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TRANSFORMANDO LOS OCÉANOS: INNOVACIÓN e ingeniería naval para un mundo CONECTADO y SOSTENIBLE

Design and Conception of a Military Submarine Pressure Hull Using Genetic Algorithms

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INTRODUCTION

Diversity of scientific works in the study of the optimisation of the structural weight and strength of a submarine, both experimental and analytical studies:

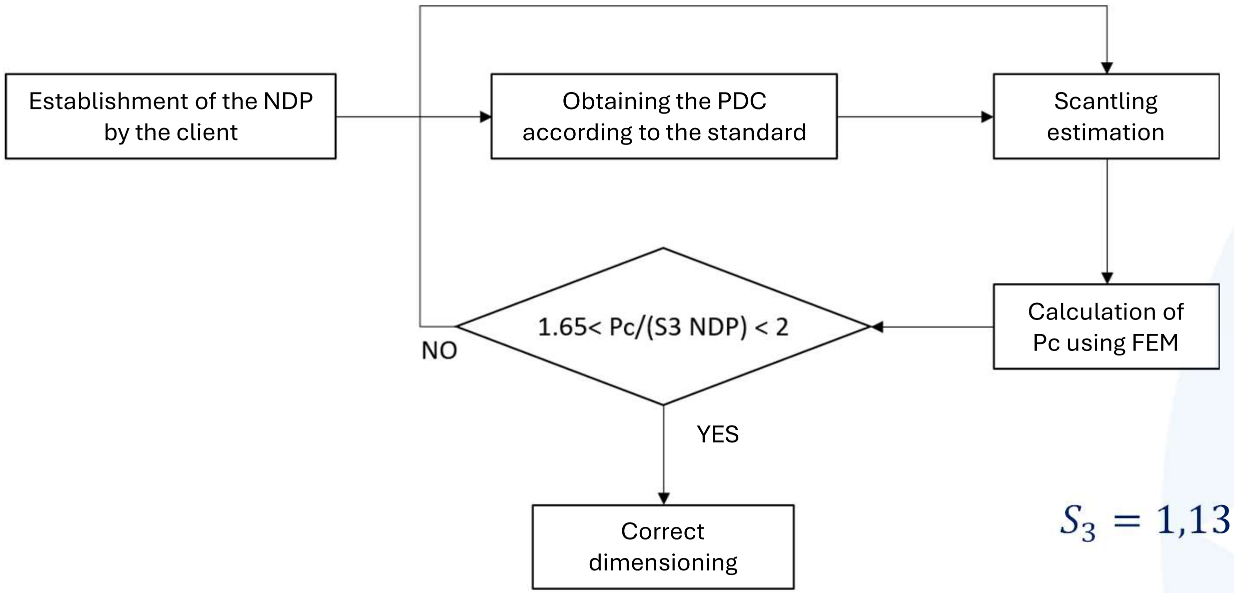
- Wullschleger et al [5]. Buckling in composite cylinders
- Graham [6]. FEM analysis of elasto-plastic collapse and experimental modelling
- Cho et al [7]. Experiments with stiffened cylinder models and empirical formulation
- Reijmers et al [9]. Predictive models of collapse as a function of imperfections
- Bo-Young et al [10]. Compartment layout optimization
- Fathallah and Helal [11]. Maximising the structural strength of an elliptical RC
- Imran et al [14]. Optimisation of a spherical composite RC using GA.

Research is mainly divided into the use of lighter materials or optimisation of the structural elements.

Our methodology: Decrease of the steel weight of the resistant hull of a submarine using a new methodology based on Genetic Algorithms.

INITIAL SCANTLING

DNV standard, based on the target maximum operating level. Once the preliminary design is obtained, its maximum operating level is evaluated by means of FEM.

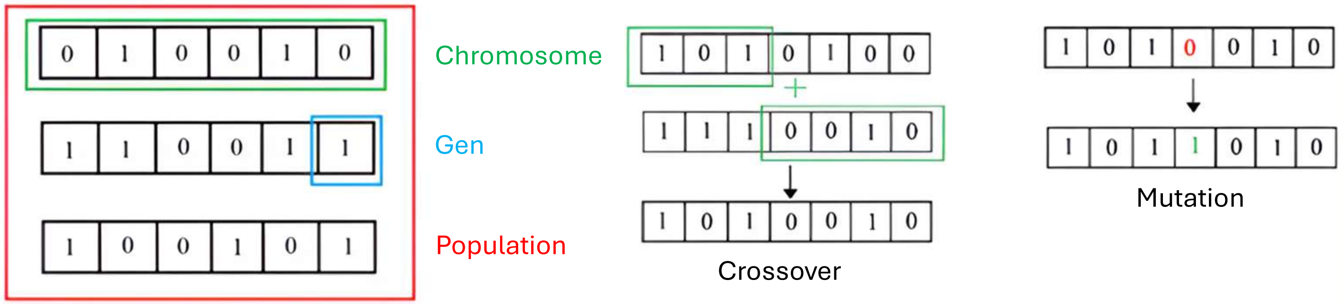


$$NDP \leq {}^{TDP}/_{S_1} \leq {}^{1}/_{S_2} \cdot CDP$$

$$S_3 = 1{,}134, \mathit{Mackay\ y\ van\ Kaulen}\ [18]$$

PROPOSED METHODOLOGY

Structural weight reduction using a genetic algorithm



- Random initial population, consisting of chromosomes
- Each chromosome has a quantitative indicator of individual's fit to the solution (fitness value)
- Reproduction probability based on fitness value
- Crossing and mutation phases:
  - Crossing. Exchange of genes between parents
  - Mutation. Modification of one or more genes in a chromosome (low probability event)

