REPLICA 55 PROJECT: AERODYNAMIC AND FEM ANALYSIS OF A WOODEN SEAPLANE

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Abstract

The engineering approach and the technical contents of an aeronautical design project is presented as the result of a students team work at their last year of bachelor's degree at Polytechnic of Turin (Italy). Starting from a complete wooden seaplane, the Savoia Marchetti S55, aerodynamic, flight mechanics and structural analysis were performed and investigated in detail.
From the point of view of structural modeling, the obtained results present how a natural composite material such as wood, can be treated as the latest generation composite materials adopted in aeronautical constructions

1 Introduction

The project of double hulled flying boat called S55 and produced by the Italian company, Savoia Marchetti was born in a military environment between the Two World Wars age. Shortly after its introduction, it began setting records for its speed, payload, altitude and range. In particular it is known for the oceanic transverse in 1933 from Orbetello to Chicago.
S55 is a non-conventional seaplane, twin-engine monoplane, it has two wire-braced booms connected to the triple-finned tail structure and to the twin hulls and wing. Passengers and cargo were placed in the two hulls. More than one version was available. We take into consideration the S55X, as shown in figure 1, where the final X was used to point out Arma Aeronautica's decennial.
The last remaining example is exhibited at TAM museum in Sao Carlos (Brazil).

Fig. 1. S55 exposed in Tam Museum [1]

To bring to the ancient splendors S55 aircraft, "Replica 55" program was born in 2016 [2].
"Replica 55" is made up of a group of professionals in the aeronautics sector with the aim of designing, building and flying the faithful replica of the S-55X aircraft. The flying version must be rationalized in accordance with current aeronautical regulations. For this purpose, the S55 Team of the Polytechnic of Turin started the necessary analysis of aerodynamics, flight mechanics, structural analysis. The team activities also deal with the definition of the flight envelope and the pressure loads acting on the hull in the ditching phase, including a sophisticated dynamic numerical / experimental impact analysis. It also aims to build a flying-scale model to validate the simulation techniques and construction technologies applied to the full-

scale model and to participate in FAI competitions for the F4C category.
This paper presents the results of the final thesis at Polytechnic of Turin [3] [4] [5] [6] [7] [8] [9] [10] [11] in collaboration with professors and aeronautical sector technicians [12].

2 Flight Loads & static stability

In order to calculate flight loads distributions and for the preliminary study of the flight mechanics of the S55 Aircraft, AVL software, developed by Prof. Drela at MIT, was used. The software receives in input a file containing the geometric characteristics of the aircraft and the appropriate reference quantities, and simulates a flight condition in which the lifting surfaces are analyzed with a VLM (Vortex Latex Method) model. The presence of a fuselage or a hull is analyzed by the software using a slender-body model. The files that contain the characteristics of the different airfoils adopted in the lifting surfaces have a structure typically used in the XFOIL software with the coordinates dimensioned with respect to the local chord and are used by AVL to recover the information regarding the camber shape. In figure 2 the airfoil used on the wing and on the horizontal tail are shown.

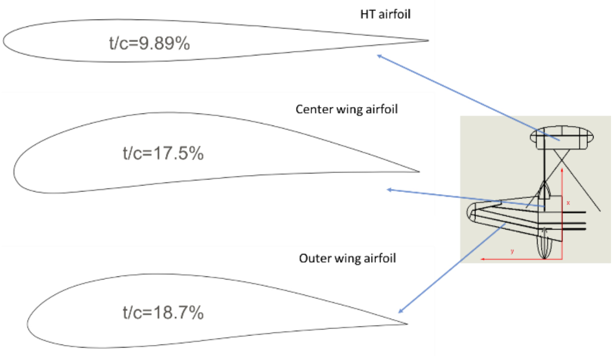

Fig. 2. Wing & Horizontal tail geometries derived from CAD

For each section of the wing it is therefore necessary to report both the local value of the airfoil chord, in order to properly rescale the section, and the value of the local angle of attack, which corresponds to the chord angle with respect to the horizontal reference axis, to realize a possible warping of the wing. The information concerning the chord distribution, the warping angle and the wing dihedral angle were obtained from the S55 CAD model and summarized in figure 3.

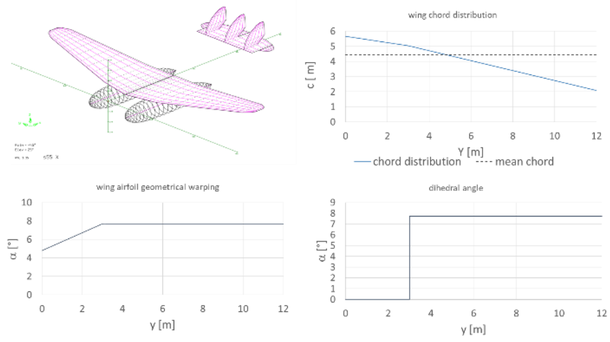

Fig. 3. Aircraft geometrical characteristics derived from CAD

Ailerons, elevator and rudders have been included according to the geometric characteristics derived by CAD and simulated in AVL by means of normal vector tilting as indicated in figure 4.

