

DUMONT'S DEMOISELLE: MODEL AND ANALYSIS

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Abstract: *Considered the master piece of Santos Dumont's designs, airplane Demoiselle presented several innovations. Simple geometric forms, common materials and constructional integration that avoided complicated details was used in the project. The idea was to make it simple so that people all over the world could construct one. Blueprints of the drawings of the plane were made available for free by Dumont himself. Many pilots and air clubs started from this action. Here this design is revisited having in mind the construction of a model of the airplane. With the model an analysis with finite elements for level flight is made in order to get the structural response of the structure of the plane. A discussion on its adequacy and structural response is then presented.*

Key-words: *Demoiselle, Drawings, Structural Model, Finite Element, Stresses*

1. INTRODUCTION

After 14-Bis flight, Santos Dumont realized that many design changes had to be included in airplanes in order to make them reliable. By 1907, tests and new model planes, led Dumont to come up with a new design concept, the Demoiselle, also known as Lebelulle (Nicolaou, 1987). This airplane had wings with nature inspired form, controlled by cables. Pilot seat, wheels and wing were disposed around a same vertical front plane. It was propelled initially by an Antoinette engine of 29 cv, placed on the top front of the wings. Stabilizers were positioned at the end of a truss type fuselage, Fig. 1.

Santos Dumont had in mind make airplanes popular, reason why made the blueprints of the constructions planes of Demoiselle available, at no cost, in an issue of Popular Mechanics published by 1910. Testing and improvement of the original design had already taken place by then. In the evolution process the airplane appeared with four series numbers, 19 for the first and 22 for the last. In each one a different engine was used. The range of powers started with 18 cv in the beginning, and ended with 50 cv in the last. With this design, Dumont broke several records, included covering a distance of 18 km in 16 minutes. Or reaching the speed record of 120 km/h in flight. Records were reached fast: a taking off in 70 m record, in less than 6.25 s, was broken in the same day with another one in 60 m.

First Demoiselle, identified as Demoiselle I, appeared in November 1907. This is considered the first ultra-light of history weighting only 550 N. With this plane, Dumont flew 200 m in Saint-Cyr, Paris. Demoiselle II appeared soon after, characterized by its two propellers constructed in aluminum and silk. Transmission problems with the chain of the propeller impeded this version to fly. Demoiselle III had an Antoinette engine of 25 cv, this time with a belt transmission. Again this version couldn't fly reason why it was abandoned. It took some time until the detected problems were solved. Demoiselle IV that appeared in 1909 was equipped with arched wings and a Dutheil-Chambers engine of 18 cv. Even though involved in accidents, this plane showed good response. A simplified version, Demoiselle V, appeared soon after, in June, 1909. Demoiselle VI appeared next, equipped with more power – a Darracq engine of 30 cv. With this version of Demoiselle, Santos Dumont broke several records of velocity and distance. Even under adverse circumstances.

Demoiselle VII was equipped with more power – a Clement-Bayard engine of 40 cv, but suffered an accident in the take-off. In 1910, the new plane, the Demoiselle VIII had its the wings broken at a height of about 30 m. Dumont didn't suffered serious injuries, but didn't pilot any longer. Last version of the plane, Demoiselle VIII, equipped with a 50 cv engine never flew.