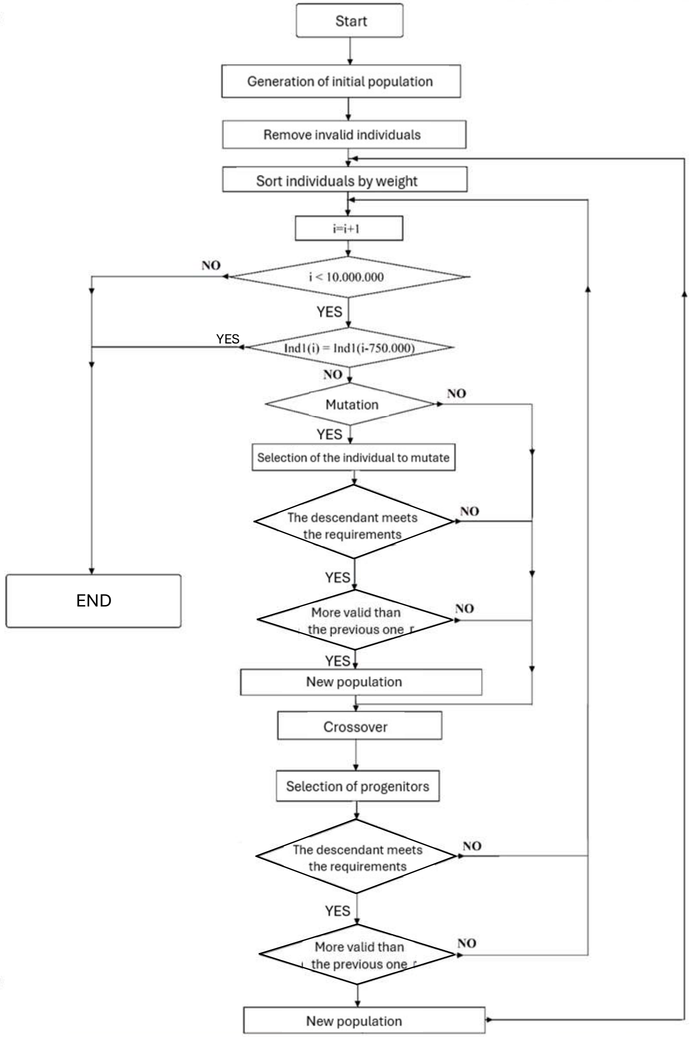
PROPOSED METHODOLOGY

With each new generation, the fitness of each chromosome will be re-evaluated, and parents will be selected again.

Nº gen	Acronym	Description
1	s	Hull thickness
2	hw	Web height
3	sw	Web thickness
4	bf	Flange width
5	sf	Flange thickness
6	sD	Web frame hull thickness
7	hwD	Web height of the web frame
8	swD	Web thickness of the web frame
9	bfD	Flange width of the web frame
10	sfD	Flange thickness of the web frame
11	sDomopp	Aft dome thickness
12	sDomopr	Bow dome thickness

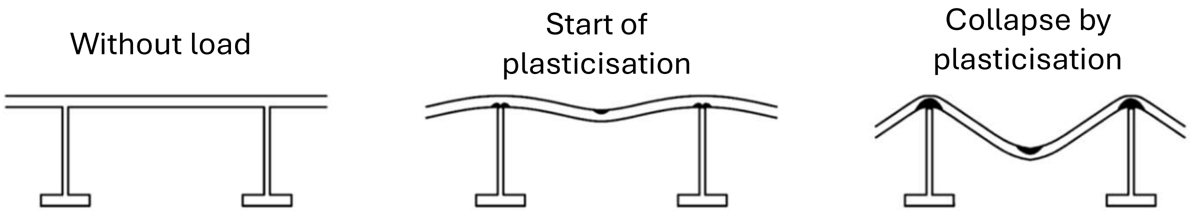
PROPOSED METHODOLOGY

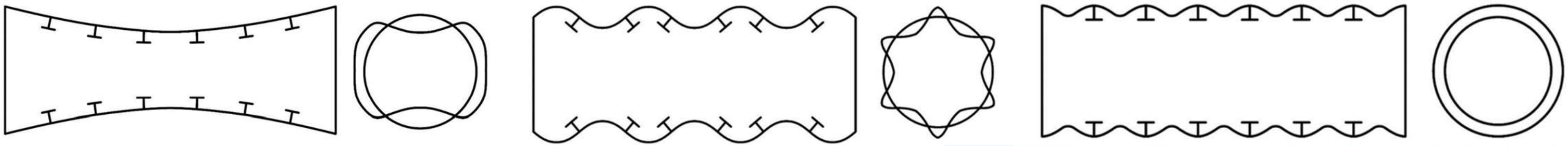
- Standard to obtain the fitness value
- 12 genes per chromosome
- Gene variation of ±10%
- Initial population of 500.000 chromosomes
- Population order based on resulting steel weight
- Reproduction is based on a steady-state model:
  - The new individual replaces the worst from the previous population
- Mutation has a 10% probability of occurrence
  - If the mutated individual has a better fitness function, it replaces the previous one
- Two stopping criteria



VERIFICATION OF THE RESULTING DESIGN

The resulting design obtained by the GA is checked using finite elements.
Evaluation of different failure modes that could experience collapse.
Static loading.