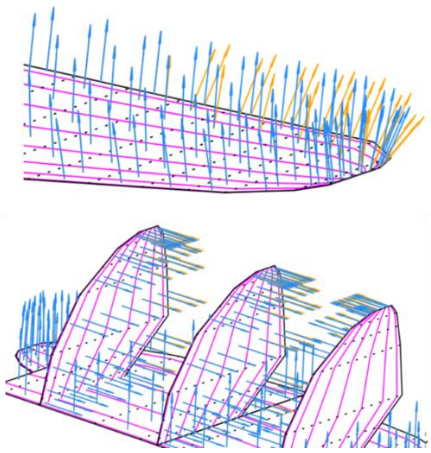

Fig. 4. Aileron and rudder simulation in AVL: normal vectors tilting

In cruise condition the deflection of the elevator is zero and the tail plane has a positive angle of about 3.46 ° with respect to the waterline. Yaw and roll angles are zero in the cruise condition. The aircraft, in trimmed horizontal flight at a cruising speed of V_{cr} = 63.9 m/, has a lifting coefficient of 0.4197 such as to balance the total reference weight of 10000 kg, an overall drag coefficient equal to 0.04093 pitching moment respect to CG equal to zero. Drag contributions relative to hulls, engine, engine mount and lifting surfaces skin friction are included in AVL by using semi empirical formulation derived from Roskam. The aerodynamic polar obtained with AVL was then compared with previous results obtained through Panel CODE [13] and with data related to a wind tunnel test done on a 1:30 scale model by Regia Aeronautica [14]. The results show an excellent correspondence both in the CL-alpha and in the CD-CL polar. The polar is shown in figure 5 for Panel Code with and without the skin friction contributions, the estimated frictional contributions obtained by semi-empirical formulas are added to the AVL result and compared with the wind tunnel data. An excellent agreement between numerical data and experimental data has been obtained.

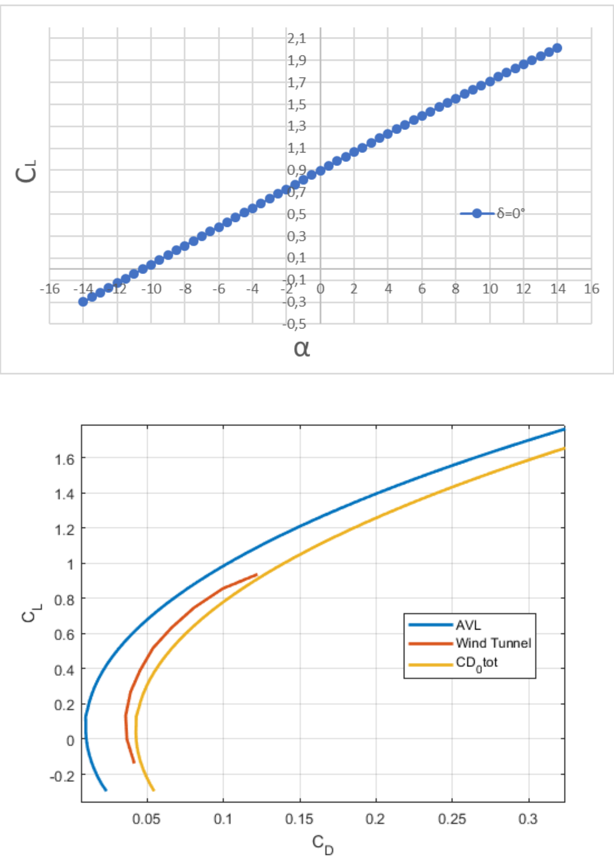

Fig. 5. Numerical/experimental aerodynamic results [4] [8]

The EASA CS-23 regulation requirements [15], has been used as reference for maneuver and gust envelope load cases definition.

Starting from the envelope diagram reported in figure 6 and critical points has been derived:

1. Point A: n = 3.17 and V = 54.92 $\frac{m}{s}$
2. Point C: n = 3.17 and V = 63.89 $\frac{m}{s}$
3. Point D: n = 2.36 and V = 89.44 $\frac{m}{s}$
4. Point ST: n = 1.00 and V = 30.83 $\frac{m}{s}$

