Structural analysis and design of a large inflatable hangar for aircrafts

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Abstract

Buildair S.A. has recently designed, manufactured and built an inflatable hangar (termed H75 hangar) for the aeronautic industry in Jeddah Airport (Kingdom of Saudi Arabia). H75 hangar is the largest air-cell inflated structure ever built in the world, finally erected in July 2019. The structural analysis and design of the main body of the hangar has involved complex structural concepts due to the specificity of the structural elements employed, like membranes and straps which lead to a highly non-linear mechanical problem, or the treatment of wind over the structure without a defined standard for inflatable structures. In this paper, the structural conception and specificities of the structure are presented, as well as the design procedure for the H75 hangar based in the numerical analysis, to fulfill the design requirements in terms of stresses, and deformations for the structural elements of the main body.

Keywords: structural; analysis; inflatable; non-linearity; membranes

Introduction

In recent years Buildair has specialized in the design and manufacturing of large inflatable hangars for maintenance, repair and overhaul activities in aircrafts. Some of the inflatable hangars already built by Buildair and working nowadays are the H45 hangar in Budapest, the H54 hangar in Madrid and the H35 hangar in Riad. The H75 inflatable hangar described in this paper has been built in Jeddah Airport in the Kingdom of Saudi Arabia (KSA) by request of the Saudia Aerospace Engineering Industries (SAEI) company. The H75 hangar is the largest air-cell inflatable structure ever conceived, designed and built in the world. This new hangar is 50% larger than H54 hangar in Getafe Air Base in Madrid (Spain), already a world record when it was built in 2013.

Structural conception

The H75 inflatable hangar has been conceived as a membrane-strap-anchorage system. The inflatable tubes are the main structural elements of the hangar. Tubes are of PVC membrane material and are filled with air by means of a blowing engines system at a known and controlled internal pressure. This low air pressure provides the required stiffness for the structure with a very low weight[1]. This pressure value is limited only by the power of the engines and the stress limit of the membrane. The internal pressure is controlled by an Automatic Control System, which increases the pressure when peak values of wind are registered. The stability of the inflated tubes is improved by an innovative straps network conceived as a cage surrounding the inflated tubes with two main objectives: limit the deformation of the tubes and transmit the internal forces of the structure to the anchoring points.

The different types of straps around the tubes have a well-defined role in the structural system. Longitudinal straps following the tube axis direction (*spines* and *ribs*) bear the bending forces reducing the deformation in this direction. Circumferential straps placed around the tubes (*braces*) bear the circumferential component of the stress and deformations, mainly produced by the internal pressure, and keep the cohesion of the tubes. Straps placed in the interphase between tubes (*radials* and *crosses*) increase the stiffness in this plane, which is relevant for sustaining transversal loads like lateral wind loads.

This *membrane-strap-anchorage* structural system is depicted in Figure 1 showing some details of the materialization of this concept in a set of inflated tubes within an inflation test.

Figure 1. Membrane-strap-anchorage system

Project requirements

The design procedure of the H75 has met the requirements of the Saudi Building Code SBC 301 “Loads and forces requirements”[2], following local regulations and customer’s demands. The structure must be stable under its own weight, the internal pressure and the pressure forces produced by a wind speed over the structure in every direction. The deformation of the structure is limited by functional and safety requirements: minimum distance from the structure to the plane must be preserved for the planned activities. The H75 hangar has been designed to host an Airbus 330-300 or a Boeing 777-200ER during an expected lifetime of 7 years.

Structural analysis

Geometrical definition

The main body of the H75 hangar is defined by thirteen inflated tubes of 7.5 m diameter for a total longitudinal length of 95,8 m. Every tube has an elliptic shape with a free horizontal width of 75m and an outer dimension of 90 m. The free vertical height is 25.5 m, while the total height is 33 m. Once inflated, the tubes present a contact area among them. Figure 2 shows the geometrical definition of the structure from a frontal view where the shape and dimensions of the tubes are depicted. Figure 3 shows a lateral and top view of the hangar where the corresponding dimensions can be observed, as well as the emergency door and the aircrafts location within the structure.