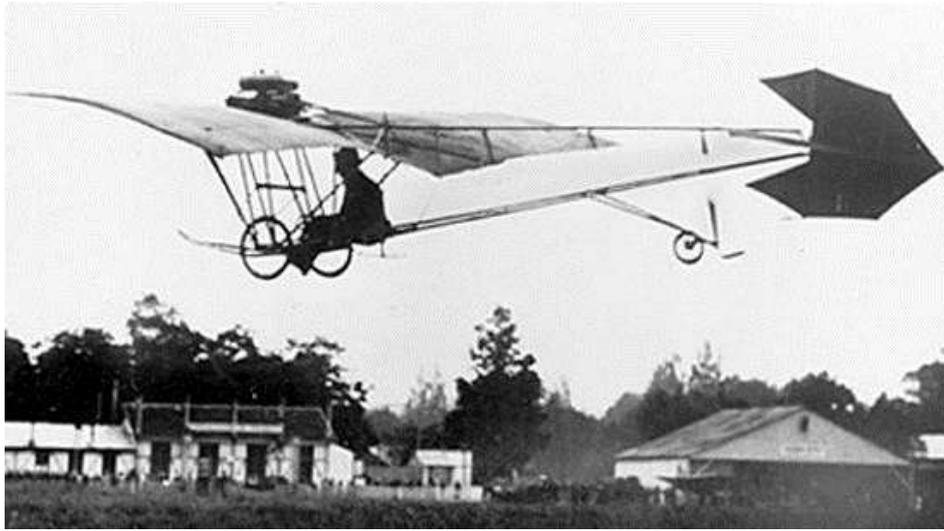


Fig. 1 Monomotor Demoiselle by Dumont

2. MODEL

In order to construct a model for numerical analysis, drawings of the structure of the airplane must be constructed. Information from blue-prints of the airplane, as published by Santos Dumont himself in Popular Mechanics (Joerin 1910), were used, as well as photographs and trial-and-error dimensions for sectional parts. Materials considered were as indicated in the literature, with their main mechanical properties used to determine the constitutive matrix. Failure criteria were used to ascertain the proposed dimensions as acceptable, as real dimensions for all parts of the structure are not available. Also as Demoiselle name comprises different versions, a set of parameters had to be chosen from a specific plane. Data in Table 1 identifies values used in the modelling process.

Table 1: Main Characteristics of Demoiselle

Parameter	Value
Lenght, m	6.07
Span, m	5.49
Height, m	2.40
Wing Area, m ²	10.68
Weight, N	1 078
Engine, cv	35
Top velocity, km/h	90

2.1. Demoiselle Drawings

Demoiselle was developed having in mind the popularization of airplanes (Taylor, 1989), reason why Dumont published the plants of the plane for free. Not only the views of the plane, but details about materials, fixtures used for the parts and construction were included. Figure 2 shows an overall view of the elevation plan, with some dimensions for the sub-systems: wings, the open frame of the fuselage, the horizontal and vertical stabilizers, the propeller, engine, some control elements and landing system. Imperial units were used in the published material. This set of data was used because of easiness of access. Not only that: it refers to a specific version of the airplane. Accompanying this view, a front view was included to further details.

Fuselage system comprised bamboo beams with diagonal strings. Engine, pilot, main and auxiliary tanks for fuel and water, landing carriage and stabilizers in the back of the plane and wings were all supported by this unit, reason why fixation of its elements had to be well done, as shown in the drawings.