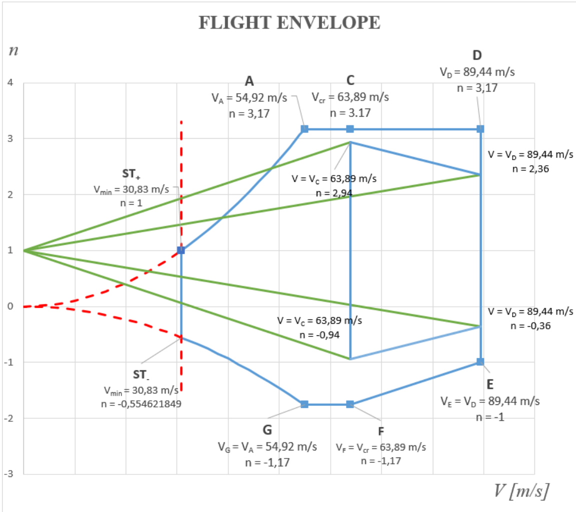

Fig. 6. Numerical/experimental aerodynamic

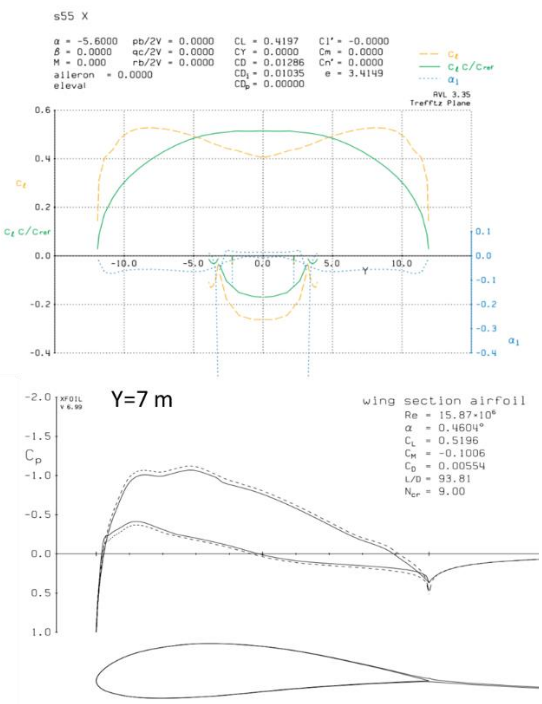

Fig. 7. Typical span and chord aerodynamic loads distributions

Preliminary loads distributions along lifting surfaces has been derived by the aerodynamic model. In figure 7 a typical span and chord

pressure distribution are shown for the cruise condition case.
A preliminary flight mechanics static stability analysis has been conducted by using the same AVL S55 model. In order to obtain longitudinal static stability, as specified in regulation requirements, the pitching moment at zero-lift angle of attack, C_{m0}, has to be positive and the derivative of the pitching moment with respect to the angle of attack, $C_{m\alpha}$, must be negative. Both these requirements are met by the S55 aircraft as shown in figure 8.

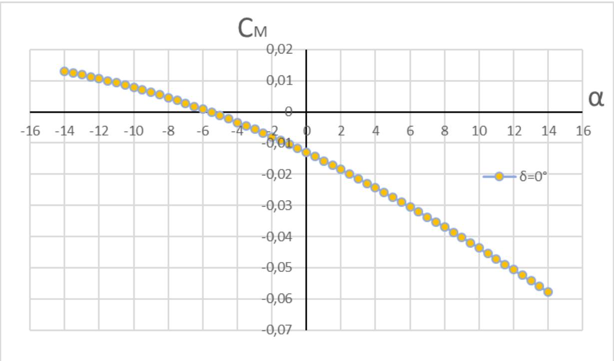

Fig. 8. Longitudinal stability [4] [8]

For static lateral stability, one requirement is that aircraft's yaw stiffness, $Cn\beta$, must be positive and also in this case the S55 aircraft satisfy the requirement as indicated in figure 9.

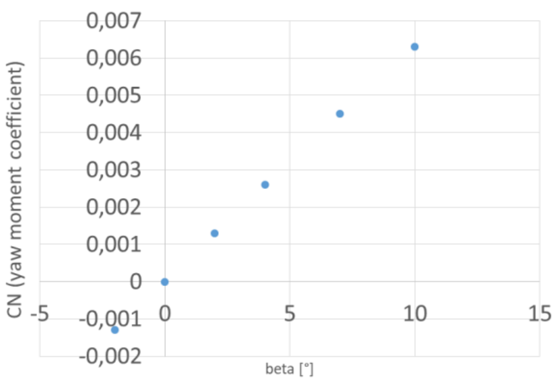

Fig. 9. Lateral stability: yaw stiffness

4 FEM analysis

The structural configuration considered as reference for FEM idealization was the CAD model, made available by Replica S55 team and developed from the original drawings. Pre- and post-processors were supplied by 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 using the NASTRAN® solver. The analysis of the results was finally conducted with the post processor META®.

4.1 From CAD to FEM

4.1.1 Geometry correction

The S55 structure divided in components: wing, hull, tail, ailerons and powerplant.

The first step after importing the CAD model in ANSA was the identification of geometry errors called "unchecked". They must be deleted by reconstructing faces or connections between surfaces, joining lines or removing overlapped surfaces. They mainly represent inconsistencies given by geometry translation problems. First of all the not structural junction elements were neglected and every part decomposed in subsets, keeping into consideration only the structural elements such as skin, ribs, spars, frames, leading edge and trailing edge. According to the structural component shapes we extract the middle surfaces which represent the support surfaces for the mesh in most cases. The real structure also presents special cases such as the one shown in the figure 11 and corresponding to the main wing spar where the mesh support geometries have been obtained by projecting the spar caps to the inner surface of the spar web as indicated. The correct positions of the material properties were then obtained by applying offsets. A similar procedure has been adopted in the case of oriented stiffeners.
What previously described is not sufficient for a ready-to-mesh model because discontinuities between the extracted surfaces are still present and it is therefore essential to restore continuity through intersections of surfaces or, if necessary, the realization of new joining surfaces. This has to be done not only between spars and ribs but

also between internal components and external skin. The final result is a bi-dimensional model without residual discontinuities. In the figure 10 and 11 the passage from the tri-dimensional CAD model to the bi-dimensional geometry is presented.