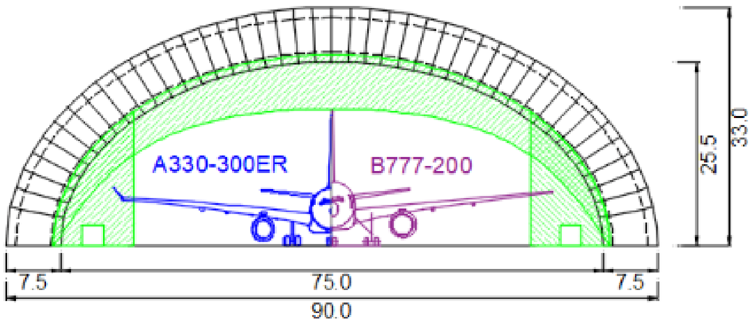

Figure 2. Front view of the H75 [units: m]

Structural units

The main body is conceived as a cluster of structural units with different structural roles: The inflated tubes and the joints involved (welded or sewn), the straps network surrounding the tubes and the anchorage devices. These structural units are complemented with some additional non-structural units, relevant for the suitable performance of the structure: The frontal and back curtains built of non-inflated membranes, a waterproof layer made of textile membrane surrounding the main body to avoid water leaks and protect the hangar from the UV rays or the emergency exit built between tubes 7 and 8 due to safety requirements.

The inflated tubes bear the internal pressure and induce the shear and bending stiffness to withstand the loads acting over the structure. Hence, the tubes are the main structural unit of the hangar. They are limited by the resistance of the membrane material and the constructive joints. The stiffness provided by the tubes must fulfill the deformation requirements for the hangar, especially in relation to the safety of the activities carried out inside the structure.

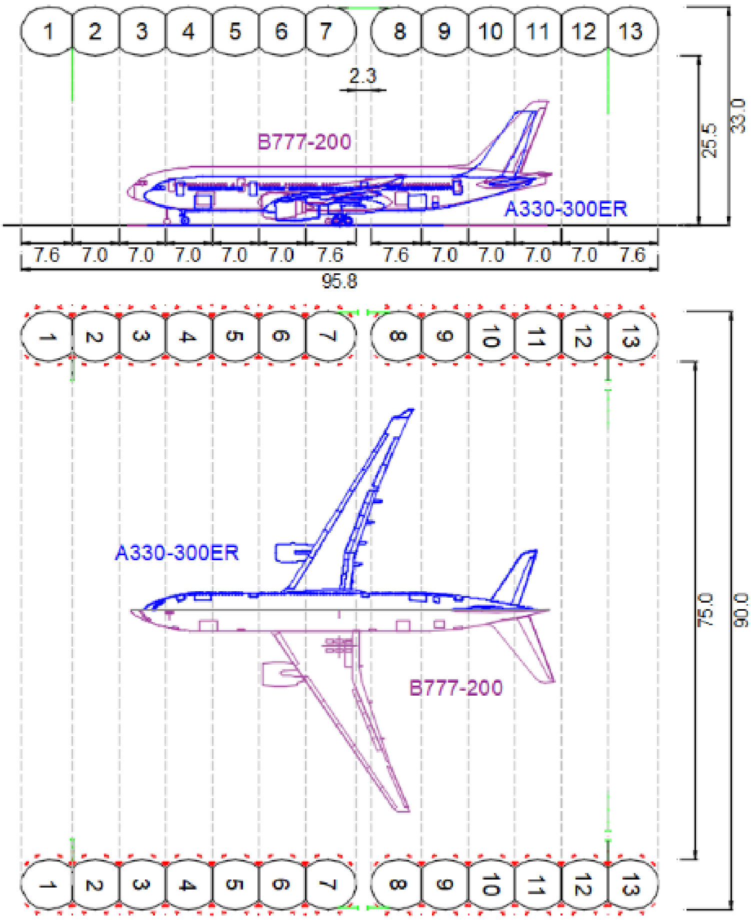

Figure 3. Lateral and top view of the H75. [units: m]

Figure 4 depicts the location of the different straps types depending on the structural role and internal forces expected.