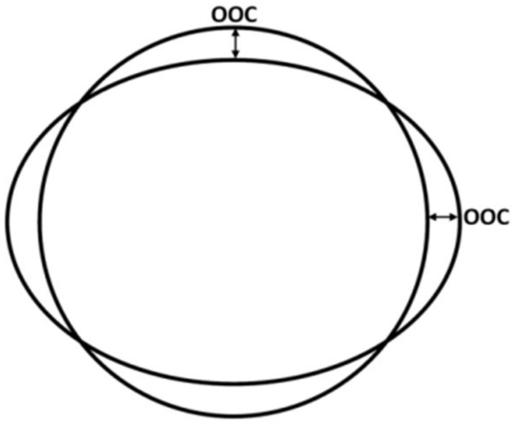
General instability

Instability of the hull between stiffeners

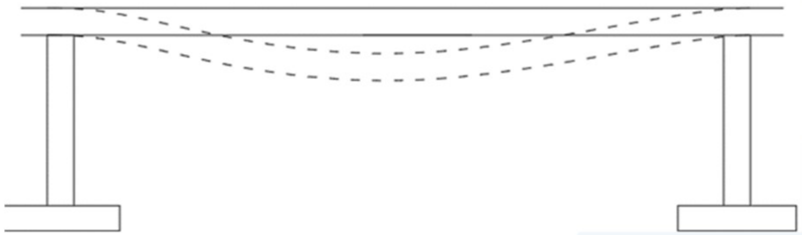
VERIFICATION OF THE RESULTING DESIGN

A series of construction defects that may result in a reduction of collapse pressure are considered:

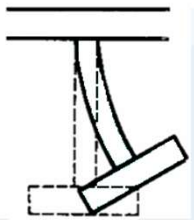
- Out of Circularity (OOC). Promotes overall instability.
- *Hungry horse & tripping*. Promote buckling between stiffeners and frames.



OOC



Hungry horse



Tripping

CASE STUDY. Initial data

The proposed methodology is applied to a specific case.
A radius of 3500mm, 3.5MPa of NDP, 580mm of frame spacing and 80 frames are imposed.
HY-100 steel is selected as the constituent material.
General arrangement based on modern conventional submarines:

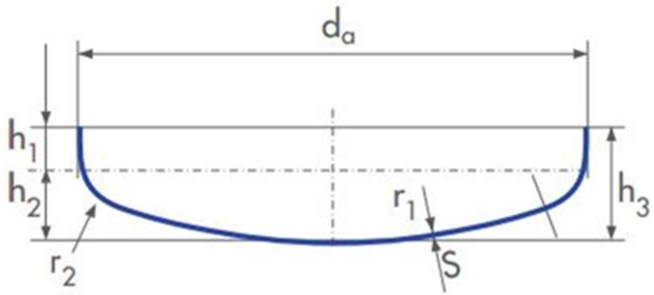
- Cofferdam separating propulsion from command and control.
- Bulwark stringer halfway through compartments separated by the cofferdam.
- Limitation of stiffness of reinforcements according to ABS.
- Toriespherical domes following DIN 28011 standard.

Mechanical properties of HY-100 steel

σ_{prop} [MPa]	552
σ_y [MPa]	690
E [MPa]	207000
ν	0.3

$$\frac{b_f}{s_f} \leq 0.3\sqrt{\frac{E}{\sigma_y}}$$

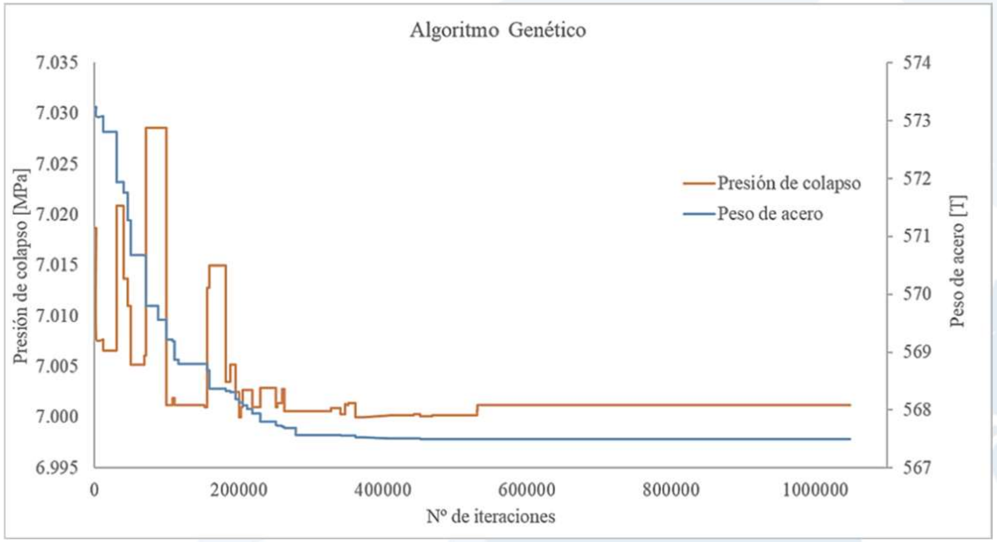
$$\frac{h_w}{h_w} \leq 0.9\sqrt{\frac{E}{\sigma_y}}$$