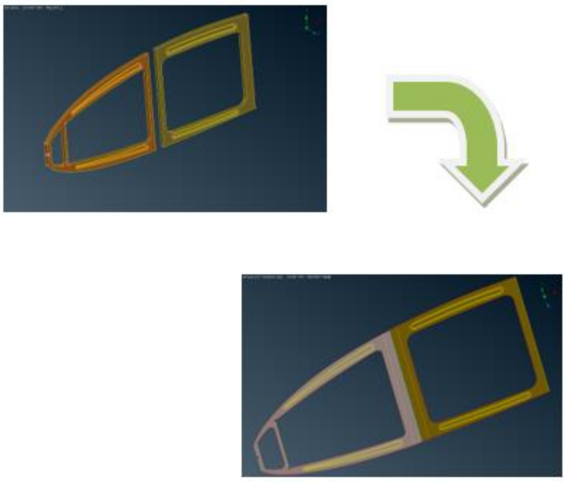

Fig. 10. From 3D to 2D model

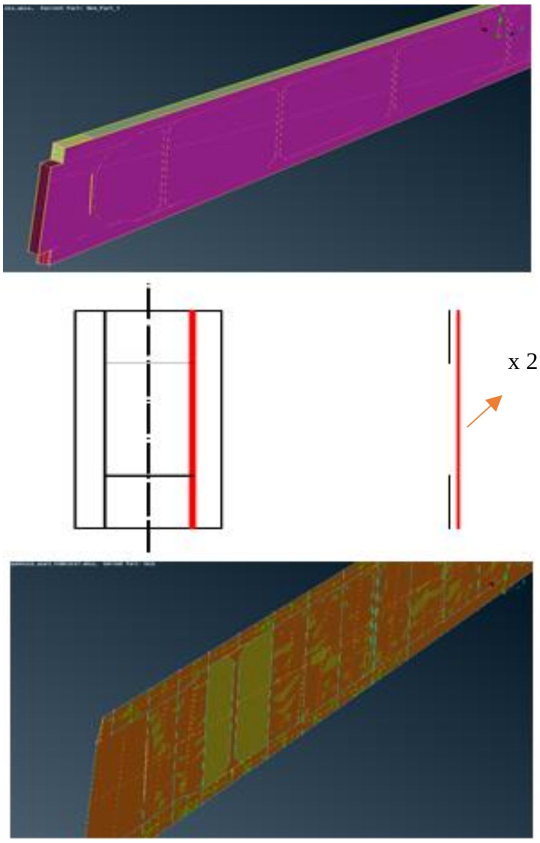

Fig. 11. S55 main spar

4.1.2 Materials and Properties

The material properties of each component have been derived according to the wood material list reported in table 1.

Table 1. Materials

Material List		
Name	**Specification**	**Status**
Hemlock Western *(Tsuga Heterophylla)*	ANC-18	Wood Planks
Douglas Fir *(Pseudotsuga Taxifolia)*	ANC-18	Wood Planks
Ash White *(Fraxinus Supp.)*	ANC-18	Wood Planks
Balsa *(Ochroma Pyramidale)*	ANC-18	Wood Planks
Yellow Poplar *(Liriodendron Tulipifera)*	ANC-18/EN314	Plywood
Birch *(Betula Spp.)*	ANC-18/DNV-GL	Plywood

Material characteristics, derived from ANC-18 regulation and from MIL Handbook, are included in the computer database so that an identification number is associated to each material. In this context MAT 1 and MAT 8 categories are used. The isotropic material, defined by MAT 1 entry, is the most commonly used material property. An isotropic material is defined as a material that has the same properties in any direction. Furthermore, the isotropic material is fully described by only two constants: a combination of Young Modulus E, Shear Modulus G or Poisson Modulus ν. MAT 8, instead, is used to define a two-dimensional orthotropic stress-strain relationship and can be used only with the plate and shell elements. It is defined by E_1, E_2, G_{12}, G_{1z}, G_{2z} ν_{12}, ρ.
Materials distribution is also visible from ANSA dedicated tools that allows to easy visualize the main used materials (figure 12).