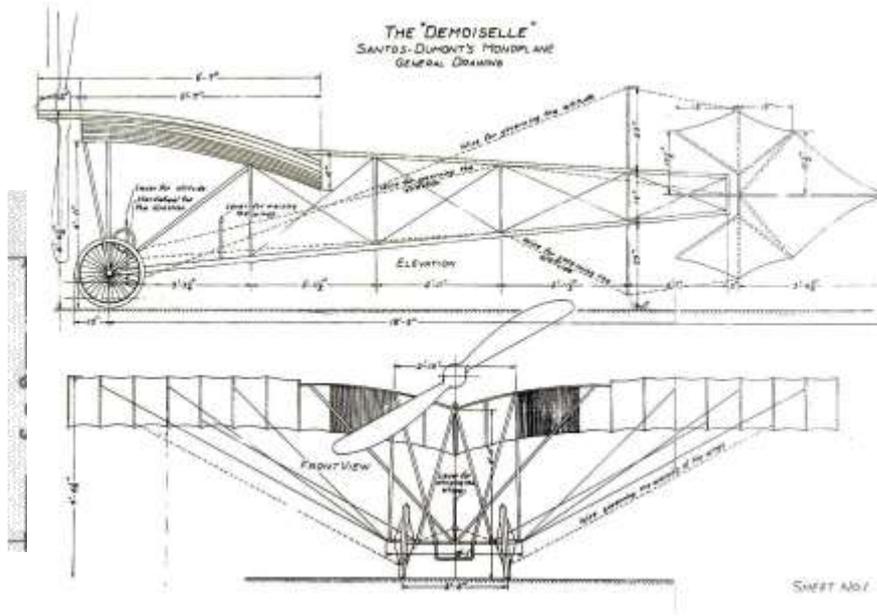


Fig. 2 General drawing of monoplaner Demoiselle as published in 1909

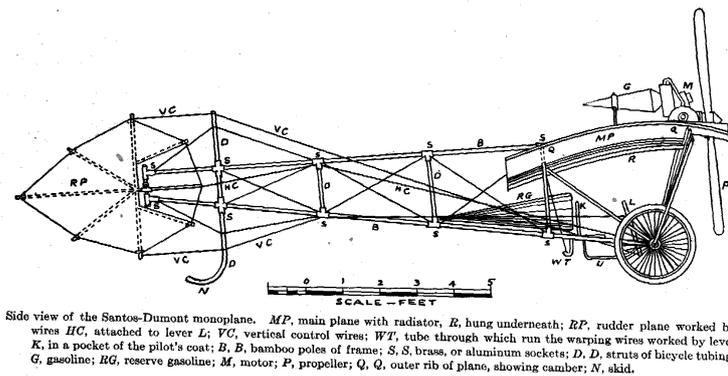


Fig. 3 Lateral view of airplane with description of function of components

The wing used by Dumont in Demoiselle was positioned on the top of the airplane, in the frontal part of it, right on top of the pilot compartment. It was a constant profile wing with cambered cord, very light and thin, symmetrically disposed about the airplane's longitudinal plane. Arching was introduced by wires. It comprised an inner part, where the propeller was placed just in front of the engine with a radiator just beneath, and having five shortened pieces. It was followed by eight complete units, supported by two transversal ribs with wires used to guarantee equilibrium of positions. Overall length of the wing 5.4864 m by 1.9558 m. Light tissue covered the wing, that had no flaps or ailerons.

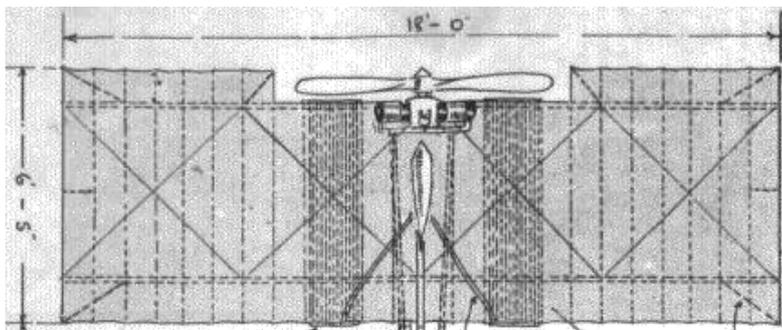


Fig. 4 Upper view of Demoiselle wing system

2.2. Computer Model

In order to construct a model of Demoiselle, drawings in computer of the structural parts of the plane are required. First element in this process is the wing system. Wing is positioned right on top of the pilot place, but not in a horizontal plane. On the external region the height of the wing, with respect to the ground, is of 1.3843 m while at the central region this number decreases to 1.2192 m. A set of cable elements is fixed in the wing system to confer the desired degree of fixation and archness. In the outer region, a wire is attached at every other profile frame. In the inner part, a pair of struts, for each side of the wing, were used. Fig. 5 shows the drawing of half wing in computer program SolidWorks™, 2013.