CASE STUDY. Implementation of the GA

Obtaining fitness function values and collapse pressure for each iteration.
Convergence after more than 1.000.000 iterations.

Acronym	Lower limit (mm)	Preliminary scantling (mm)	Upper limit (mm)
s	32,4	36,0	39,6
hw	234,0	260,0	286,0
sw	16,4	18,2	20,0
bf	144,0	160,0	176,0
sf	32,4	36,0	39,6
sD	40,5	45,0	49,5
hwD	270,0	300,0	330,0
swD	31,5	35,0	38,5
bfD	225,0	250,0	275,0
sfD	40,5	45,0	49,5
sDomopp	39,1	43,4	47,7
sDomopr	54,3	60,3	66,3

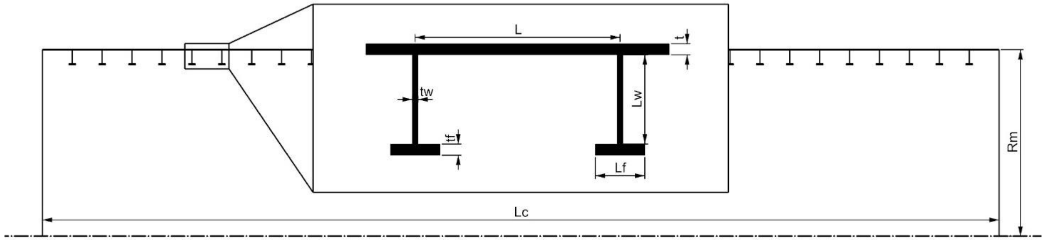


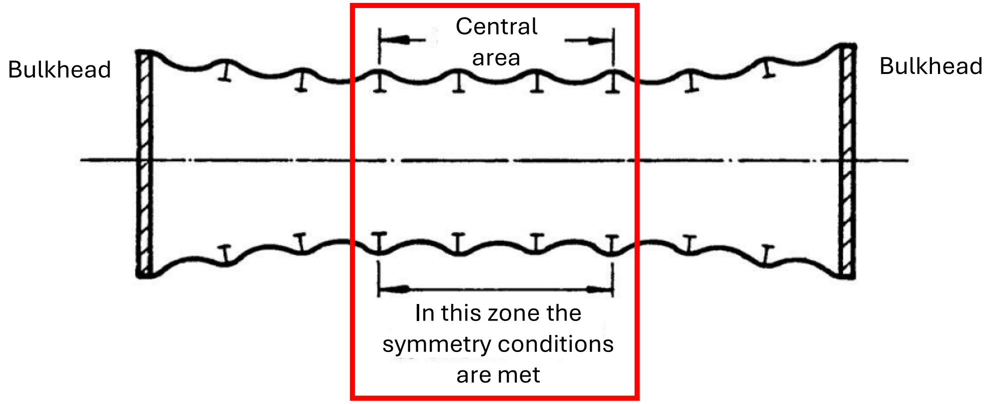
CASE STUDY. Implementation of the GA

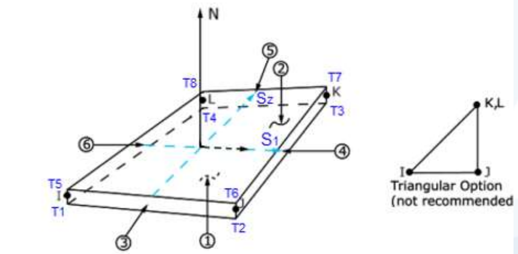
Description	Acronym	Preliminary scantling (mm)	Optimised scantling (mm)	Variation
Hull thickness	s	36,0	32,4	-10,00%
Web height	hw	260,0	272,9	4,96%
Web thickness	Sw	18,2	18,9	3,85%
Flange width	Bf	160,0	175,0	9,38%
Flange thickness	sf	36,0	33,3	-7,50%
Web frame hull thickness	sD	45,0	49,5	10,00%
Web height of the web frame	hwD	300,0	329,4	9,80%
Web thickness of the web frame	swD	35,0	31,5	-10,00%
Flange width of the web frame	bfD	250,0	225,4	-9,84%
Flange thickness of the web frame	sfD	45,0	42,4	-5,78%
Aft dome thickness	sDomopp	43,4	41,5	-4,38%
Bow dome thickness	sDomopr	60,3	58,5	-2,99%