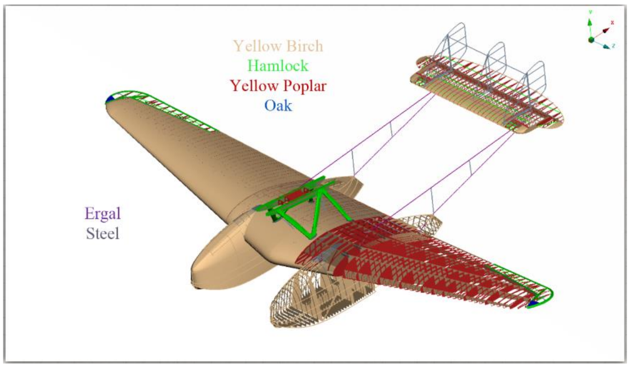

Fig. 12. Materials distribution

Materials are strictly related to properties which list and report all components' characteristics as thickness, material id, type of fem elements (shell, beam or solid). Each element belongs to different categories as PCOMP, PSHELL or PBEAM. In particular PCOMP, which defines composites' property, is largely used like is described in table 2. It best represents natural composite behavior and allows us to recreate laminated panels as the original S55.

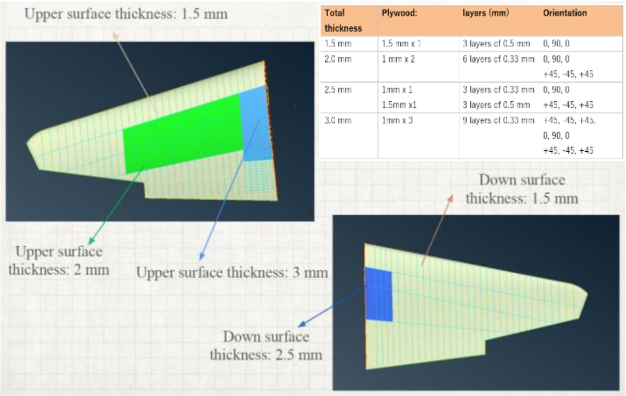

Fig. 13. Wing laminated panels

Wing, hulls and tail present laminated panels. An example is wing external skin which is made of panels with different thicknesses like it's shown in figure 13. This implies a sequence of layers with different orientations that simulate wood fibers orientation along longitudinal direction of the component.

Table 2. wing components properties.

WING	Beams		BEAM BAR	Mat1	Hemlock
		Multiholed	PCOMP	Mat8	Birch
		Reinforcement for Central Body	PCOMP	Mat8	Birch
		Normals	PCOMP	Mat8	Poplar
		Connection with Central Body	PCOMP	Mat8	Poplar
	Spars	Spar 1 & 5	PCOMP	Mat8	Birch
		Spar 2 3 4 & slanting	PCOMP	Mat8	Poplar
		Reinforcement for 2 3 4 & slanting	PCOMP	Mat8	Birch
	Leading and Trailing Edges		PCOMP	Mat8	Birch
	Fasciame	Principale	LAMINATE	Mat8	Birch
		Superiore verso Tronco Centrale	LAMINATE	Mat8	Birch
		Inferiore verso Tronco	LAMINATE	Mat8	Birch
		Superiore esteso	LAMINATE	Mat8	Birch

Lamination sequences should be symmetric and balanced to avoid undesired distortions. Fibers orientation in ANSA is quickly and easy represented by oriented arrows as it is shown in figure 14.

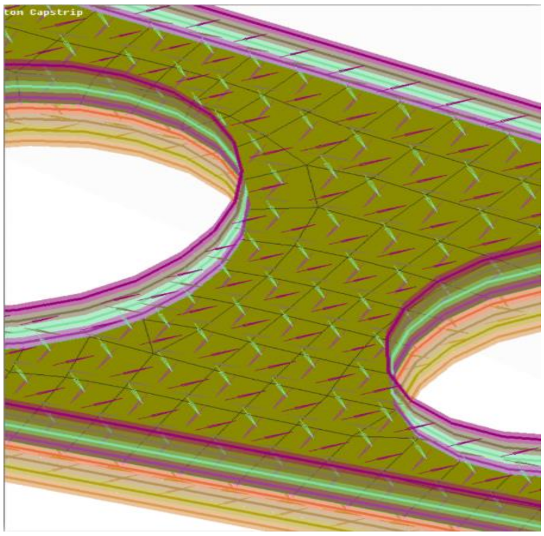

Fig. 14. Laminated panel

4.1.3 FE Model

After cleaning up the geometry the following step is the creation of mesh. Software ANSA provides procedures for which different parameters and behaviours can be automatically applied and replicated, this is the example of setting up the mesh length parameters and the mesh behaviour in the neighbourhood of a hole. The mesh elements must respect some quality criteria: aspect ratio, warping, skewness, minimum and maximum length, internal angles and percentage of triangles. In table 3 adopted values are reported.

Table 3. Quality criteria numerical values.

Criteria	Calculation	Color	Failed
☑ aspect ratio	NASTRAN		5.
☑ skewness	NASTRAN		45.
☑ warping	NASTRAN		15.
☑ min length			2.
☑ max length			15.
☑ min angle quads	NASTRAN		45.
☑ max angle quads	NASTRAN		135.
☑ min angle trias	NASTRAN		20.
☑ max angle trias	NASTRAN		120.
☑ triangles %			3.

The mesh is automatically generated respecting the set rules as much as possible.
The created mesh elements are the bi-dimensional CQUAD4 and CTRIA3.

