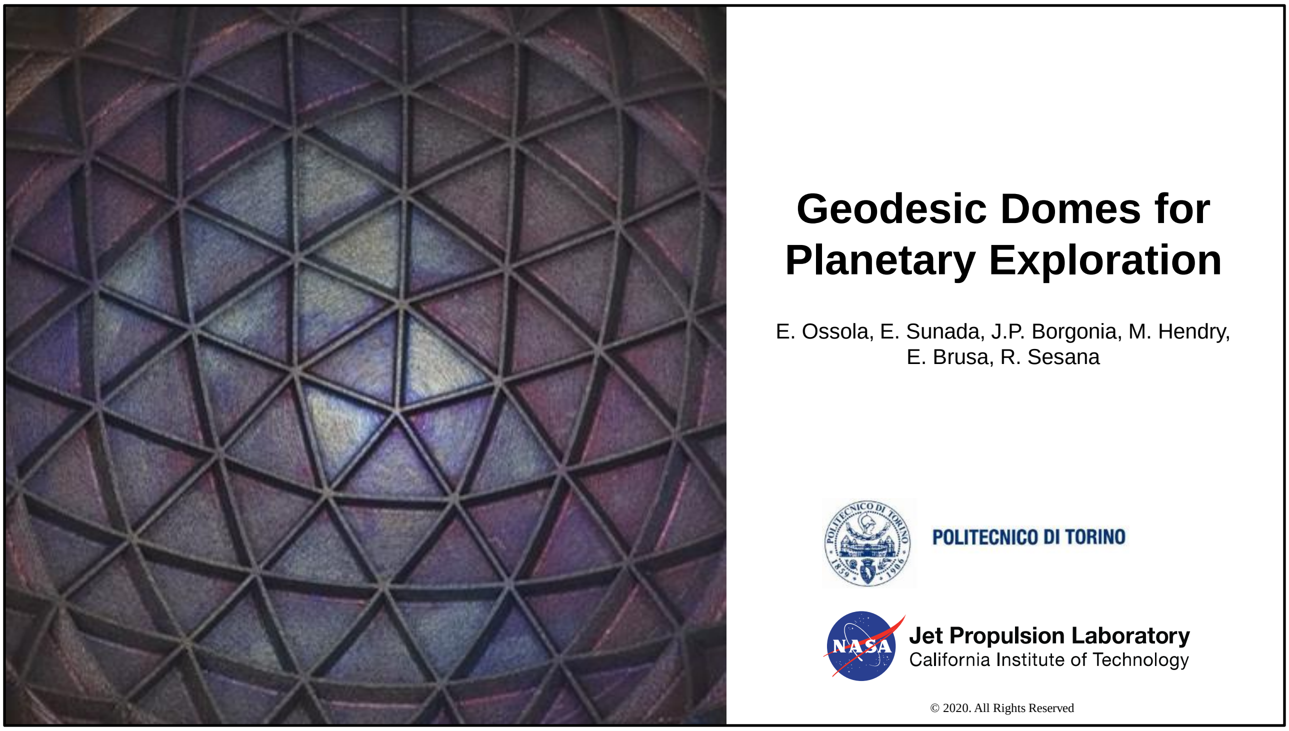

Geodesic Domes for Planetary Exploration

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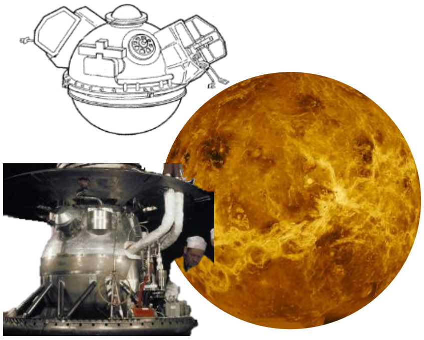
PROBES FOR EXTREME ENVIRONMENTS

Photo by Jeff McDonald, Woods Hole Oceanographic Institution

The exploration of harsh environments, such as the surface of Venus, Jupiter's moon Europa or Earth's oceans, poses unique challenges for shell structures, which are subjected to severe loading conditions: **high external pressure**, **extreme temperatures** and **corrosion**.

Spherical shells are usually employed, because of the high internal volume to surface ratio. Past robotic missions to Venus, for example, adopted plain spherical shells, composed by 2 or 3 components assembled together. Internal ribbing, although beneficial, is very difficult to manufacture using traditional techniques.



