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WAGNER: a new code for parametrical structural study of fuselages of civil transport aircraft

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Abstract

In the present paper, a new code (named WAGNER) for a parametric and automatic Finite Element mesh generation of fuselages of civil transport aircraft is presented. The code aims at providing a time-cheap and reliable tool in the conceptual design phase in order to evaluate stresses and deformations in the whole fuselage structure; these data allows us a preliminary structural sizing to be used as a baseline for deeper investigations and to determine the empty weight of the fuselage on view of a preliminary prediction of the maximum take-off weight of the aircraft. As an example of application, two layouts have been analysed: a non conventional two aisle single-deck (SD) with 2-4-2 passengers abreast and a double-deck (DD) with 3-3 passengers abreast/deck. FEM results for two different load cases (combined loads at limit load factor and ultimate pressurization) with geometrical linear and non-linear solutions, are finally discussed.

Nomenclature

α	Angle of attack
α_Λ	Auxiliary angle
β	Angle of sideslip
γ	Beam inclination angle
η	Bending moments ratio with and without a rod
$\dot{X}$	Time derivative of X
$\frac{t}{c}$	Airfoil thickness (percent)
Λ	Sweep angle, beam slenderness
λ	Taper ratio
$\mathcal{L}_b$, $\mathcal{M}_b$, $\mathcal{N}_b$	Moments resultants along body frame axes
Φ	Roll angle
Ψ	Yaw angle
Θ	Pitch angle
A	Cross section area
c, c_R, c_T	Airfoil chord, root chord, tip chord
CG	Center of gravity
CL	Combined loads
DD	Double-deck configuration
E	Young 's modulus
g	Gravity acceleration
IR	Inertia relief
J	Cross section moment of inertia
L	Wing planform span, beam length
M	Bending moment
$MTOW$	Maximum take-off weight
n_z	Vertical load factor
p	Pressure
PrP	PrandtlPlane
q	Line load
RP	Reference Point
SD	Single-deck configuration
UP	Ultimate pressure load case
V_0	Flight speed
X_b, Y_b, Z_b	Forces resultants along body frame axes
x_b, y_b, z_b	Body frame axes

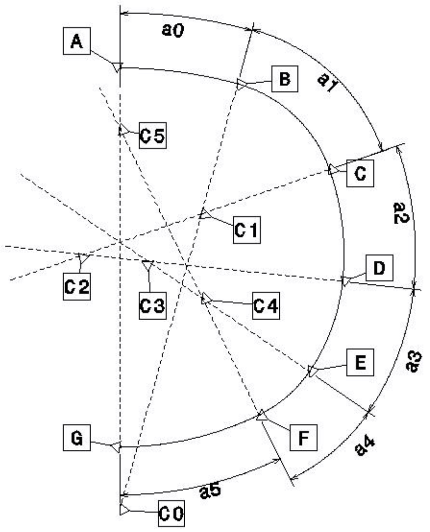
1. Introduction

WAGNER code has been carried out in the frame work of Parsifal project ([4], [6], [17], [12]); the input of this code is the internal layout of a fuselage of a civil transport aircraft and the output is the automatic generation of the Finite Element mesh of the complete fuselage, ready for static and dynamic preliminary analysis. In the very preliminary structural analysis, a large amount of structural configurations need to be analysed in order to compare benefits and drawbacks of different layouts, to verify the effects of modifications of geometry and material properties and, finally, to provide a preliminary sizing to be used as a baseline for future and deeper studies; hence, the generation of the FEM model is required to be simple, automatic and small time consuming. WAGNER code is written in *Python* language (release 2.7) to be run in *Abaqus FEA* software.

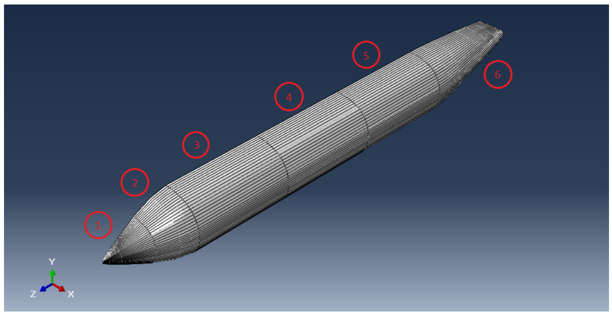
2. Geometry definition

2.1. Fuselage

The fuselage cross-section is realized by means of circular tangent arcs, so that the contour results in a C^1 piecewise-continuous function. The section internal contour is made of 12-arc cross-sections that, taking into account the longitudinal symmetry plane, it results in 6 independent circular arcs. The complete internal layout is generated by defining two other cross sections, one for the nose and one for the tail and, then, by using the *Abaqus Lofting* feature. The skin is longitudinally divided into six regions (an example is shown in Fig. 1); the user can set material and geometrical properties for each of them.



(a) General cross section



(b) Skin lofting

Figure 1. Fuselage

2.2. Frames

Frames are generated with a Z-shaped cross section; the user can define, for each of the aforementioned six zones, the web height and the angle-to-web ratio; by default, this value is fixed to 0.3 according to [2]. In nose and tail regions owing to the curvatures of the skin in both circumferential and longitudinal directions, frames orientation follows an averaged reference normal unit vector computed by the code (Fig. 2). Frames pitch is an input and it is maintained as constant in any region wherein the length is a multiple of the pitch itself; if not, the pitch for that sector is adjusted automatically. In WAGNER, some bulk frames can be introduced (e.g. to connect wings, empennages or main landing gears in the fuselage structure); for these bulk frames the overall dimensions result from a scaling factor chosen by the user, while the thickness can be assigned independently for any single element.