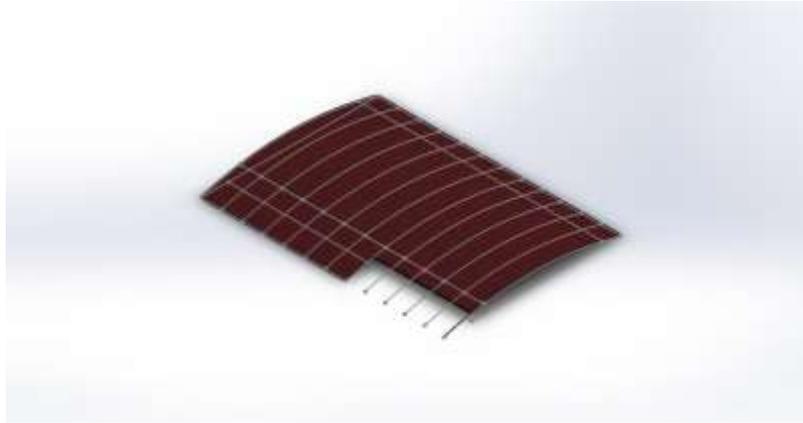


Fig. 5 Half wing drawing developed in computer

Next component to be drawn is the fuselage of Demoiselle. This is an open frame construction with truss elements reinforced in some points by cable elements, used also as a fixation means for other components. The fuselage was constructed using different materials: bamboo was used in the upper and lower longitudinal elements, fixed by brass or aluminum sockets, while transverse elements were built from struts of bicycle tubing. Control wires were attached to this structure on their way to the controlled surfaces, rudder and horizontal stabilizer. Fig. 6 shows the drawing of the fuselage frame produced in computer. Seat of the pilot, auxiliary fuel and water tank, as well as landing wheel system are mounted in this unit. This frame had 5 bays, with different sizes, with overall length of 5.56 m and maximum height of 1.22 m. Diagonal strings are not represented.

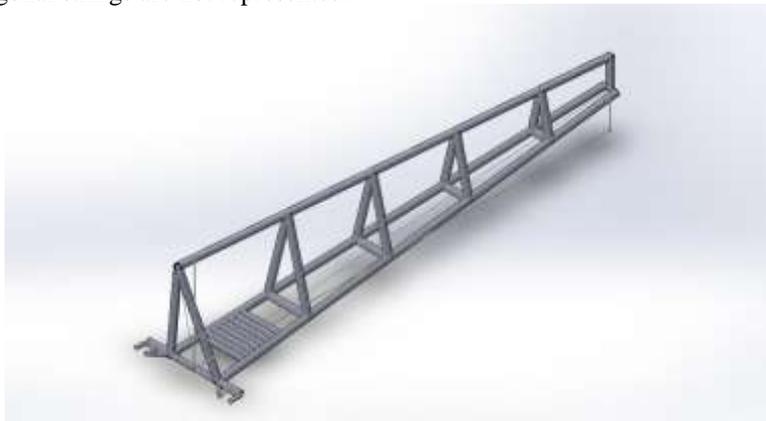


Fig. 6 Drawing of the open frame of fuselage of Demoiselle

Next elements in the model construction process are the rudder and horizontal stabilizer. Fig. 7 shows the horizontal control surface. This is a multi-body surface, constructed of bamboo sticks and tissue, acted by wires. It works as a membrane surface responsible for direction control in maneuvers, guided by a lever and wheel set at the pilot hands. It possesses 1.9558 m by 1.4478 m, being symmetric with respect to the longitudinal plane, being acted to rotate about a transversal axis 0.98 m long. From rotating axis, the unit measures 1.04 m.

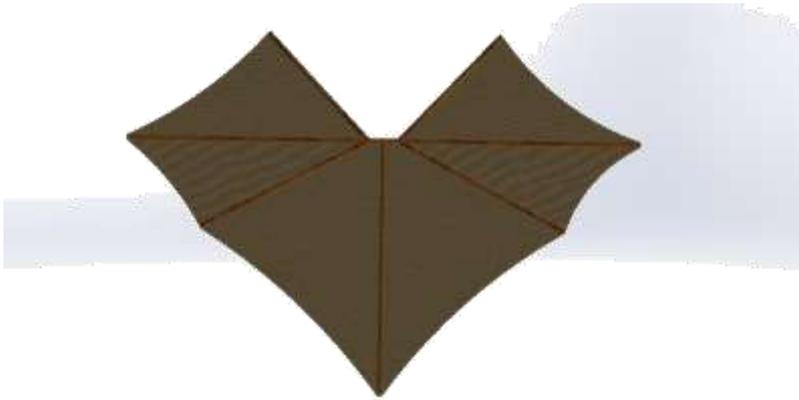


Fig. 7 Drawing of the horizontal stabilizer surface

Vertical stabilizer surface, the rudder, has a similar form of construction and control. Dimensions are different, however: it has 1.543 m in length by 1.0922 m. It comprises different bodies, with different geometries fixed to the same vertical pole. It is a symmetric construction. Upper unit has 0.4572 m in the front side and 0.381 m in the rear side with central axis located 0.4445 m above the main axis of the plane. Central element is all set in the rear side, being symmetric with respect to the longitudinal axis, measuring in this direction 1.0859 m with a lateral height of 0.4445 m. Fig. 8 shows the drawing of this unit. Table 2 the main mechanical properties of the material used in modelling, Khosrow, G and Marinho, A.B, 2005.