ADDITIVE MANUFACTURING AND GEODESIC DOMES

Isogrid structures are lightweight structures composed by a skin and a number of ribs, forming triangular patterns. Due to their high performance, they are largely used for aerospace applications.

If metallic isogrid plates and cylindrical shells are manufacturable by milling or machining and forming, doubly curved shells are very difficult to be manufactured with traditional techniques. On the other side, large isogrid spheres are very common in architecture, as geodesic domes.

Things have changed with Additive Manufacturing. Aim of this work is proposing a design approach for Additively Manufactured metallic geodesic domes undergoing external pressure.

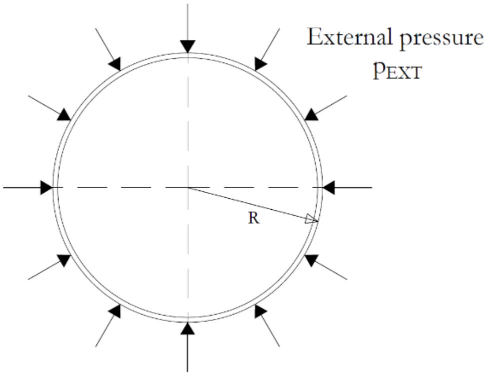
Francine Orr / Los Angeles Times

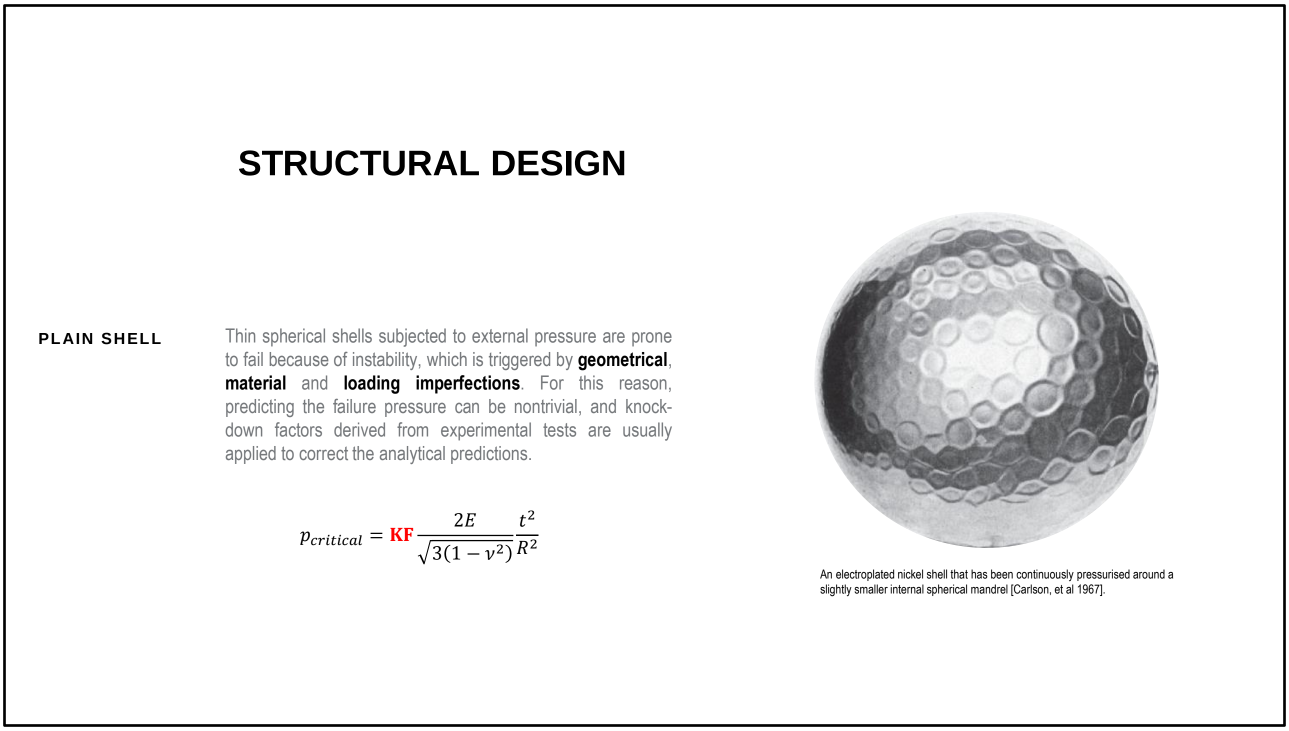
Studio Obicua Architettura

STRUCTURAL DESIGN

LOADING CONDITIONS

Let's consider a thin spherical probe subjected to **uniform**, **high external pressure**. In the case of a landing mission to Venus, for example, the most critical load is due to the Venus environmental conditions, whose pressure at surface is about 100 bar.