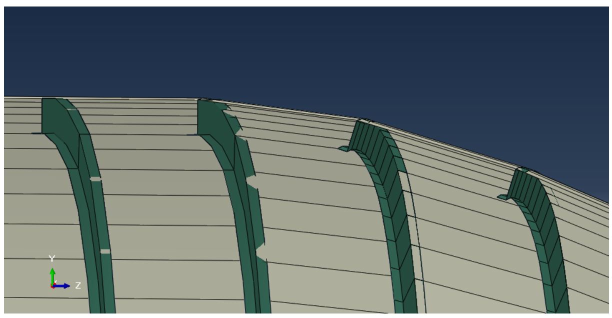


Figure 2. Frames orientation

2.3. Stringers

Stringers are designed with a Hat-shaped profile. The heights can be chosen independently for any of the arches composing the fuselage cross section; the flanges have the same flange-web lengths ratio along any of the arches. At the points connecting two arches (corresponding to a change of curvature of the internal layout of the fuselage), Hat-shaped stringers are substituted by symmetric closed box-shaped ones; with this solution, the high bending stresses occurring in these points ([5]) are significantly reduced. The stringers direction is automatically designed parallel to the skin.

2.4. Floor beams and Struts

Floor beams are generated as I-profiles. The height of the web is constant for all the beams of the passenger deck and the same occurs for the other(s). The user can specify the positions of beams of the decks independently in the fuselage; once the section has been designed, the beam is obtained by extrusion. By default, all the floor struts are generated as circular cylinders; the user can set the external diameter and the thickness and also choose whether to interrupt struts generation (i.e. in the intersection of the fuselage with the box wing) or not. In the nose and tail regions, struts disposition follows a straight line, as depicted in Fig. 3. This technique allows to generate struts all at once.

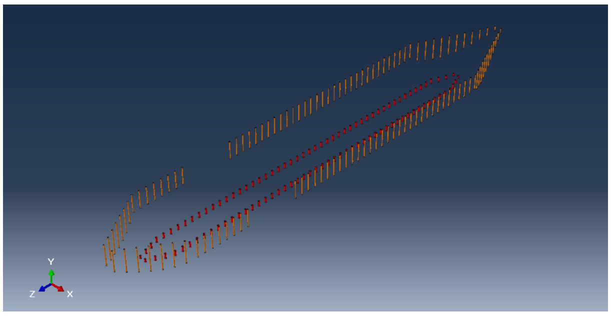


Figure 3. Passengers and cargo deck struts

2.5. Main Landing gear sponsons

The sponsons are a new feature that modify the bottom fuselage in order to allocate the main landing gears. These elements are used in the case of PrP aircraft and, more in general, for military (as C130 or C27J) or civil aircraft with high wing. Due to the impact on the aerodynamic drag, its exact shape should be the result of an aerodynamic design and, thus, just a simple standard profile has been implemented in the code. In the example of Fig. 4, the arc RGQ is a spline, the arc PCCQ is circular and DP is a straight line; a tool has been created for the automatic generation and for the solution of the problem of tangency. The user can define longitudinal and transversal dimensions of the sponson and can choose its relative positions with reference to the fuselage.

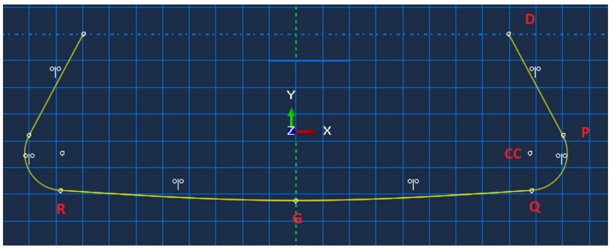


Figure 4. Sponson profile

2.6. Link beams

WAGNER code is provided of a tool for the generation of an innovative cross section of a fuselage where top and bottom fuselage are connected by a truss in the middle of the frames. This vertical link is the only 1D element in the code and reacts only to tension. The user can set the net area, the elastic properties and the pitch above fuselage frames. Their function is to reduce the vertical relative displacements of the fuselage under pressurization loads and reduce the stresses correspondingly.

2.7. Bulkheads

Pressurization bulkheads are automatically generated as planar shells because more realistic revolution-shells bulkheads would depend dramatically on the shapes of the 6 arches and, in most cases, *Abaqus* could not warrant the geometrical continuity of the parts. Hence, in order to maintain the robustness of the code, it has been decided to generate bulkheads as planar shells at this preliminary design stage, to be refined in a further design step.

2.8. Meshing

By default, the fuselage is meshed with shell elements, with the exception of the trusses, when present; the code assigns seed side, shape of the elements and meshing technique (all can be set by the user). Tab. 1 reports the default properties, with about half million elements to mesh the half fuselage; the standard elements are chosen from the *Abaqus* library.

2.9. Assembly

All the parts communicate each other during the solution process by means of the *Tie* method of *Abaqus Interaction* module. *Tie* command allows to connect regions having different mesh grids at the boundary interfaces; implemented connections are reported in Tab. 2. Contrary to the solutions for actual aircraft, stringer ties are not modelled in the code in order to