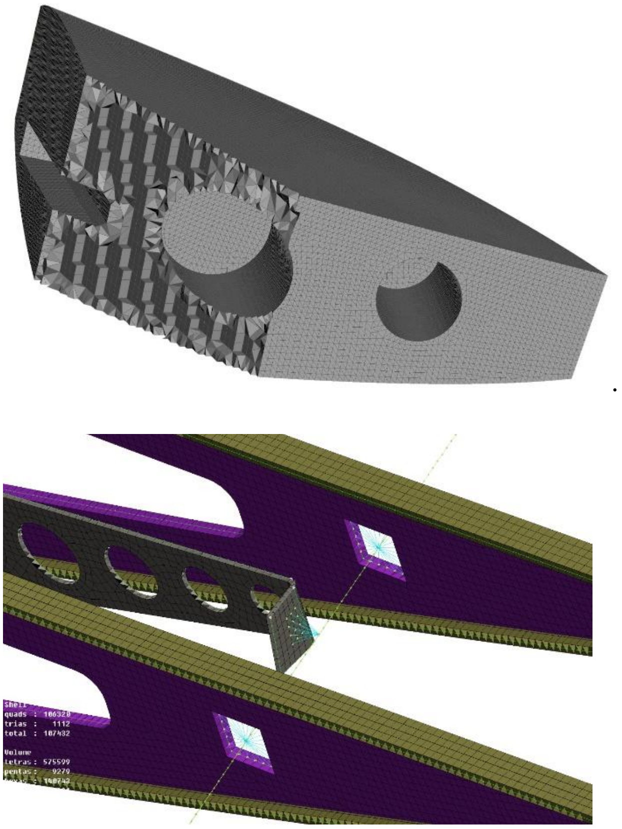

Fig. 15. 1D, 2D, 3D Elements and Rbe

The area of the mesh elements that are not pre-imposed rules "Off elements" are evidenced for a possible modification.

In addition to the bi-dimensional elements in the S55 model there are also Beam elements and Solid elements. Relevant to beams elements the software ANSA offers a catalogue where common areas section like box, cylinder, H, C and T sections are suggested. Furthermore, the creation of solid requires the presence of bi-dimensional elements on the whole object surface, the solid functions create a solid mesh as TETRA, PENTA and HEXA, starting from the bi-dimensional ones, as it is visible from table 4.

Table 4. Number of elements in S55 model

		shell		Volume				
	Beam	Quads	Trias	Tetras	Pentas	Hexas		Total
Wing	1282	362394	9740	-	-	-	x 2	746832
Central Body	4994	384480	10601	-	-	-		400075
Hull	8289	756547	27276	20944	525	12945	x 2	1653052
Tail	20595	477455	2905	-	-	-		500955
Aileron	1733	304463	2196	575599	9279	140743	x 2	2068026
Powerplant	800	78182	1982	911264	1484	121878		1115590
					complete aircraft elements			6484530

Finally, all mesh elements must be joined together simulating bonding, joints, welding, rivets and pins. This connection can be made by a rigid body element (RBE) (figure 15). The function allows us to select some elements grids, the Slaves, that must have the same behaviour; the reference movement is taken from another grid, the Master. In this way a part, or all the Slaves degrees of freedom, will be blocked and they will follow the DOF of the Master grid. With this function, shell and solid components that were not joined by geometrical constraints are bounded together. Special attention must be paid to the RBE used to merge the interfaces of components. The real degrees of freedom shall be properly simulated.

The complete S55 model is finally obtained by the joining at the proper interfaces of all the components together, un example in figure 16.

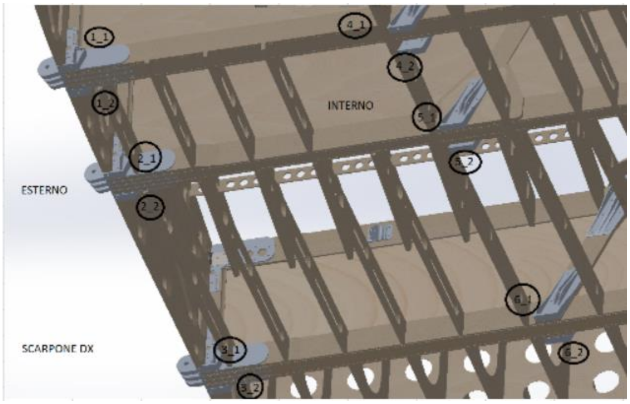

Figure 16. Hull-central body interface points

Analysis

4.2.1 Modal analysis

Modal analysis represents the preliminary step which allows to have a preliminary information about the FEM idealization adequacy. Firstly, single component analysis, called SOL 103, was performed.

SOL 103 is a dynamic analysis that determine the object's own natural frequencies, i.e. those frequencies that depend on shape, materials and boundary conditions. An example is given by the simulation of external constraints applied on ailerons. The natural frequencies produce a resonance response of the entire component. It is important that engines have different operational frequencies and we need to evaluate the influence of coupled perturbations in order not to amplify resonance vibrations.