STRUCTURAL DESIGN

PLAIN SHELL

Thin spherical shells subjected to external pressure are prone to fail because of instability, which is triggered by **geometrical**, **material** and **loading imperfections**. For this reason, predicting the failure pressure can be nontrivial, and knock-down factors derived from experimental tests are usually applied to correct the analytical predictions.

$$p_{critical} = \mathbf{KF} \frac{2E}{\sqrt{3(1-\nu^2)}} \frac{t^2}{R^2}$$

An electroplated nickel shell that has been continuously pressurised around a slightly smaller internal spherical mandrel [Carlson, et al 1967].

The main design challenge for spherical landers for harsh environments is withstanding the high pressure. The buckling behavior of a spherical shell subjected to uniform external pressure was firstly studied by Zoelly in 1915, who obtained the “classical” formulation (without KF)

STRUCTURAL DESIGN

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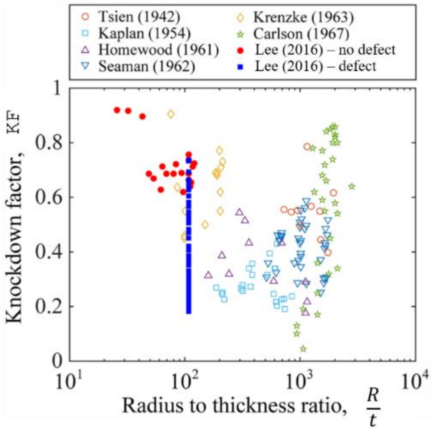
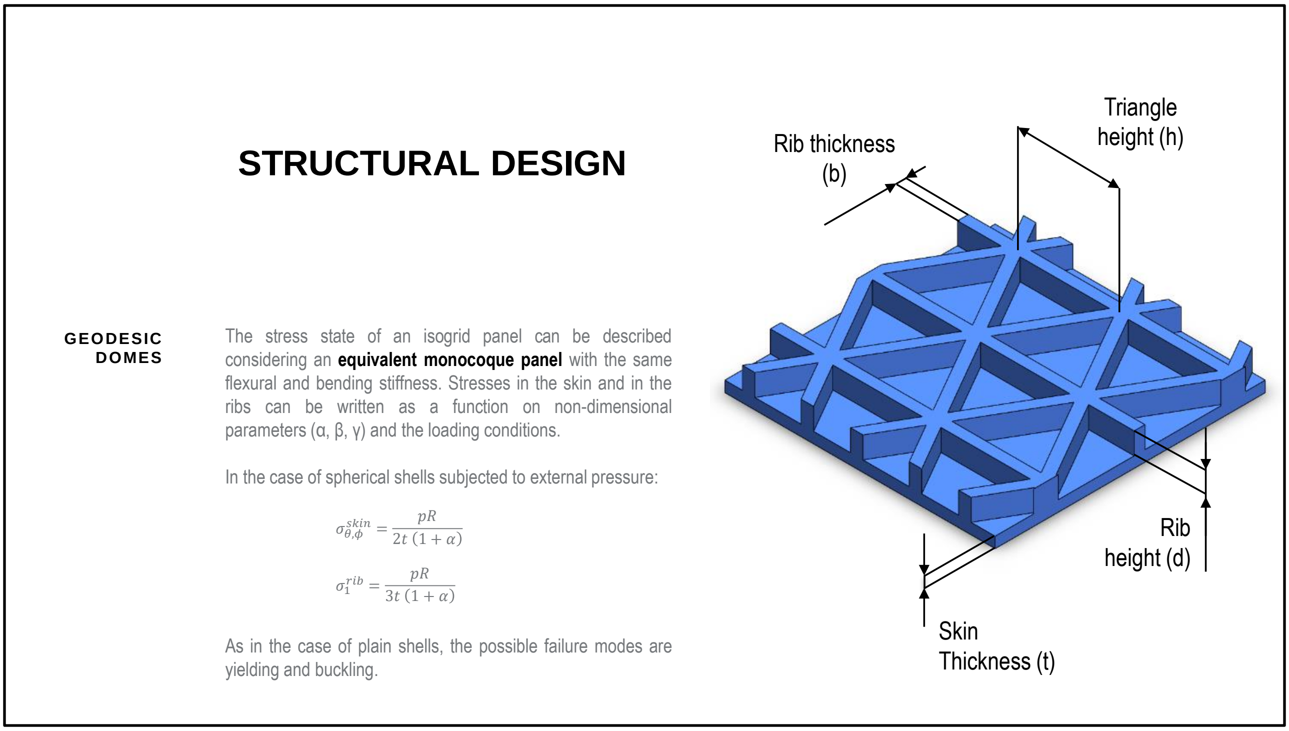