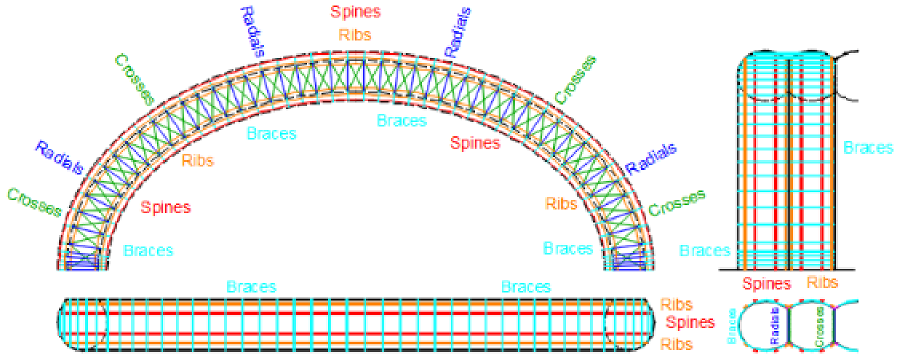

Figure 4. Straps network. Typologies and location

The membranes and straps network transmit the internal forces produced in the structure to the ground by means of anchorage devices: anchorage plates and eyebolts. The anchorage plates involve a specific structural analysis, briefly presented below. Table 1 lists some of the technical features of the main body of the H75 hangar.

Structural item	Item	Measure
Tubes (13 units)	Membrane surface	36,065 m^2
	Internal pressure	15-25 mbar
	Air volume per tube	6,632 m^3
	Total air volume	8,6211 m^3
Straps	Longitudinal tube	11,601 m
	Braces	12,327 m
	Tubes Interphase	7,620 m
Anchorage	Number of plates	208 plates
	Number of eyebolts	40
Waterproof	Membrane surface waterproof	11,266 m^2
Curtains	Membrane surface	1,697 m^2
Emergency exit	Width	2.3 m
	Membrane surface	527 m^2

Table 1. Main technical features of the H75 hangar

Numerical model

The H75 is a singular air inflated structure by its dimensions and structural conception, designed and built as an evolution of the air-inflated technology[3], structural knowledge and construction experience accumulated in Buildair along the last two decades of air inflated hangars engineering.

Structural elements

The numerical analysis of the structure has been performed using the standard FEM. The geometry was modeled using different types of finite elements, according to their particular structural behavior.

The inflated tubes were modelled as membranes. The curtains at the enclosures and the emergency exit layer have a structural role in the hangar and were also modelled as membranes. Membranes were discretized with standard *3-noded linear membrane triangles*[4], with folding and wrinkling capabilities, although the structure is mainly in tension[5]. The contact interphase of the tubes was modeled as a surface, assuming that no relative displacement is produced in between.

The straps network was modeled by *linear 2-noded one dimensional rod elements* that sustain tension axial forces only. Straps were treated as cables embedded in the membranes, assuming that they transmit a part of the axial load through the strap-membrane anchor points or by friction.

In the edge of the tubes an additional membrane, called *thimble,* has been built to reinforce the tubes in order to withstand concentrated stresses located close to the anchoring points. The thimble is reinforced by circumferential 90mm wide welded straps.

Definition of the loads and boundary conditions

The loads over the structure considered in the numerical analysis are the self-weight of the structural components, the internal pressure and the wind loads. Snow, seismic or thermal actions were neglected in the analysis. The self-weight of the main body concerns to all the structural elements involved: the membranes for the tubes, the front and back curtains, and the straps network.