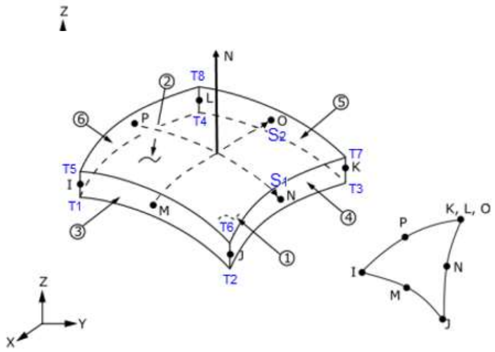
CASE STUDY. FEM testing

Linear static, non-linear static and dynamic analysis.
Use of two models depending on the failure modes: complete or infinite compartment
Shell elements with and without intermediate nodes



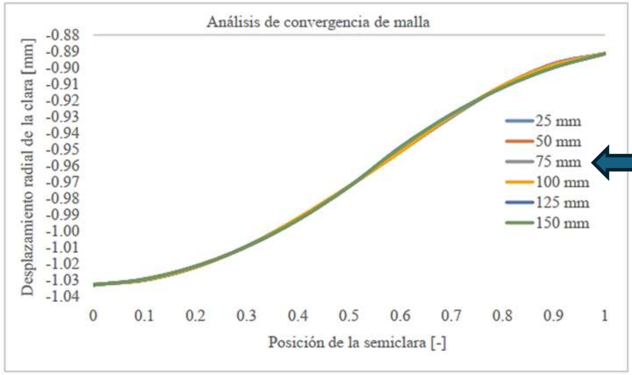


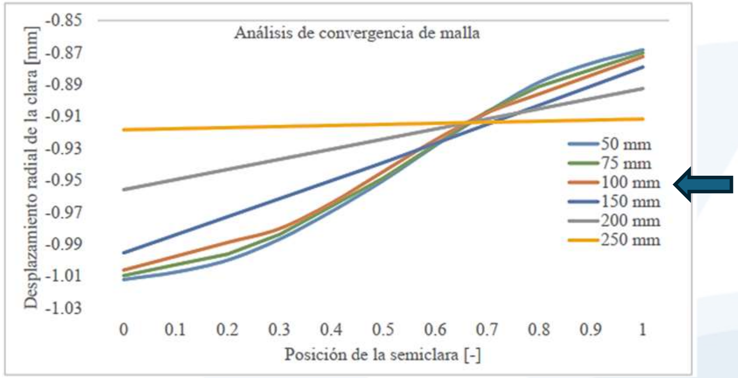


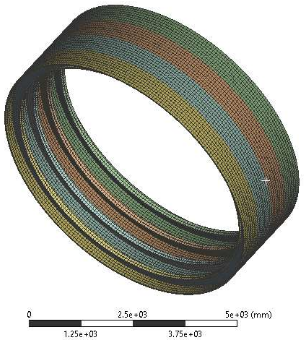


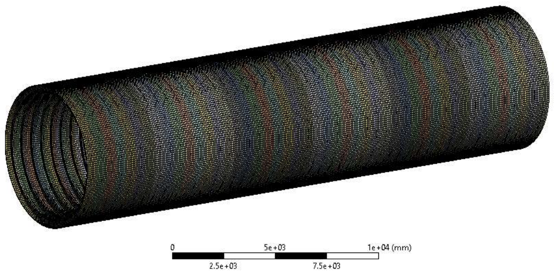
CASE STUDY. FEM testing

A mesh sensitivity analysis is performed to select the appropriate element size.