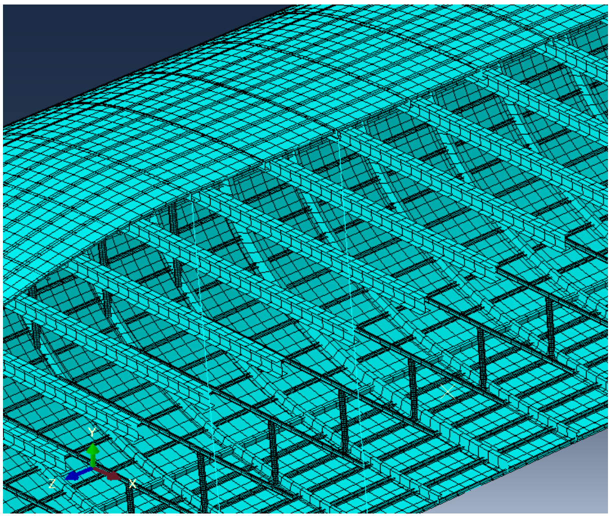


Figure 5. Mesh detail

Table 1
Meshing default properties

Part	*Element*	*Seed size*	*N elements*
Skin	S4R	100	7×10^4
Frames	S4R	100	4×10^4
Stringers	S4R	100	2×10^5
FloorUp	S4R	100	2×10^4
FloorDown	S4R	100	1×10^4
StrutsUp	S4R	100	5×10^4
StrutsDown	S4R	100	6×10^3
Sponson	S4R	50	3×10^4
Bulkheads	S4R	100	1×10^3
LinkBeam	T3D2	-	1×10^1

avoid a very complicated meshing algorithm (to be implemented afterwards) without significant advantages in terms of weight evaluation.

Table 2
Tie connections

Master	*Slave*
Skin	Stringers flanges
Skin	Sponson
Frames Webs	Link Beams
Frames Webs	Bulkheads
Frames Webs	Floor Beams
Floor Beams	Struts
Frames Webs	Struts
Frames Flanges	Skin

2.10. Materials

By default, four different materials are implemented in the code, namely: Aluminum alloy of the AA2XXXfamily; Aluminum alloy of the AA7XXX family; an equivalent isotropic sandwich panel; a C/E composite material. For metallic materials, density, Young and Poisson modules and a bilinear stress-strain curve are set; the user can choose elastic or elasto-plastic behaviour during the analysis with references material data in [7].

3. Loads and Boundary conditions

Among all the possible loading combinations [8], the following have been chosen as test case:

- pressure differential loads corresponding to the maximum relief valve setting multiplied by a factor of 1.33, omitting other loads;
- flight loads combined with pressure differential loads from zero up to the maximum relief valve setting.

3.1. Pressurization

As reported in [9], design limit pressure (corresponding to the maximum relief valve setting) is:

$$p_{dl} = 0.0627\,\text{MPa},$$

and, therefore, design ultimate pressure ($1.33\,pdl$) is

$$p_{ul} = 0.0834\,\text{MPa}.$$

3.2. Aerodynamic forces

In order to introduce aerodynamic forces into the structure, the following procedure has been adopted.

- determination of the aerodynamic lifts and moments in trim condition

$$\{X_b,\, Y_b,\, Z_b,\, \mathcal{L}_b,\, \mathcal{M}_b,\, \mathcal{N}_b\} \tag{1}$$

along the body frame reference system (CG, x_b, y_b, z_b) in the flight conditions defined by the following set of parameters:

$$\{V_0, \alpha, \beta, \Phi, \Theta, \dot{\Phi}, \dot{\Theta}, \dot{\Psi}\}; \tag{2}$$

- adoption of a clumped parameters method (Fig. 6) in the case of a PrP configuration (e.g. Parsifal project, with front and rear wings positioned at different levels). The same is valid independently of the configuration adopted for the lifting system (PrP or tube and wing);
- the aerodynamic loads on the wings in trim conditions are applied to the fuselage.

By means of WAGNER any load combination can be managed.

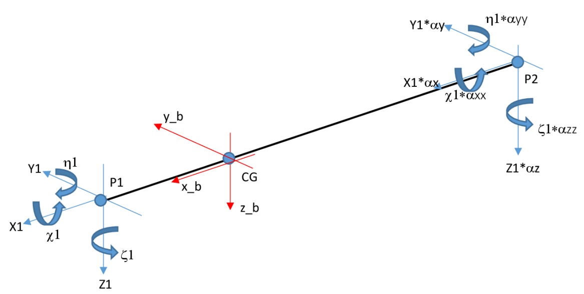


Figure 6. Aircraft scheme for evaluation of aerodynamic forces

3.3. Payload

As stated in [13], the following data for passengers are assumed in WAGNER code :

- body mass: 75 kg;
- luggage mass: 20 kg;
- seat mass: 11.5 kg;
- density of containers: 176 kg m^{-3} (containers empty weight has been also taken into account).

WAGNER allows us to compute how many passengers and how many containers (geometric data must be given in input) will fill the available volumes. After that, the total weight (separately for passengers and containers) is distributed as a pressure load to the relative floor beam upper flanges.

3.4. Inertias

For the evaluation of mass, centre of gravity position and inertia tensor of the whole aircraft (performed internally by *Abaqus*), an estimation of payload, engines and wing inertial properties is mandatory.

3.4.1. Passengers

As for passengers, the sitting human tensor of inertia has been computed with reference to [14], by using an equivalent mass comprehensive of body, luggage and seat and a human height of 1750 mm (Fig. 7). Hence, the passengers system mass and inertia tensor is applied at a RP in correspondence of the passengers system CG (A similar procedure is used for containers).

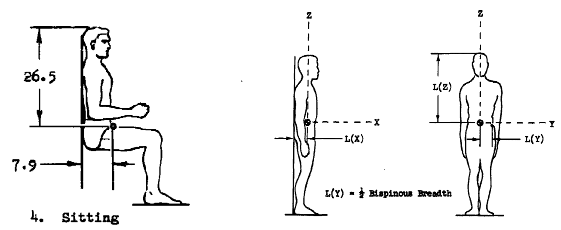


Figure 7. Human body standard

3.4.2. Wing

Wing properties have been computed with reference of a elementary wing planform (Fig. 8). Wing box has been assumed as rectangular, from 10% to 70% of the local chord. Chord law along the spanwise direction has been assumed to be:

$$c(x) = c_R\Big(1 - \frac{1-\lambda}{L}x\Big) \tag{3}$$

and

$$\alpha_\Lambda = -\arctan\left(\frac{c_R\ (\lambda - 1)}{2\,L}\right). \tag{4}$$

Inertia tensor, CG position, volume for a generic wing part have been analytically derived in [1].