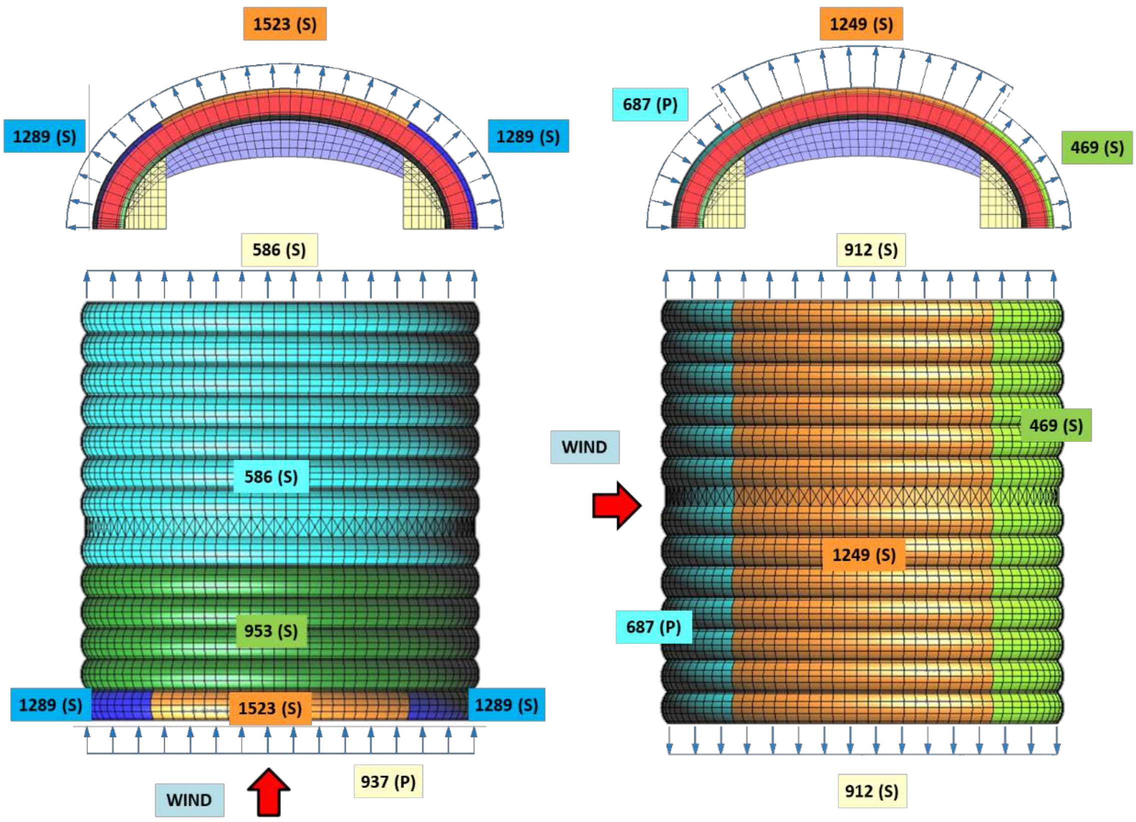

Figure 5. Pressure distribution: frontal wind (left) lateral wind (right). [units: Pa]

The working internal pressure in the tubes of the main body was prescribed to 1500 Pa (15mbar) during its lifetime. For safety reasons, this internal pressure has to be increased under peak wind loads. Hence, the structure was designed for an internal pressure of 2500 Pa (25mbar). The numerical simulation assumes that this pressure value as constant since there exists a control pressure system that ensures this condition.

To determine the wind loads over the hangar, the Saudi Arabian standard SBC 301 and the European codes were taken as reference[6]. The KSA standards stablish a basic wind speed of 152 Km/h corresponding to a 3-second gust speed at 10 m above ground. European standards have also been accepted by the customer as a reference to define the wind pressure distribution. The basic pressure obtained from the KSA norm leads to a pressure distribution over the structure according to European norm UNE-EN-1991-1-4 for frontal and lateral wind[7], as depicted in Figure 5, showing the different exposed zones, and the values applied for pressure (P) or suction (S). The wind is applied as a local static pressure, orthogonal to the wind-exposed surface.