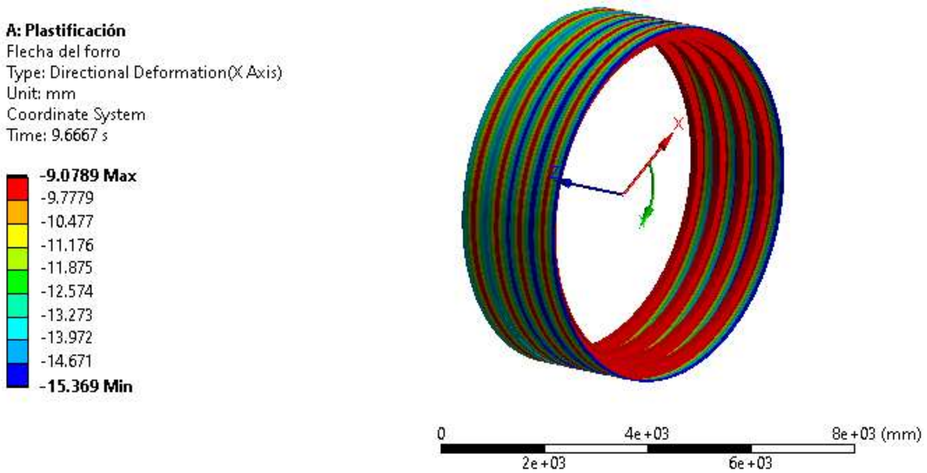




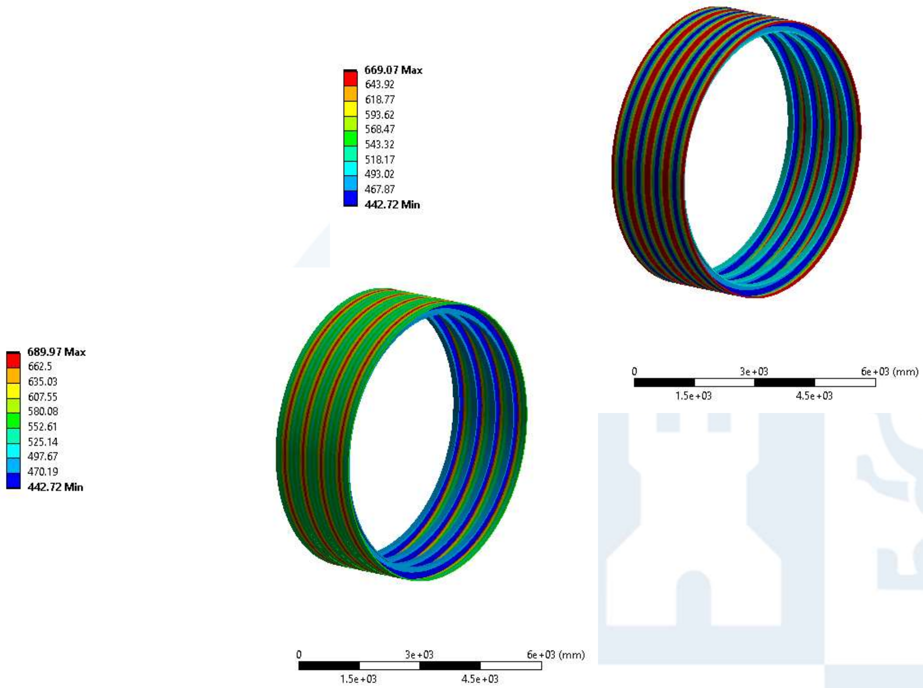


CASE STUDY. FEM testing

As a starting point, the behavior of the proposed design without any defects is analysed.
A non-linear analysis is performed, increasing the pressure at each time step until the yield strength of the material is achieved.
The infinite cylinder model is used in this case.

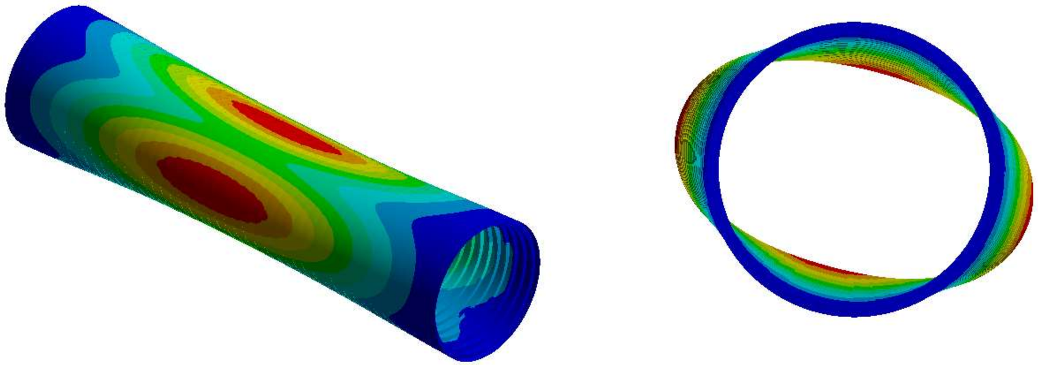


9.67 MPa

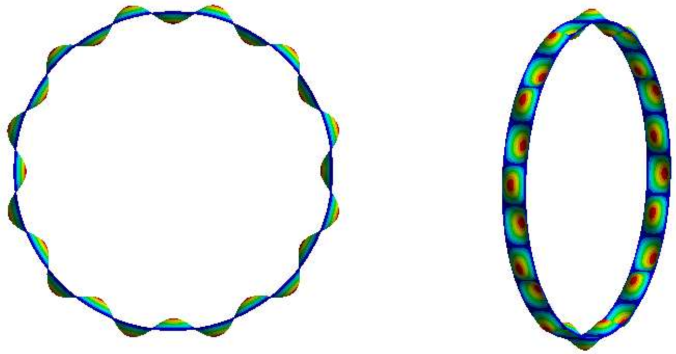


CASE STUDY. FEM testing

A dynamic analysis is carried out to obtain the eigenvalues and thus determine the instabilities of the assembly.
To study the general instability, the full compartment model is used, while the study of the instability of the lining between reinforcements is carried out with the infinite model.
It should be noted that the latter is reduced to a single clear one for correct comparison with the analytical formulation [24, 25, 26].