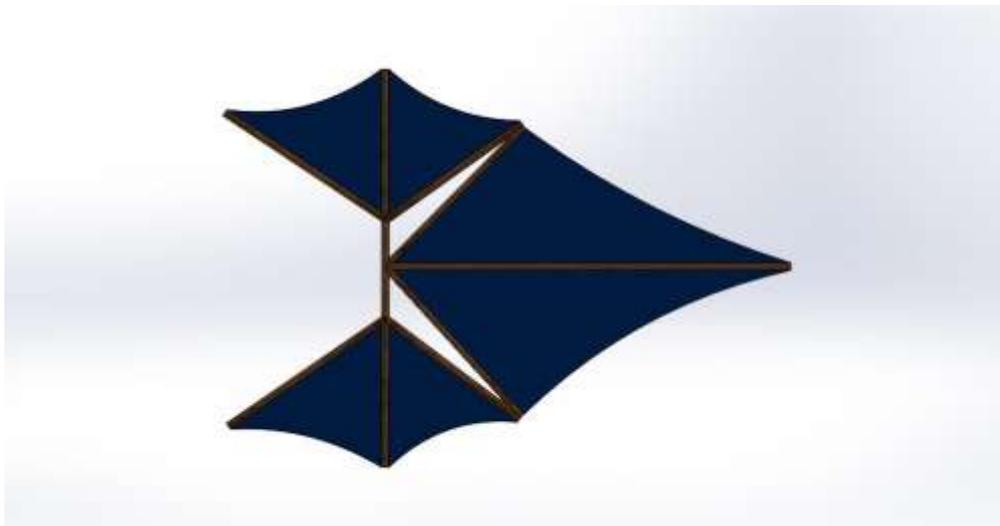


Fig. 8 Vertical control surface of Demoiselle

Table 2 Mechanical Properties of Materials

Material	Elastic Modulus, GPa	Traction Strength, MPa	Compressive Strength, MPa
Aluminum	71.70	124.	124.
Bamboo	19.00	14.8 - 38.4	6.2 - 9.3
Silk	1.40	55.2	55.2

2.3 Equilibrium Problem

Kinematics of the airplane depends on the interaction with the air around it. Prescribed the geometry of the plane, with its total weight \mathbf{W} and thrust force \mathbf{E} , aerodynamics lift \mathbf{L} and drag \mathbf{D} resultants are required to equilibrate inertia forces. These actions have different directions and point of application, indicating the existence of resultant couples. Lift and drag result from integration of contact stresses over the surface of the plane. Lift was produced in wings and control surfaces. They are obtained in the flow problem analysis, being dependent on the settings of the engine group and control surfaces for a particular trajectory

Newton's second law (Clancy, 1975) establishes that the rate of change of the linear momentum $\mathbf{L}_p = \int_{V_c^p} \mathbf{I}_p dV$ equals the summation of external forces applied to the plane. Here $\mathbf{I}_p = \rho_p \mathbf{v}_p$ with the subscripts identifying plane quantities. Therefore

$$\frac{\partial}{\partial t} \int_{V_c^p} \mathbf{I}_p dV = \mathbf{W} + \mathbf{E} + \mathbf{F}_a \quad (1)$$

representing \mathbf{F}_a the resulting interaction with air, obtained from integration of pressures p_a and tangential stresses τ_a :

$$\mathbf{F}_a = \int_{V_c^p} \mathbf{b}_a dV + \int_{S_c^a} \{-p_a \mathbf{n} + \tau_a \mathbf{t}\} dS \quad (2)$$

Force \mathbf{F}_a components in the vertical and horizontal directions are lift and drag:

$$\mathbf{L} = \mathbf{F}_a \cdot \mathbf{e}_k \quad (3)$$

$$\mathbf{D}_x = \mathbf{F}_a \cdot \mathbf{e}_x; \quad \mathbf{D}_y = \mathbf{F}_a \cdot \mathbf{e}_y \quad (4)$$

being $\langle \mathbf{e}_x, \mathbf{e}_y \rangle$ the in-plane unit vectors in x, y directions with the vertical direction identified by \mathbf{e}_k .