The stability of the structure is ensured by anchorage plates for the straps and eyebolts for the non-inflated membranes. The boundary conditions were modeled by a set of nodes at the anchoring points of the tubes, the straps, the curtains and the emergency door, in which the displacements are prescribed to zero.

Nonlinear mechanical problem

The numerical analysis of the structure requires a geometrically non-linear analysis due to the large displacements observed in the deformation, especially in the membranes and straps. Elastic behavior of the materials is also assumed. The prescribed loads are treated as normal-to-surface, static follower loads, updated to the geometry every calculation step. The numerical problem was solved using an iterative procedure based on a prediction-correction, incremental load control and stabilization algorithms[8][9], using the finite element code RAMSeries from *Compass Ingeniería y Sistemas*[10].

Deformations

One of the main requirements of the hangar is the safety of the aircraft. This is translated into minimum distances from the plane to the deformed membranes. Figure 6 shows the transversal displacement (wind direction) due to lateral wind. The maximum transversal displacement is 3.66 m at the central part of the hangar. The closest point of the membrane is 4.82 m far from the wing of the aircraft in the non-deformed structure. The displacement of this point reduces this distance to 1.73 m in the wind design scenario.

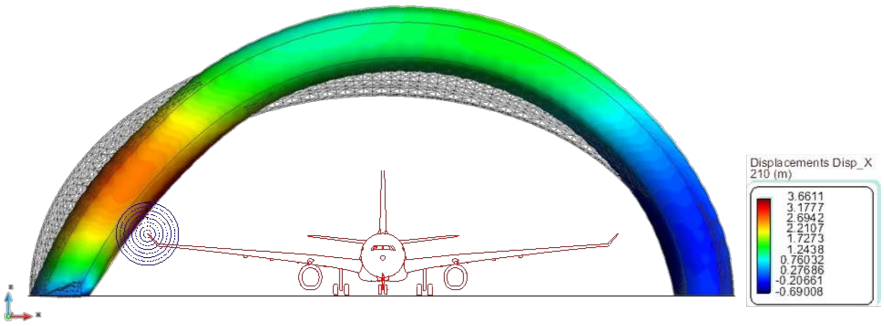

Figure 6. Transversal deformation of the hangar. [units: m]

Structural analysis of the membranes

The membrane material for the inflated tubes is SIOEN TT0117E while for the curtains is Ferrari 902 whose main mechanical properties are shown in Table 2.

Property	SIOEN TT0117E	Ferrari 902 S2	Units
Specific weight	11582	12 931	N/m^3
Thickness	0,55	0,72	Mm
Elastic modulus	0,38	0,38	GPa
Strength (weft/warp)	270/290	400	daN/5cm

Table 2. Mechanical properties of the membrane

The characteristic strength of the membrane for the tubes is established as the lowest value from warp and weft for every membrane. The partial safety factor according to the norm is γ_M = 2,5. The maximum axial force observed in membranes was 212,9 daN/5cm close to the anchorages, in the thimble reinforcement. The joints and the internal pressure ensure that the tube and the thimble works together in such way that the design strength, contributed by both structural elements, reaches 216 daN/5cm, which fulfills the design criteria with SF = 2,54. The maximum axial force observed in the tubes is 91,5 daN/5cm fulfills the design criteria with SF = 2,95. In the curtains, the maximum axial force observed is 149 daN/5cm which fulfills the design criteria with SF = 2,68. In consequence, the stresses over the membranes fulfill the resistance design criteria.

Structural analysis and design of the straps

For the design of the straps network, the characteristic strength provided by the manufacturer is considered. This lead to a design strength considering a safety factor γ_M which depends on the equivalent diameter. The mechanical properties of the straps are detailed in Table 3.

Property	Straps				Units
	300mm	90mm	75mm	50mm	
Specific weight	6705	7656	8371	8330	N/m^3
Cross section	1140	288	240	100	mm^2
Elastic modulus	2.5	2.5	2.5	2.5	GPa
Characteristic strength (f_{tk})	450	135	112,5	50	kN
Design strength (f_d)	166.7	33.8	28.1	12.5	kN

Table 3. Mechanical properties of the straps

The maximum axial force over the straps network is extracted for the critical loading case, namely, frontal or lateral wind, and the safety factor calculated for every typology.