Adapted from A. Lee, et al.. The geometric role of precisely engineered imperfections on the critical buckling load of spherical elastic shells. J of Applied Mechanics, 2016.

Since the early studies on shell buckling, a large discrepancy between the theoretical critical pressure and the experimental evidences was observed. The cause of this discrepancy was identified in the high sensitivity of thin spherical shells to geometrical, material and loading imperfections. The most common procedure to estimate the actual critical pressure still consists in calculating the ideal critical pressure and applying a ‘knockdown factor’ (KF), in order to take into account the detrimental effect of imperfections. Recommeded values of KF to use in the early design stage vary from 14% (Meyer, 1973), to 30% (Roark’s).



STRUCTURAL DESIGN

GEODESIC DOMES

The stress state of an isogrid panel can be described considering an **equivalent monocoque panel** with the same flexural and bending stiffness. Stresses in the skin and in the ribs can be written as a function on non-dimensional parameters (α, β, γ) and the loading conditions.

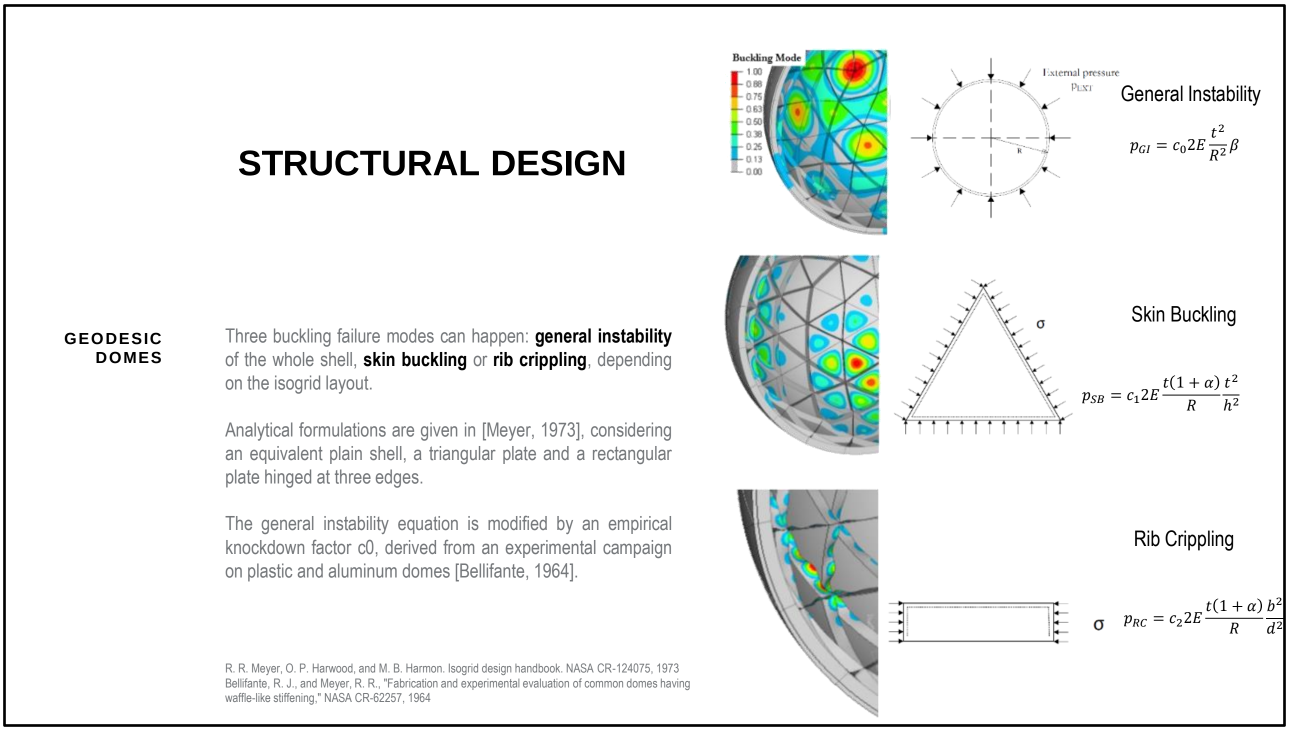
In the case of spherical shells subjected to external pressure:

$$\sigma_{\theta,\phi}^{skin} = \frac{pR}{2t\,(1+\alpha)}$$

$$\sigma_{1}^{rib} = \frac{pR}{3t\,(1+\alpha)}$$

As in the case of plain shells, the possible failure modes are yielding and buckling.

In order to mitigate the effects of material and geometric imperfections, as well as improving the bending stiffness of the shell, internal ribs can be added. At the same time, the development of Additive Manufacturing (AM) for industrial applications has made possible the fabrication of complex internal features, difficult or even impossible to be manufactured using traditional processes. Among all the different configurations, the isogrid layout has been investigated, due to the isotropic mechanical behavior.



STRUCTURAL DESIGN

GEODESIC DOMES

Three buckling failure modes can happen: **general instability** of the whole shell, **skin buckling** or **rib crippling**, depending on the isogrid layout.

Analytical formulations are given in [Meyer, 1973], considering an equivalent plain shell, a triangular plate and a rectangular plate hinged at three edges.

The general instability equation is modified by an empirical knockdown factor c0, derived from an experimental campaign on plastic and aluminum domes [Bellifante, 1964].

General Instability

$$p_{GI} = c_0 2E \frac{t^2}{R^2}\beta$$

Skin Buckling

$$p_{SB} = c_1 2E \frac{t(1+\alpha)}{R}\frac{t^2}{h^2}$$

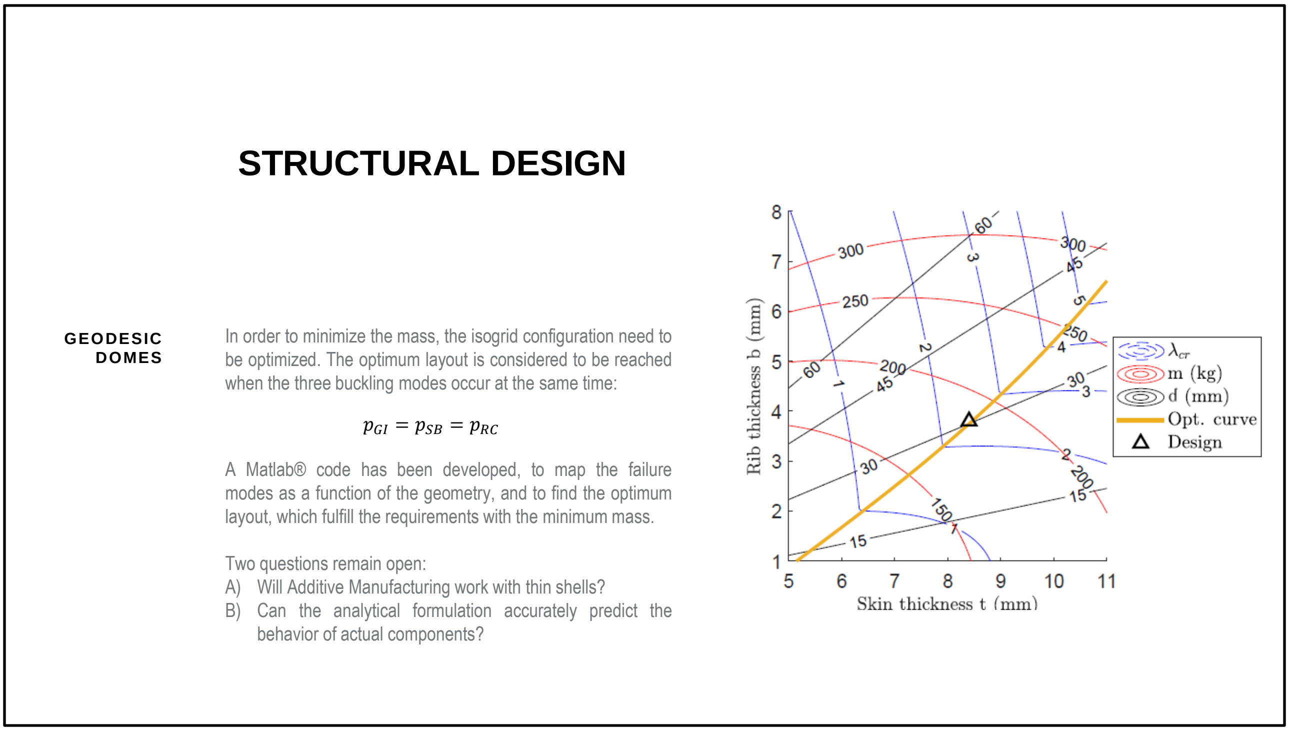
Rib Crippling

$$p_{RC} = c_2 2E \frac{t(1+\alpha)}{R}\frac{b^2}{d^2}$$

R. R. Meyer, O. P. Harwood, and M. B. Harmon. Isogrid design handbook. NASA CR-124075, 1973
Bellifante, R. J., and Meyer, R. R., "Fabrication and experimental evaluation of common domes having waffle-like stiffening," NASA CR-62257, 1964

If the yielding failure can be estimated by comparing the Von Mises stresses to the material properties, the buckling failure can be harder to predict.

Considering an isogrid sphere subjected to external pressure, three buckling modes can occur, involving the General Instability (GI) of the whole structure, the Skin Buckling (SB) on the shell of the triangular cells, or the Rib Crippling (RC).



STRUCTURAL DESIGN

GEODESIC DOMES

In order to minimize the mass, the isogrid configuration need to be optimized. The optimum layout is considered to be reached when the three buckling modes occur at the same time:

$$p_{GI} = p_{SB} = p_{RC}$$

A Matlab® code has been developed, to map the failure modes as a function of the geometry, and to find the optimum layout, which fulfill the requirements with the minimum mass.

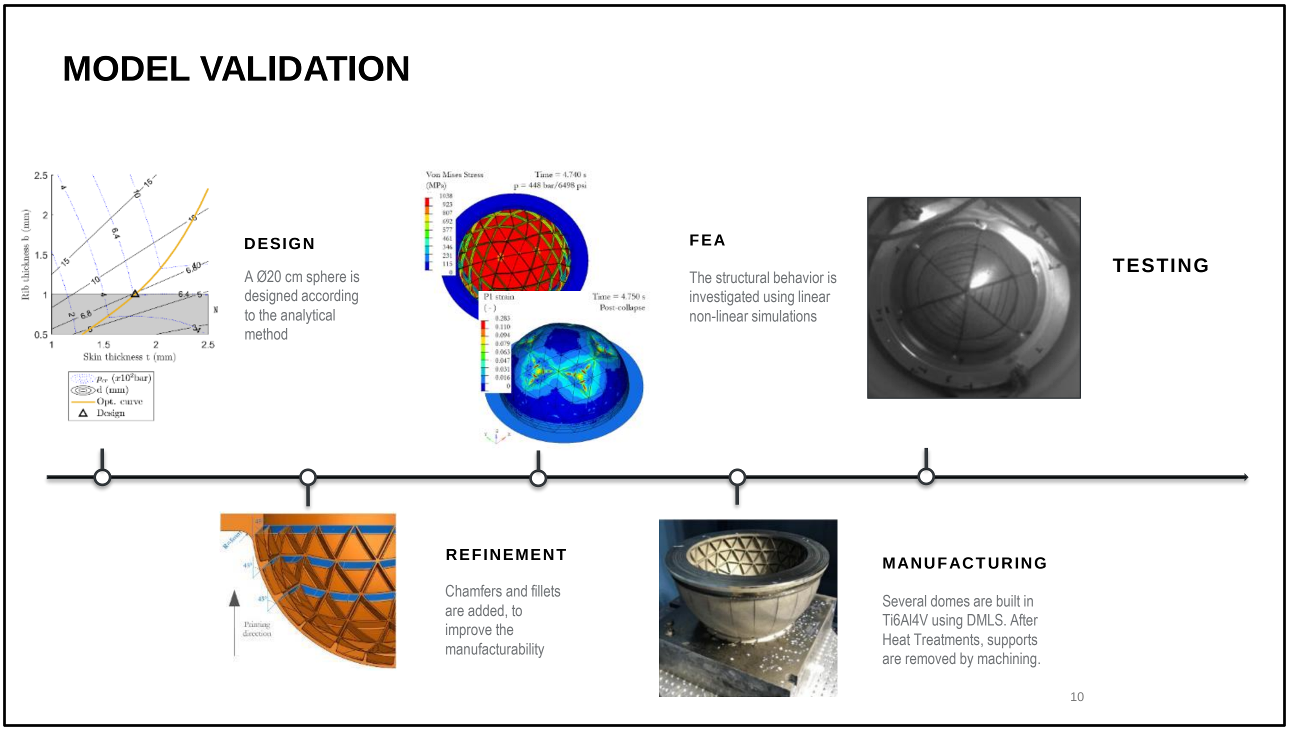
Two questions remain open:

A) Will Additive Manufacturing work with thin shells?
B) Can the analytical formulation accurately predict the behavior of actual components?

Objective of the optimization problem is finding the configuration (i.e. h, t, b and d) of minimum mass, which satisfies the requirements in terms of stress and critical buckling pressure.

Starting from the previous work of Meyer and Bellifante, a Matlab script was developed, to find the optimum geometry. The optimum layout is considered to be reached when the three buckling modes occur at the same time.
Here the output of the code is shown. Given the sphere radius, the mass and the non-dimensional failure pressure (lambda) are mapped within the main isogrid parameters (skin thickness, rib thickness and rib height).
The yellow curve represents the points where the three buckling modes occur at the same time. The optimum design is chosen by intersecting the yellow curve with the required value of the buckling pressure lambda.

Testing activities are required, to compare experimental evidences to analytical and numerical predictions, calibrating the models and finding the correct value of KF to apply in the design stage. The experimental activities were aimed also to evaluate the capability of AM processes to fabricate thin and double-curved shells.



MODEL VALIDATION

DESIGN

A Ø20 cm sphere is designed according to the analytical method

FEA

The structural behavior is investigated using linear non-linear simulations

TESTING

REFINEMENT

Chamfers and fillets are added, to improve the manufacturability

MANUFACTURING

Several domes are built in Ti6Al4V using DMLS. After Heat Treatments, supports are removed by machining.

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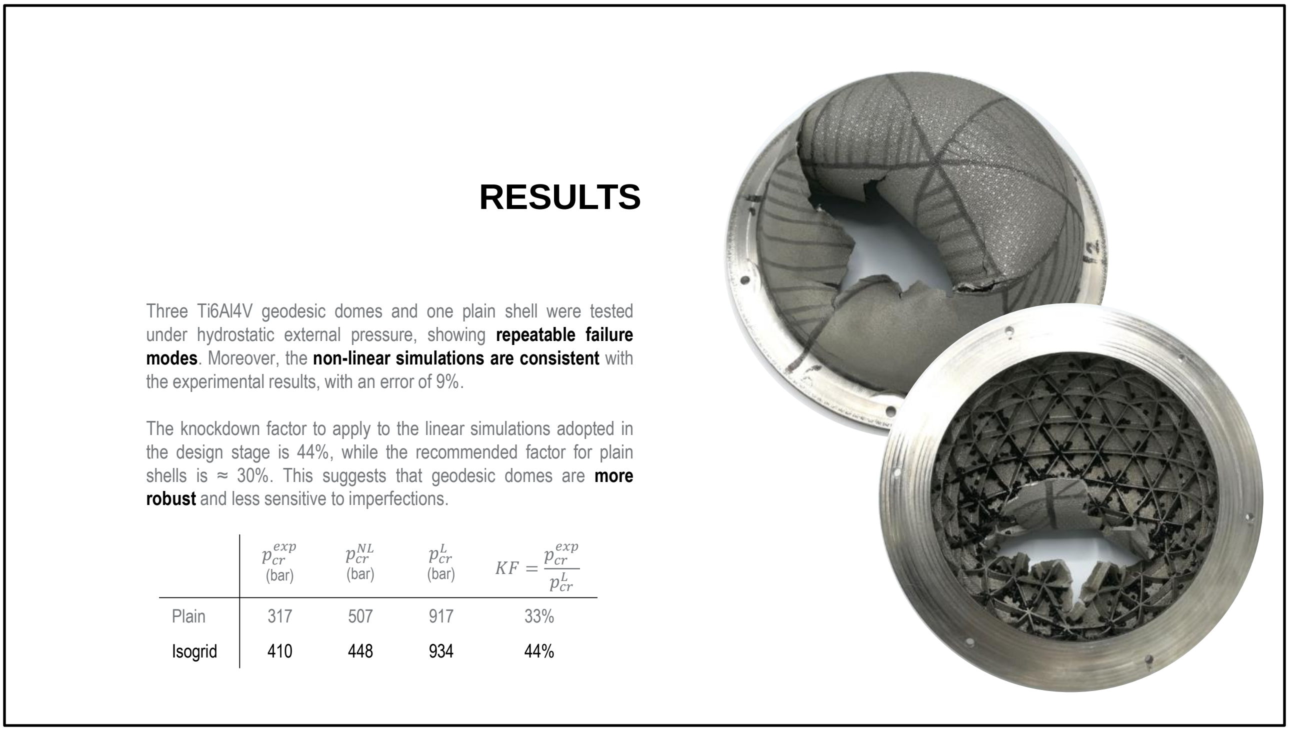
The design process previously described was applied to scaled spheres (R = 100 mm), less expensive to be fabricated, handled and tested. Tests at high pressure were performed, increasing the external pressure until failure.