Before studying the whole seaplane, all single components must be checked by a SOL 103 analysis. A preliminary study consists on evaluate the deformation energy of the structure using a grounding check analysis on the stiffness matrix by moving the model rigidly. If the deformation energy is restrained the component is modelized in a good manner and his eigenvalues, in SOL 103, can well represent the reality. The Nastran output file, which has format .f06, shows a list of eigenvalues (eigenvalues' number is chosen before the analysis) with their characteristic frequencies (cycles). Values are listed in increasing order. The first six modes are rigid, they are translations and rotations around body axis, then there are global and local modes. Global modes can be torsional, flexural or combined; while local modes can be, for example, different panel modes. Local mode must be at higher frequencies so if not, a revision of local stiffness must be carried out. Single component analysis was firstly performed; below powerplant (figure 17), aileron (figure 18), tail (figure 19) and hull (figure 20) behaviours are presented. Fringe modality allows us to immediately read results.

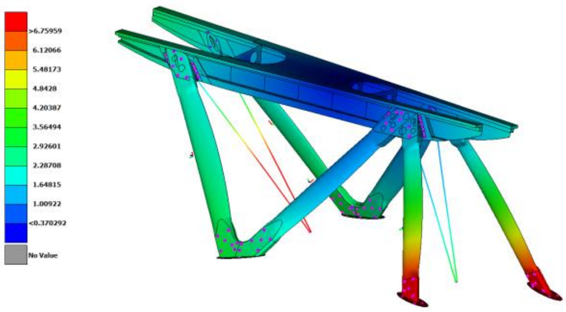

Fig. 17. Powerplant behaviour in modal analysis Flexional free at 7.18 Hz

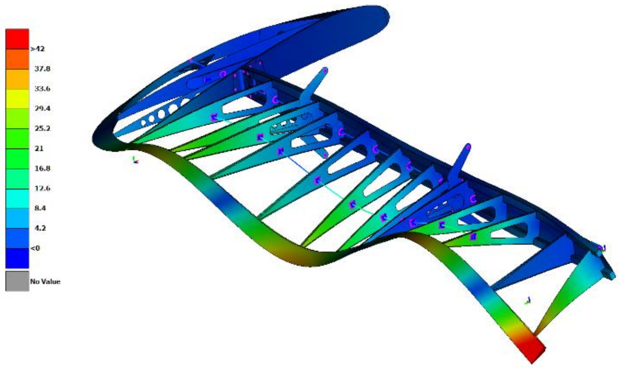

Fig. 18. Aileron behaviour in modal analysis: flexional bounded at 33.98 Hz

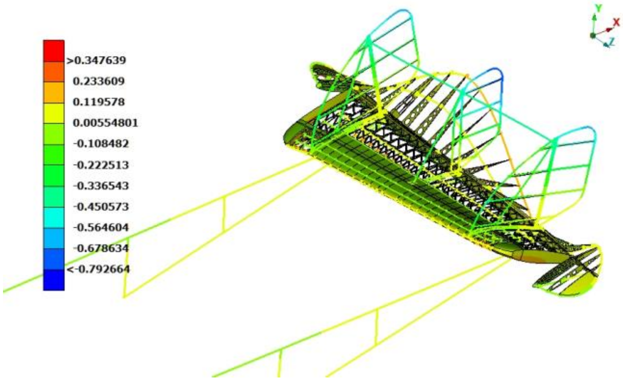

Fig. 19. Tail behaviour in modal analysis: Torsional free at 4.64 Hz

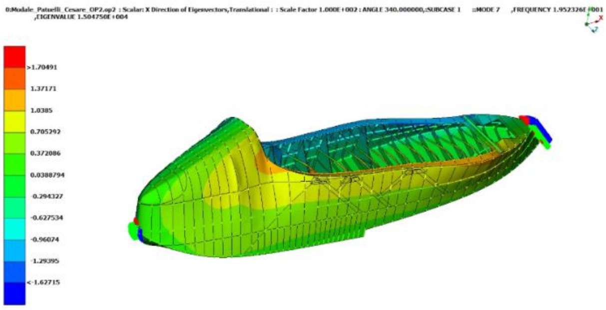

Fig. 20. Hull behaviour in modal analysis: torsional Free at 19.5 Hz

Finally, entire S55 modal analysis was computed. The result is visible in figure 21.

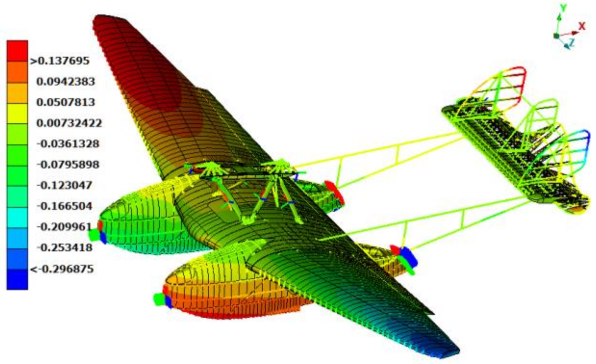

Fig. 21. Global S55 behaviour in modal analysis: flexional bounded at 6.65 Hz

4.2.2 Static analysis

Purpose of the static analysis is to verify the behavior of the various components by different load conditions as indicated in flight envelope. The objective of the static analysis is therefore to determine stress and strain present in the structure when subjected to external loads including the inertial effects. In this kind of analysis, it is of fundamental importance to obtain a failure index capable of defining the safety margins with respect to the design parameters.