In the same form, the rate of change of the angular momentum $\mathbf{H}_p = \int_{V_c^p} \mathbf{h}_p dV$ where $\mathbf{h}_p = \mathbf{R}_p \times \mathbf{v}_p$ equals the summation of the moments of the external efforts:

$$\frac{\partial}{\partial t} \int_{V_c^p} \mathbf{h}_p dV = \sum_p \mathbf{M} \quad (5)$$

which comprises the moment resultant from air flow:

$$\mathbf{M}_a = \int_{V_c^p} \mathbf{R}_p \times \mathbf{b}_a dV + \int_{S_c^a} \mathbf{R}_p \times \{-p_a \mathbf{n} + \tau_a \mathbf{t}\} dS \quad (6)$$

This moment has also three components – pitch, yaw and roll.

2.4 Finite Element Approach

Upon specification of flight trajectory, from which plane velocities and accelerations may be found from solution of Eqs. (1) and (5), stresses and deformations in plane's structure will depend on the external actions derived in the flow problem. For any instantaneous configuration, internal stress field on the plane, may be determined using the principle of virtual work based on displacement field, (Zienkiewicz et al, 2010) as:

$$\int_{V_p} \delta \boldsymbol{\varepsilon}_p^T \boldsymbol{\sigma}_p dV = \int_{V_p} \delta \mathbf{d}_p^T \mathbf{b}_p dV + \int_{S_p} \delta \mathbf{d}_p^T \{-p_a \mathbf{n} + \boldsymbol{\tau}_a \mathbf{t}\} dS + \delta \mathbf{d}_p^T \{\mathbf{W} + \mathbf{E}\} \quad (7)$$

This equation depends on the velocity of the airplane \mathbf{v}_p and on the contact stresses on its surface, a function of the air velocity. In Eq. (7), displacement field is denoted as \mathbf{d}_p .

Discretizing the space occupied by the airplane by finite elements using bar, beam and shell elements as suited, leaves displacement field written in terms of the nodal displacements $\hat{\mathbf{d}}_p$ through interpolation functions N^v as,

$$\mathbf{d}_p = N^v \hat{\mathbf{d}}_p \quad (8)$$

Considering the stress-strain relationship for the structural materials and strain-displacement given by:

$$\begin{aligned} \boldsymbol{\sigma}_p &= \mathbf{C}_p \boldsymbol{\varepsilon}_p \\ \boldsymbol{\varepsilon}_p &= \mathbf{B}^d \hat{\mathbf{d}}_p \end{aligned} \quad (9)$$

and taking $\hat{\mathbf{v}}_p = \hat{\mathbf{d}}_{p,t}$ leads to:

$$\mathbf{M}_p \frac{\partial^2}{\partial t^2} \hat{\mathbf{d}}_p + \mathbf{K}_p \hat{\mathbf{d}}_p = \mathbf{R} \quad (10)$$

where:

$$\mathbf{K}_p = \int_{V_p} \mathbf{B}_p^T \mathbf{C}_p \mathbf{B}_p dV \quad (11)$$

$$\mathbf{M}_p = \int_{V_p} \mathbf{N}_p^T \rho_p \mathbf{N}_p dV \quad (12)$$

Here \mathbf{R} stands for the sum of the external forces, including the aerodynamic forces. \mathbf{M}_p stands for the consistent mass – derived from the separation of the body forces into inertia and the remaining others, $\mathbf{b}_p = \mathbf{b}_p^i + \mathbf{b}_p^o$. \mathbf{K}_p represents the stiffness matrix of the airplane, (Bathe, 2007) If constant velocity conditions are considered, the problem reduces to, at any instant, the solution of a simple system. From the solution, deformation displacements, and therefore stress and strain distribution on the plane are determined. From the deformed shape, an iterative procedure may be devised to recalculate the flow problem as affected by the iteration fluid-structure.