3.5. Free flight simulation

WAGNER simulates the free flight conditions. Efforts have been made to avoid constraints in favour of imposing acting forces. Consequently, IR is introduced in the model. Further informations can be found in *Abaqus Documentation.*

4. A first structural optimization

Once the model is assembled, the evaluation of mass, CG position and inertia tensor are performed by

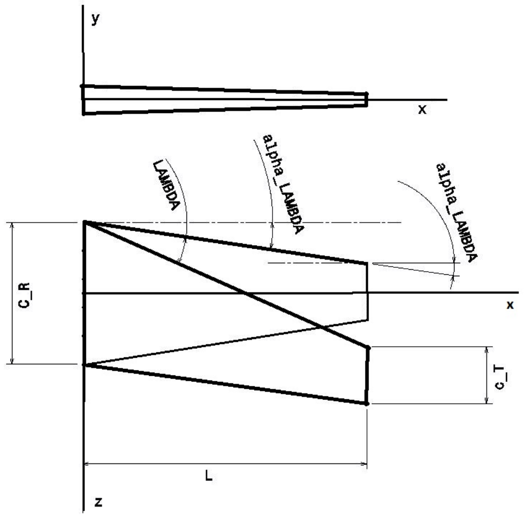


Figure 8. Elementary wing part

Abaqus. These data are inserted in the Nasa Weight model [16] to obtain a first estimation of MTOW; fuselage and fuel masses (obtained as previously described) are superimposed. A very first sizing is derived from previous works (e.g. [3]) and from theoretical analysis [18]. An heuristic procedure has been hence adopted to get to more efficient fuselage structure, by means of Finite Element analysis conducted by means of WAGNER to manage the input parameters. A typical result of this procedure is shown in Tab. 3 and Tab. 4 in the case of a SD PrP aircraft (more details to be found in [1]). The results are in agreement with classic statistical-based approaches as those in [19].

Table 3
Weight saving for SD configuration

Part	Former mass [Mg]	Actual mass [Mg]	Gain [%]
Skin	2.95	2.4	18.6
Frames	1.22	1.04	14.8
Stringers	2.37	1.65	30
FloorUp	0.9	0.81	10
FloorDown	0.4	0.14	65
StrutsUp	0.36	0.186	48
StrutsDown	0.15	0.085	43
LinkBeams	0.11	0.07	36
Sponson	1	0.6	40
Bulkheads	0.59	0.93	−58
TOT	10.06	7.94	21

Table 4
Optimised SD layout weight composition

	Former	Actual	
OEW	43	41.13	[Mg]
$MTOW$	119.25	117	[Mg]
$\frac{W_{fuel}}{MTOW}$	0.23	0.236	
$\frac{W_{passengers}}{MTOW}$	0.2	0.2	
$\frac{W_{containers}}{MTOW}$	0.21	0.21	
$\frac{OEW}{MTOW}$	0.36	0.354	

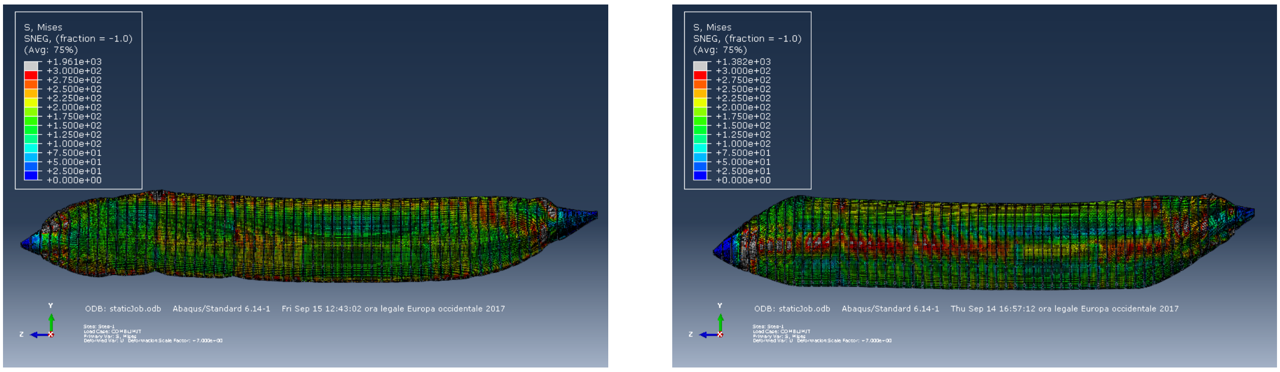
5. Some results

In this section some typical results relevant to two fuselage configurations are presented under Combined Loads (CL) and Ultimate Pressure (UP) conditions, under both linear and geometrically non-linear solutions.

5.1. Combined Loads

The CL condition consists in the aerodynamic loads combined with the inertial loads with a 2.5 load factor. This CL condition is a reference sizing condition at this stage and, as a result of the FE analysis following the mesh generation by WAGNER code, the von Mises stress and displacements are presented in the following. The stresses in the fuselage skin are presented in Fig. 9 and the global deformations show the typical features of the PrP fuselage, with compressed upper zone and stretched lower one in the fuselage segment between the two wings. It must be pointed out that the presence of symmetric closed cross section stringer positioned at the points of curvature change, reduces the stress picks, typical of previous solutions with open section stringers; Fig. 10 shows that the points wherein the curvature changes lay very close to the undeformed reference configuration (in the limit case of no stiffeners); bending stresses present the maximum (minimum) approximately in the central part of any single arch. The hoop stresses are depicted in Fig. 11; high stress levels are present close to the beam-frames connections.