The maximum axial force over the *spines* or the *ribs* is 140,1 kN for the frontal wind case, and so, the 300 mm straps fulfill the resistance criteria with a safety factor SF=3,2. The maximum axial force over the *braces* is 28,4 kN for the lateral wind case. In consequence, the 90mm fulfill the resistance criteria with a safety factor SF = 4,8. The maximum axial force over the *radials* is 10.4 kN for the lateral wind case, and so, these straps fulfill the resistance criteria with a safety factor SF=5.0. The maximum axial force over the *crosses* is 40.6 kN for the lateral wind case. These straps do not fulfill the resistance criteria. For this reason, a reinforcement was projected for this set of straps. An additional 50 mm wide strap was added to increase the design strength up to 41 kN. The joint of 75 and 50mm wide straps now fulfills the resistance criteria with SF=5.0.

Structural analysis and design of the anchorages

The anchorage system of the hangar mainly consists in a set of steel anchorage plates specifically designed by Buildair, where the straps network is anchored to. Small straps are anchored to eyebolts. The plates are fixed to the ground by means of an adhesive anchor system (HILTI). These anchorage plates require a structural analysis considering both, the resistance of the continuum body and that of the anchorage to the ground. The anchoring devices are basically formed by a cylinder where the straps are laced to, welded to two plates where a set of holes are drilled to host the HILTI anchors, which fix the whole device to the ground using an adhesive mortar.

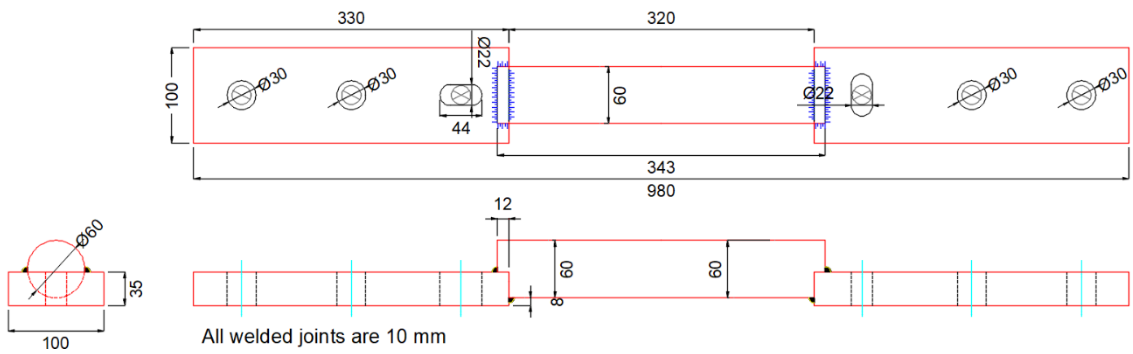

Figure 7. Anchoring plate. [units: mm]

Table 4 shows these maximum reactions for frontal and lateral wind cases. The maximum force was found for frontal wind in the windward tube.

Component	Frontal wind	Lateral wind
Rx	-64.7	-127.4
Ry	52.4	-104.3
Rz	-245.8	-57.1
Modulus	259.5	174.3

Table 4. Maximum reactions in anchorages [kN]

Several types of anchoring devices are considered in the project depending on the location and force supported. Figure 7 shows an scheme of plate type C2, bearing the maximum reaction, with the dimensions of the cylinder (diameter, 60mm; free length, 320mm) and the plates (330x100mm, diameter holes 2xϕ22 mm/4xϕ30mm) and welded joints location.