1) A R=100 isogrid dome was designed according to the analytical procedure previously described
2) The CAD was updated, considering the manufacturability
3) Linear and Non linear structural simulations were performed, to estimate the failure pressure
4) Domes were built in DMLS Ti6Al4V. Stress relief and HIP were performed.
5) Three isogrid domes were tested under hydrostatic external pressure.

One plain dome (without ribbing) was designed, fabricated and tested as well.



RESULTS

Three Ti6Al4V geodesic domes and one plain shell were tested under hydrostatic external pressure, showing **repeatable failure modes**. Moreover, the **non-linear simulations are consistent** with the experimental results, with an error of 9%.

The knockdown factor to apply to the linear simulations adopted in the design stage is 44%, while the recommended factor for plain shells is ≈ 30%. This suggests that geodesic domes are **more robust** and less sensitive to imperfections.

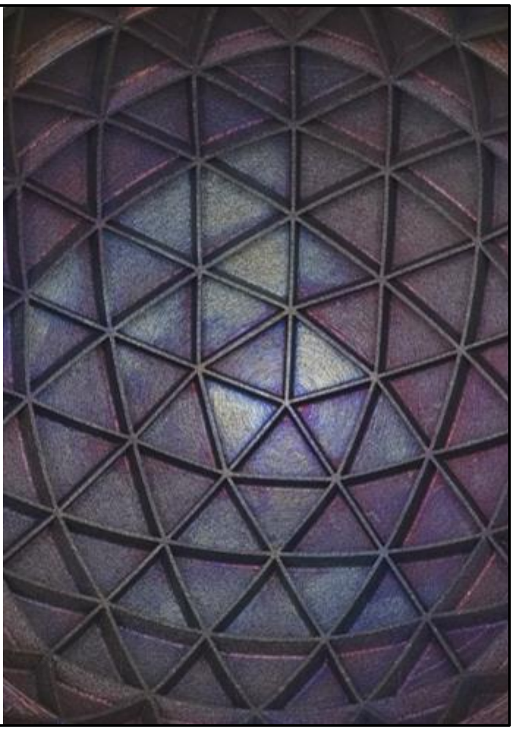
	p_{cr}^{exp} (bar)	p_{cr}^{NL} (bar)	p_{cr}^{L} (bar)	$KF = \frac{p_{cr}^{exp}}{p_{cr}^{L}}$
Plain	317	507	917	33%
Isogrid	410	448	934	44%

Four articles (3 isogrid and 1 plain hemispheres) were tested, one per each run. The test article was sealed to a plate and inserted in a pressure chamber, then the pressure (acting on the external surface of the shell) was increased by pumping water inside the chamber using a pneumatic piston, until the failure of the specimen. The plain shell suddenly collapsed at 317 bar. All the three isogrid hemispheres failed at 410.3 ± 4.0 bar (414, 411, 406 bar).

CONCLUSIONS

Thanks to Additive Manufacturing, probes for harsh environments can be stiffened with complex internal ribbing. Experimental testing showed that metallic geodesic domes perform very well under external pressure loading, being less sensitive to imperfections.

Analytical formulations provide a fast and effective method for optimizing the grid layout during the design phase, while non-linear FEA, computationally very expensive, can accurately predict the mechanical behavior.



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