The displacements and stresses for the DD configuration are presented in Fig. 12. Fig. 12(b) is relevant to the elastic analysis and shows the presence of severe stress on the top fuselage but local modifications to reduce the stress level cannot be performed in the framework of WAGNER code, owing to the modalities of frames generation and thickness attribution (but they can be performed on the generated FE configuration). Fig. 12(a) shows that the cross section displacements are governed by the presence of the deck beams which, being extremely rigid against axial extension, force the nodes of the deformed shape as shown in Fig. 12(a). The ventral part is very stiff owing to the presence of two decks; the upper and central parts withstand large



(a) SD layout (7x) (b) DD layout (7x)

Figure 9. Von Mises Stress

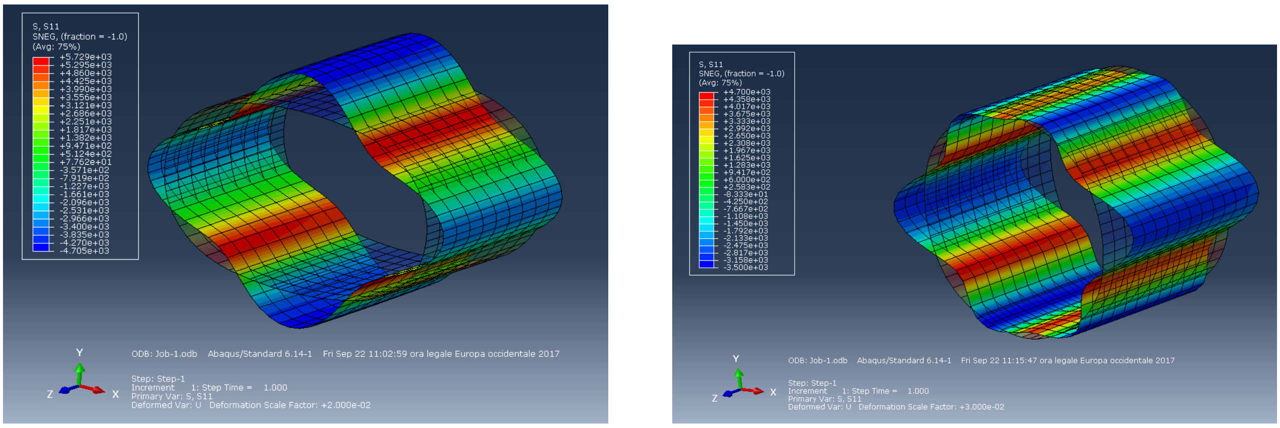


Figure 10. Bending stress at curvature change in absence of any stiffener

deformation, being less constrained. The difference in rigidity leads also to an enhancing in stress in the very upper part (Fig. 12(b)).

In order to try to quantify this effect, we consider the model in Fig. 13 composed by two beams and a linking rod. Let the beam of length L be inclined of an angle, say γ, and be loaded by an uniform load per unit length, say q, perpendicular to the beam axis. The beam has bending stiffness EJ, the axial stiffness of the rod is EA. Without the rod, the bending moment in the upper vertex would be $M_0 = -q\,L^2 \sin^2\gamma$.

By solving the problem with the rod, the actual moment is $M_1 = \eta\, M_0$ where

$$\eta = 1 - \frac{40\cos^2\gamma - 17}{2\left(16\,sin\gamma + \frac{192}{\Lambda^2\,tan\gamma}\right)} \qquad (5)$$

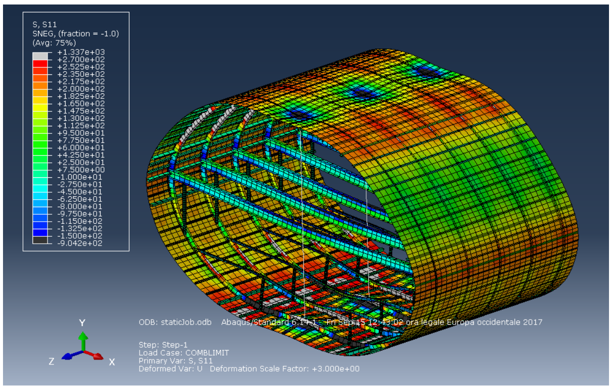
having defined $\Lambda = \sqrt{\frac{J}{A\,L^2}}$. Performing a parametric study of $\eta = \eta(\gamma)$, we obtain the curves in Fig. 13 where $|\eta| <= 1$ means $|M_1| <= |M_0|$.

With a proper choice of the rod area and a beam length, it is possible to reduce the bending moments significantly. This simple model can explain the big difference in stress between top and bottom frames webs and the role of the floor beams on the stress in the arches under the pressurization loads.

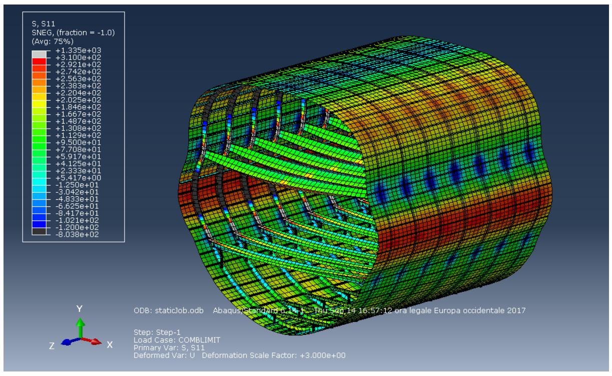
Preliminary results shown in [1] confirm the major role of lower floor beams in stiffening the ventral fuselage part.

