The current simulation and methodologies of analysis have been continuously compared with the ones used in the past (20's, 30's) that were usually the result on a brilliant intuition supported by a sound engineering judgement. The use of CAD techniques pointed out some inconsistencies between drawings of different edition. The use of wood, as an aeronautical material, has opened a new scenario in terms of availability and reliability of wood mechanical properties. The extensive use of the modern tools of simulation in different fields as aerodynamics, flight mechanics, structural with FEM, water impact et caetera, and the comparison with the formulas and the old test results has provided unending stimulus in pushing us towards a holistic conception of the aircraft as a whole integrated system the capabilities of which are over and above those of the single systems. Furthermore, this paper is a tribute to the genius of Alessandro Marchetti, the Italian engineer who created the Savoia-Marchetti S55 Aircraft.

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