This task is done by the SOL 101 provided in Nastran, specific for the analysis of body in equilibrium under the action of applied loads and relevant constraints.

The applied load is a self-equilibrated load system that include aero and inertial effects.

The selected critical load case is the maximum contingency factor $n_z = 3.17$**.** In particular, as we can find from regulations, maximum value of envelope diagram has been considered.

From the aerodynamic parameters the pressure distribution of the entire envelope diagram of S55 aircraft has been defined (fig. 22 and fig. 23).

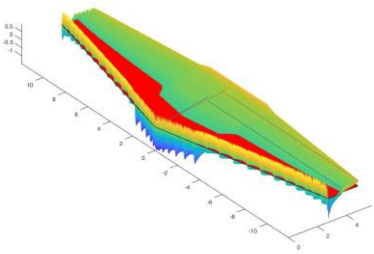

Fig. 22. Pressure distribution on wing

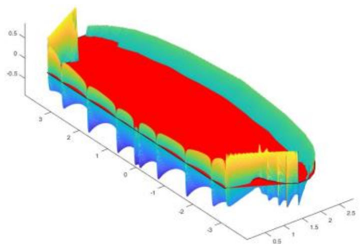

Fig. 23. Pressure distribution on tail

By adopting the specific interpolating function from the CFD calculation it was therefore possible to define the load value at the prior grid of the mesh and grounded at its interfaces.

Once the specific pressure values have been obtained for each node, PLOAD2 have been defined from a Nastran deck. The values used were obtained through the typical pressure law having available the various distributions of C_p + - at the different x, y, z coordinates of the wing profile.

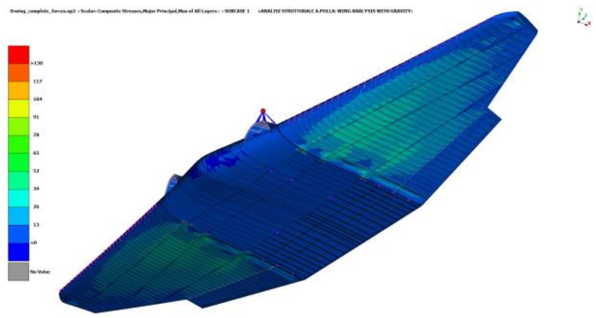

Fig. 24. Wing stress

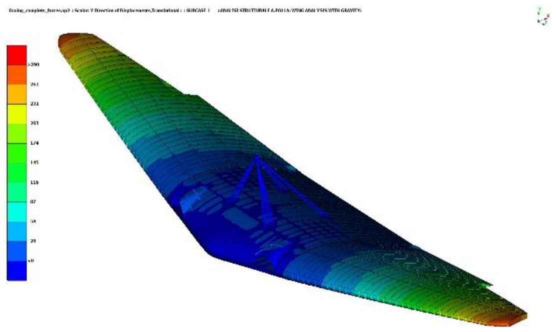

Fig. 25. Wing deformation

Results (figure 24) define the distribution of stress in the ventral part of the wing profile to highlight a tension field in traction after a deformation of the whole wing system under the applied loads. The maximum stress load present in the panels is around 65MPa. The type of lamellar woods used for the coating presents an admissible breaking point of about 120MPa. We can therefore identify a safety factor of around SF = 2. The load case examined is confirmed as the critical one in the flight envelope of the S55 aircraft. Despite the analysis at the diagram limits we can see how the design of the aircraft provides a safe flight for any situation.

From figure 25 deformations can be appreciated for the same load case. The maximum deformation of about 290mm is reached at the wing tip. Considering a wingspan of 24m and the wooden material constituting the entire aircraft, we can confirm that deformations of 1.16% to contingency factor n_z = 3.17 are more than acceptable. The S55 wing has a safety margin of about 2 compared to the design load case. The deformations at the wing tip is consistent with the stress field. Next step will be to apply aero and inertial load to the complete aircraft. By adopting the PARAM, INREL, -2 a complete static of the maximum contingency factor aircraft can thus be obtained.

5 Conclusion

In this study many technical details have been investigated. An aerodynamic model has been calculated and a FEM model has been analyzed. We found out that computational results are in fairly good agreement with experimental data. However, an improvement in each field can be necessary for better accuracy.

This experience gave us the chance to simulate the integrated activity of a real structural design team including team working, review meeting and project management. Grateful to the fantastic chance given to us, we continue initial project in a students' team, called "Team S55" at Polytechnic of Turin. The main purposes that Team S55 is determined to carry on are: scaled hull construction, hull impact in water modeling by LS-DYNA® software, model aircraft scaled 1:12 and improvements on current model.

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