5.2. Ultimate pressure

In the ultimate pressurization load case, no mass or payload have been taken into account; both linear and geometrical non-linear analyses have been conducted. Indeed, as stated in [18], when the assumption of small-deflection Love-Kirchhoff theory (i.e.: small of deflection of the plate mid-surface is small compared with the thickness of the plate) is not satisfied, a non-linear large deflections von Karman approach could be adopted. During the Step definition, *Abaqus* can take into account for large displacements and rotations, by the switch NLGEOM. The model has no

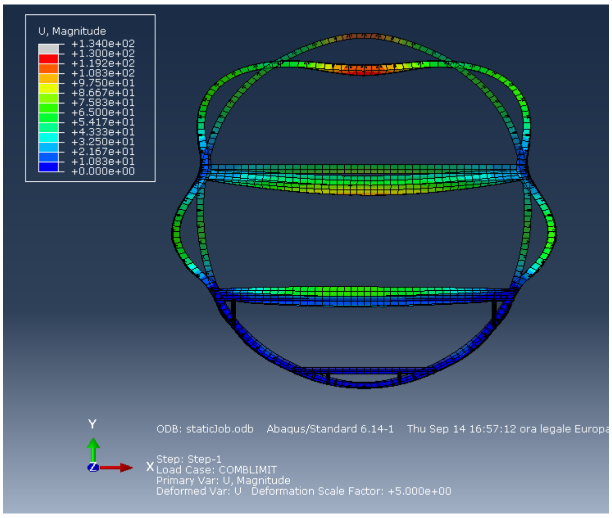


(a) SD layout (3x)

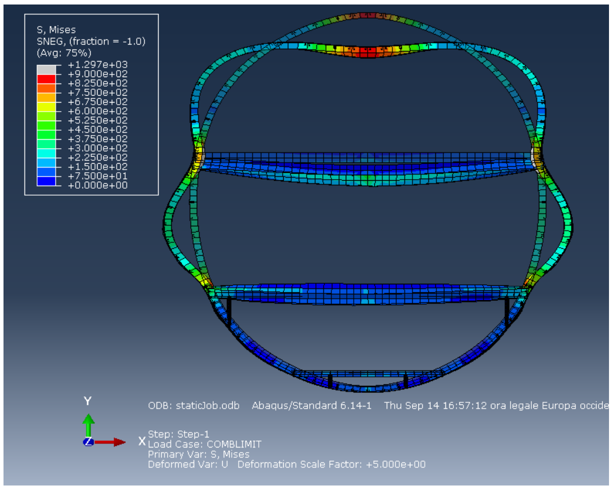


(b) DD layout (3x)

Figure 11. Hoop stress



(a) Cross section displacements DD layout (5x)



(b) Cross section Von Mises stress DD layout (5x)

Figure 12. DD layout cross section displacements and Von Mises stress

boundary conditions, but IR, which can be geometrically linear or non-linear; a constrained node must be defined, in order to avoid numerical singularities when processing nodes; this node is on the longitudinal symmetry plane of the onward bulkhead, where elastic solution presents a small displacement (thus, the boundary condition effect on the final deformed configuration is minimized). The non linear analysis under ultimate pressure is very time consuming; after a relaxation of convergence and step parameters to ensure a relatively-rapid as well as reliable solution, the simulations needed about nine hours to get the final convergence. An effect of non-linearity in the fuselage design can be seen in Fig. 14, where a cross section is deformed according to the linear solution (on the left) and the non-linear one (on the right). As expected, the displacements are lower in non-linear case because geometrical non-linearity takes into account stiffness secondary effects; hence, the structure is virtually more rigid than in a linear solution. This effect can be seen in the same figure: in the linear case, some parts of at the upper fuselage tend to bend inward and, in non-linear solution, inward deflections are smaller resulting in a smoother contour. The DD configuration presents an interesting behaviour of the upper sector. Fig. 14(b) shows that, as expected, the displacements magnitude is smaller in the non-linear solution and the shapes of the top sector in the linear and non linear solutions are different. In particular, the top sector in the linear solution tends to be more dome-like than in the linear solution where, contrary, the non linear solution produces a more regular de-