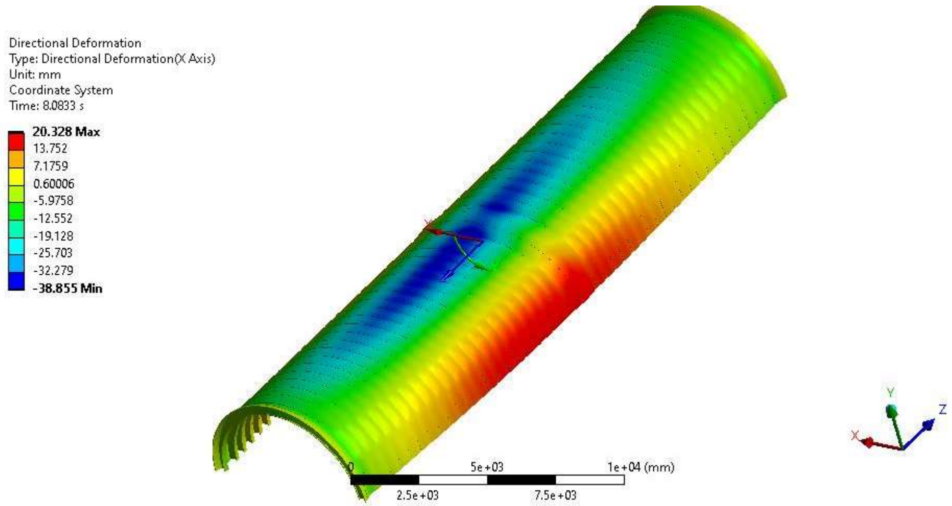
14.44 MPa



16.33MPa

CASE STUDY. FEM testing

It is concluded that the most constraining failure for the proposed ideal design is plasticization collapse.
The influence of the circularity defect, hungry horse and tripping, both separately and jointly, on this failure mode is studied.
Separately, the OCC flaw results in a reduction of the collapse pressure by 16.39%.

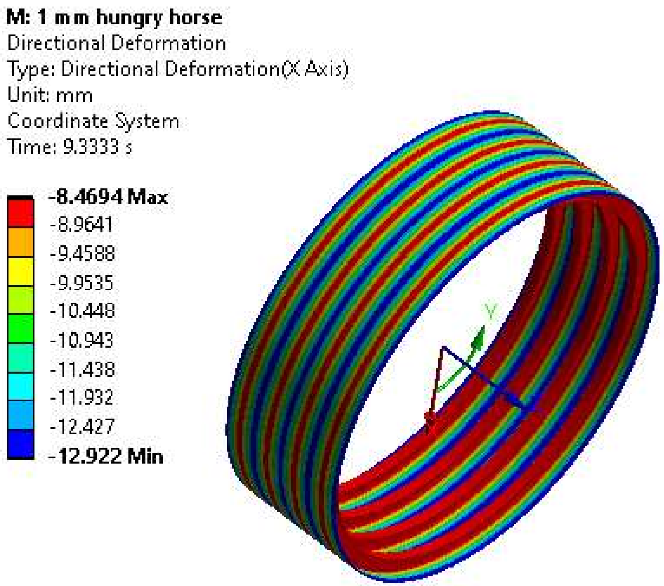


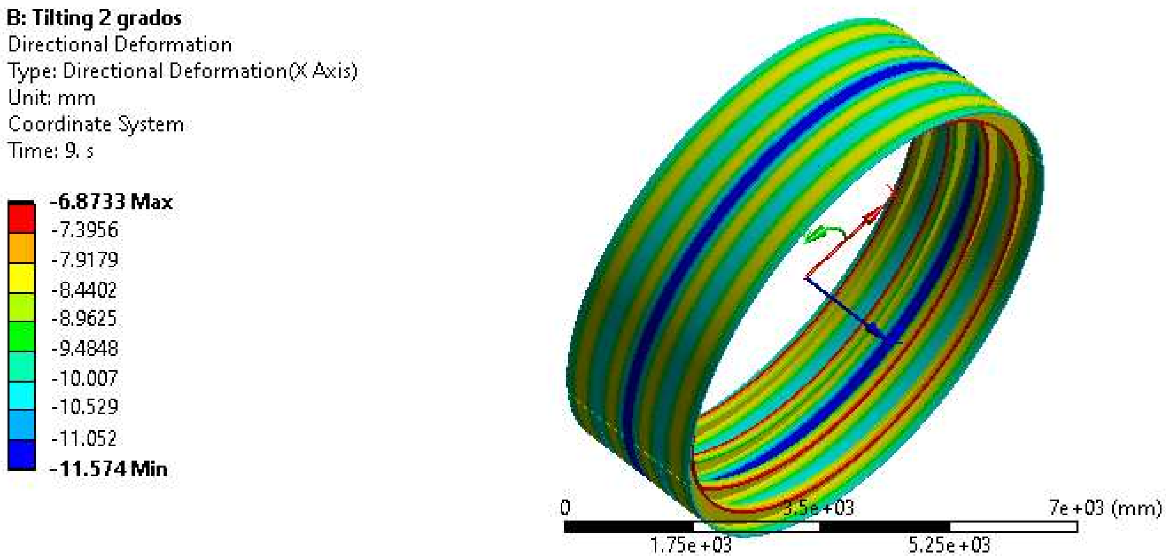
OCC (% average radius)	P_c [MPa]	ΔP_c [%]
0.0	9,667	-
0,1	9,167	-5,17%
0,2	8,833	-8,63%
0,3	8,500	-12,07%
0,4	8,333	-13,80%
0,5	**8,083**	**-16,39%**

CASE STUDY. FEM testing

The maximum permissible values for hungry horse and tripping defects according to DNV are selected, 1 mm for hungry horse and 2° of inclination for tripping.