3. RESULTS

A normal flight comprises several phases: take off, level flight with some maneuvers and possible level changes, followed by the descending phase. In the level flight, at constant velocity, drag forces are equilibrated by thrust forces, whereas lift forces equilibrate weight of the airplane. Under these conditions, stress distribution in the fuselage of the plane have the distribution shown in Fig. 9. Bamboo thickness of 5 mm was supposed, resulting in maximum compressive stresses of 2.2 MPa in upper bar of fuselage. Positive stresses of the order of 25% of resistance were found. Efforts in the wings of the plane are transferred to the fuselage and to the strings responsible for the arching of the wings. Higher stresses, or the order of 60 % of bamboo strenght were found. In Fig, 10 the displacement field caused by action of these strings, as centered in the pilot post, is shown.



Fig. 9 Stress distribution in the fuselage of the plane

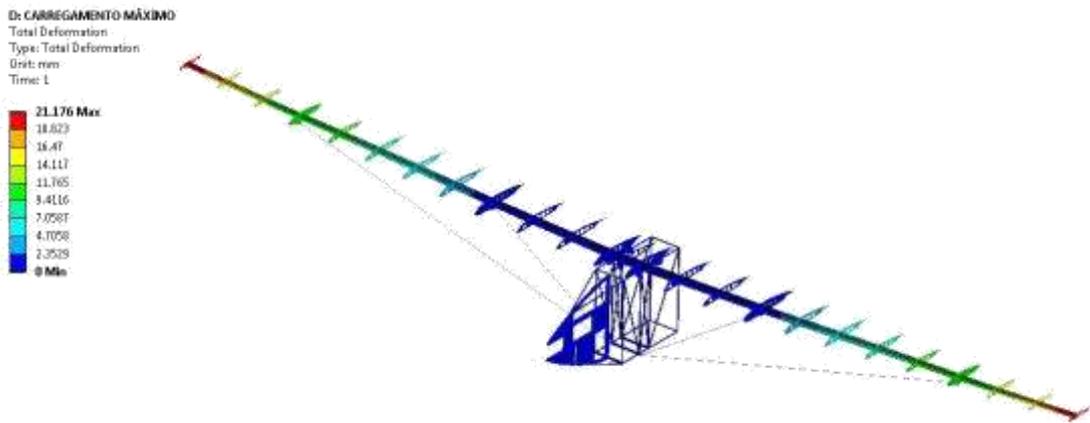


Fig. 10 Displacement field in the wing of the plane

4. MODEL CONSTRUCTION

A 1:10 scale model of Demoiselle was constructed as part of the work. Balsa wood was used all over, with thicknesses of parts between 5 and 10 mm. This material was chosen because of its lightness and easiness of work. It is basic material in model construction also. Fig. 11 shows the constructed fuselage while Fig. 11 shows that model wing. As shown in the wing model, bamboo sticks were used together with fiber glass, held with cotton fibre and aramide. Control surfaces were made of depron, Fig. 12.



Fig. 11 Fuselage of the scale model of Demoiselle



Fig. 11 Photograph of wing of scale model before skin application

Once constructed the main parts of the structure, the model was assembled. Servo-driven equipment was then installed in the model. The servomotors were commanded by means of a transmission radio in contact with a receptor in the plane. Motor used was a Emax 2228. Velocity controllers were used to exert functions assigned to the pilot. A battery Lipo 3S of 1380 mAh of 11.1 V was used to power the system.



Fig. 12 Control surfaces of the scale model

Demoiselle scale model was constructed in the installations of UFABC, where Harpia team works. Performance of the model was adequate under normal conditions. The model however failed in a crash created under harsh conditions.

5. CONCLUSIONS

A finite element model for structural analysis of Demoiselle was developed in this work. In it detailed drawings of the parts of the airplane were constructed and assembled. Flow problem of the complete model was not solved, resorting the solution to level flight conditions. Under these circumstances, stresses and deformations were computed using the processor of program SolidWorksTM. Chosen thicknesses of elements led to safe stress levels all over. Even though the wings of the plane were quite flexible, with large deflections, brittle failure of the sticks or membranes was not found. However, as stress resultants depend upon velocity and trajectory, much more cases would have to be considered in order to ascertain the safe domain of velocities for the plane. No matter that, the design parameters assumed for the analysis process represent a feasible solution to the structural dimensioning problem.

6. REFERENCES

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7. RESPONSABILITY

Authors are the only responsible for the contents of this work.