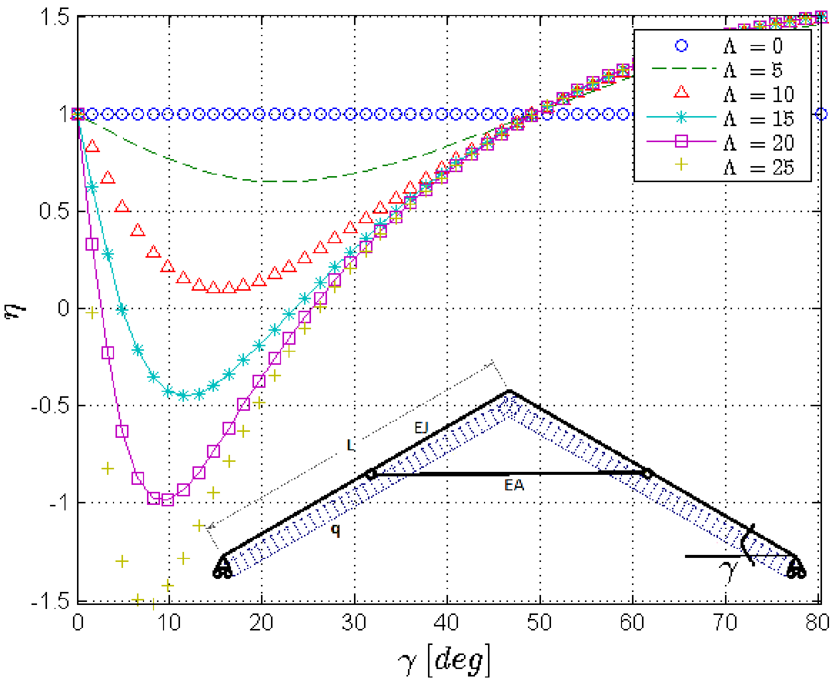


Figure 13. Arch simplified model and $\eta(\gamma)$ curves

formed curvature. Thus, keeping in mind that bending stress in curved beams has an hyperbolic profile, it results in a severe stress raise in the lateral portions of top fuselage. Hoop stress are smaller in the non linear solution as well (Fig. 15).

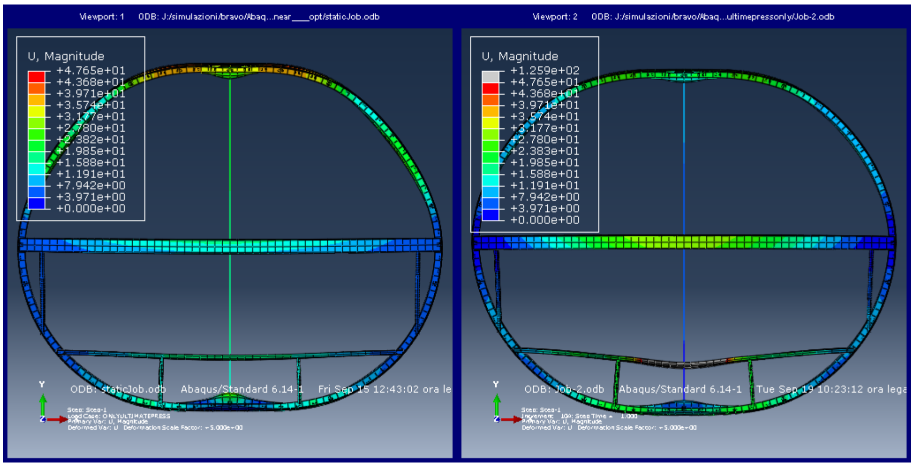
6. Conclusions

WAGNER code allows a quick and robust generation of the FE mesh of fuselage of civil transport aircraft; in the case study presented in the paper, a half fuselage with about 5×10^5 elements has been generated in 150 sec with a Work Station HP-Z440. The code is written in *Python* language and the default element library is that of *Abaqus*. Many load cases can be set up easily and with a high degree of automation, including aerodynamic loads (even in the case of two wings, as in the case of a PrP configuration), inertial loads and pressurization loads. Different materials can be used in the analysis; different geometrical configurations can be created quickly even though structural details are not included; more refined analyses could be conducted after that a preliminary optimization based on FE results will be carried out after the mesh generated with WAGNER code. As example cases, two different fuselage configurations have been presented and weight estimations have been carried out resulting in line with statistical based approaches. Different structural innovative solutions can be analysed as well; in the paper, an example was studied where cables made in composites connect bottom and top fuselage in the symmetry plane in order to design an efficient solution against pressurization loads. In summary, WAGNER code has proved to obtain the following results:

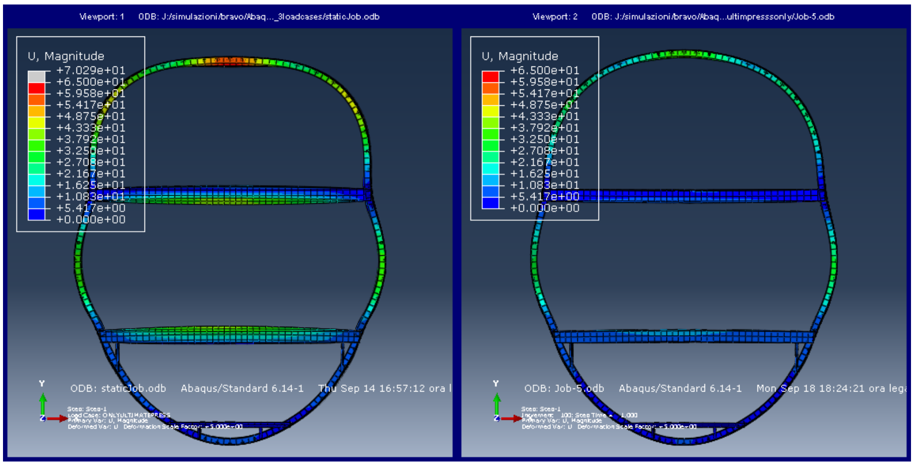
- to conduct an automatic preliminary weight optimization of a fuselage, in the presence of different load cases;
- to study different innovative structural solutions;
- to provide an empty weight estimation to be compared with different solutions (without windows and doors) as far as shape and materials adopted are concerned;
- to provide automatically the Finite Element model for further refinement of the fuselage design;
- to generate structural models to be included into a integrated and coupled structural aerodynamic optimization code.