- Hungry horse: 3.45% reduction of collapse pressure.
- Tripping: 6.90% reduction of collapse pressure.

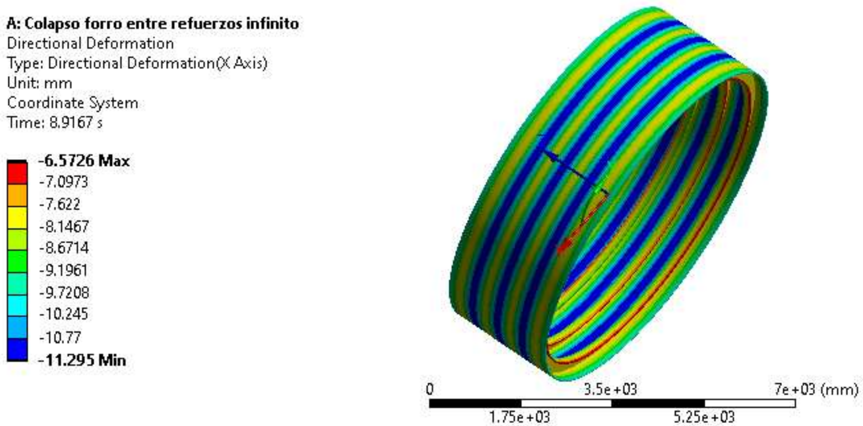


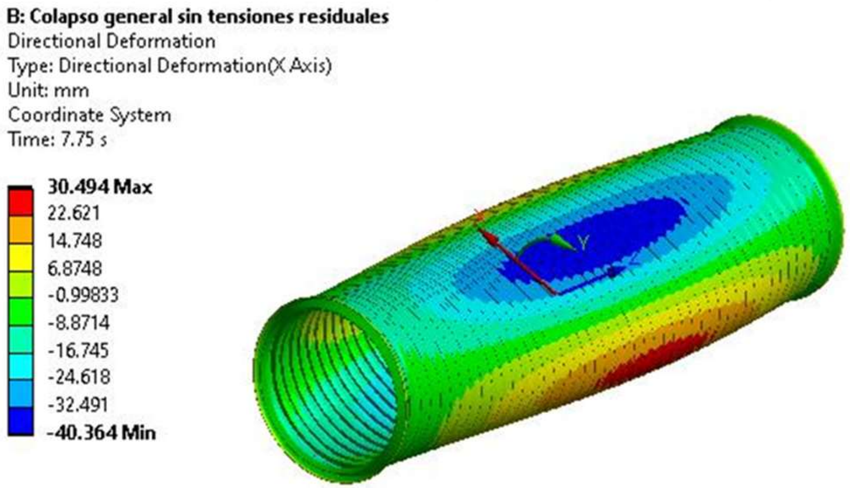


CASE STUDY. FEM testing

The interaction between these failure modes is studied, first the combination of hungry horse and tripping, then the combination of all of them.

- Hungry horse and tripping: 7,76% reduction of collapse pressure.
- OCC, hungry horse y tripping: 19,83% reduction of collapse pressure.





CASE STUDY. Discussion of results

Reduction of steel weight from 590.3 to 567.3 tonnes, almost 4% less.

The genetic algorithm has prioritised the reduction of the thickness of the shell, frame flange and domes; compensating for the loss of cross-section strength by increasing the main dimensions of the frame and the thickness of the web.

The web frame, being a point structural element, the reduction of the shell thickness does not imply an excessive increase in the total weight, so the GA opted to reduce the thickness of the web and flange.

Descripción	Preliminary scantling (mm)	Optimised scantling (mm)	Variation
Hull thickness	36,0	32,4	-10,00%
Web height	260,0	272,9	4,96%
Web thickness	18,2	18,9	3,85%
Flange width	160,0	175,0	9,38%
Flange thickness	36,0	33,3	-7,50%
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Aft dome thickness	43,4	41,5	-4,38%
Bow dome thickness	60,3	58,5	-2,99%

CONCLUSIONS

The application of an GA has resulted in a significant reduction of steel weight.

The GA achieves the optimal solution by increasing the inertia of the section with a lower structural weight.

The proposed design complies with the applicable regulations.

It is found that in the ideal hull collapse occurs without any previous structural instability.

The defects considered together imply a reduction of the collapse pressure by almost 20%, although the OOC alone implies a reduction of 16.39%, being the most critical defect.

A factor of safety is taken for the FEM calculations of 1.134 following [18], finally resulting in a collapse pressure of 6.834MPa.

A factor of safety S2 of 1.952 is obtained considering the maximum operating pressure at 3.5MPa.

THANKS FOR YOUR ATTENTION

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