The numerical simulation of the anchoring plate under the design loads was carried out using FEM. Figure 8 shows the distribution of Von Mises stresses and the plasticity zones where the elastic limit was exceeded. High Von Mises stresses are found in the cylinder-plate joint and in the edges of the holes to fix the anchors. These don't represent a problem, since they are caused by a singularity of the numerical results due to edge conditions set in the numerical analysis, leading to a small plastification zone in the bottom side of the plate close to the hole, which will not cause problems in the real component. The maximum displacements observed are 0.63 mm in the central section of the cylinder, which is acceptable.

The design procedure for the anchorage to the ground was performed using the HILTI verification tool (HILTI-Profis_anchor_v2.7.7). The whole set of structural verifications was fulfilled.

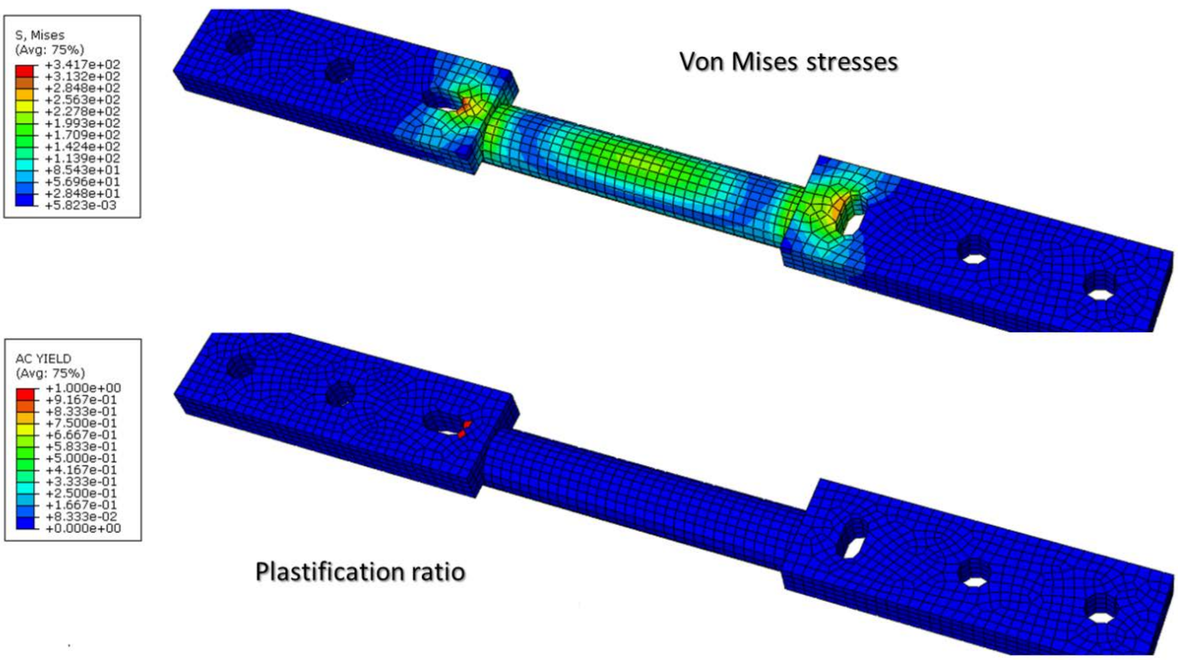

Figure 8. FEM analysis of the anchoring plates. a) Von Mises stresses [MPa] b) plastification [-]

Conclusions

This paper presents the main features and the structural analysis of H75 inflatable hangar, conceived, designed and built by Buildair as a singular structure due to its structural conception and dimensions, being the world largest inflatable hangar ever built up to date. In this innovative context, the numerical analysis of the structure, using FEM method, has proven to be crucial to predict the structural behavior of the hangar. Structural hypothesis and numerical assumptions have been made related to geometry, materials, loads and boundary conditions, altogether leading to a geometrically highly non-linear problem. The numerical simulation has led to a solution fulfilling the structural requirements for deformations and resistance criteria, with the safety factors required for every structural component. The H75 inflated hangar was successfully deployed in Jeddah airport on July 2019, and hosted an Airbus A330 on October 10th, 2019.

Acknowledgements

Disclosure of interest

The authors report no conflict of interest.

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