7. Aknowledgement

The present paper presents part of the activities carried out within the research project PARSIFAL ("PrandtlPlane ARchitecture for the Sustainable Improvement of Future AirPlanes"), which has been

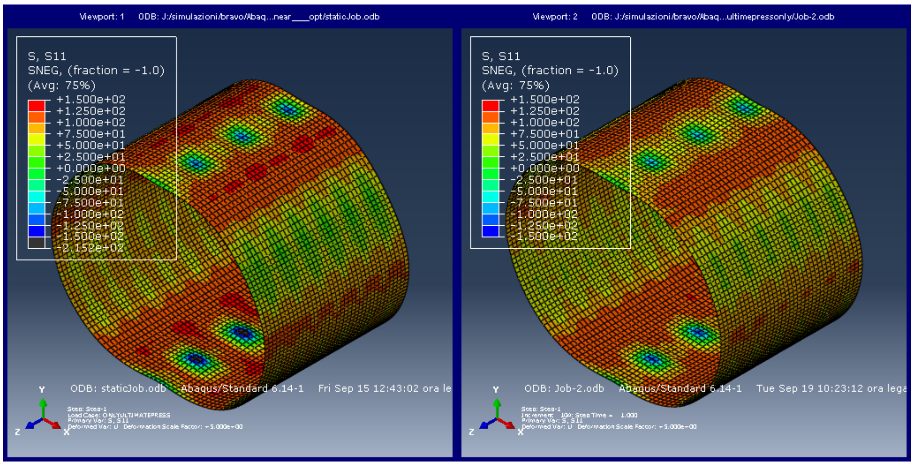


(a) SD layout (5x)

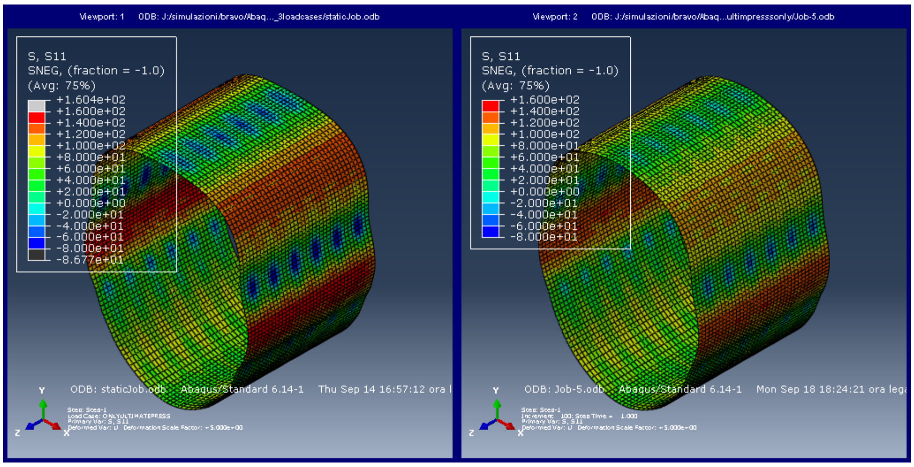


(b) DD layout (5x)

Figure 14. Linear and non-linear solution cross section displacements



(a) SD layout (5x)



(b) DD layout (5x)

Figure 15. Linear and non-linear solution hoop stresses

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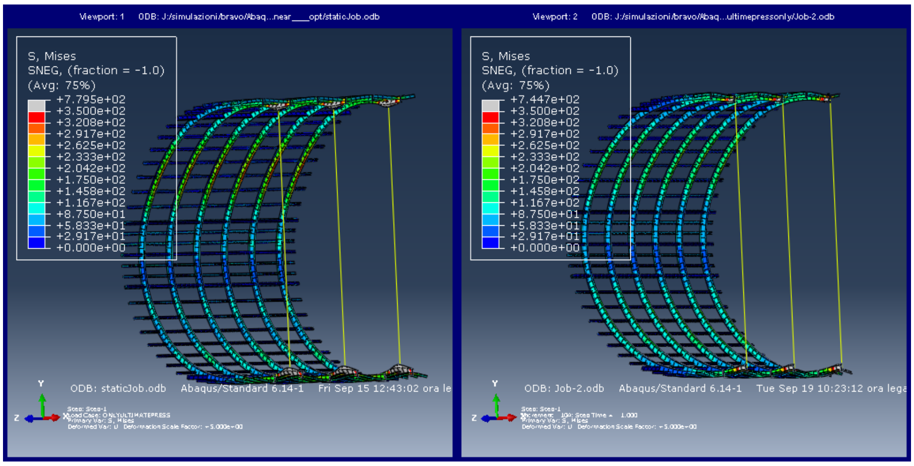
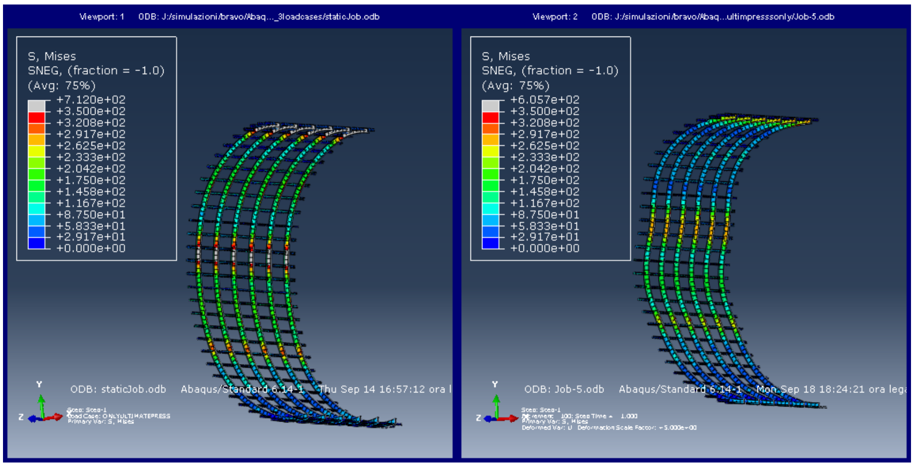


(a) SD layout (5x)



(b) DD layout (5x)

Figure 16. Linear and non-linear solution frames stresses

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