Structural optimization methodology of the 2-D inner-leg cross-section for the TF Coils of fusion reactors

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Abstract

A novel methodology is proposed for the structural optimization of inner-leg cross-section of Toroidal Field (TF) coils of a fusion reactor to achieve significant improvements in the structural response of the component. In fact, the original Winding Pack (WP) configuration, used as starting point of the optimization process, despite being compliant in terms of the electro-magnetic behavior, causes the entire component cross-section to be far beyond structural limits, because of intensive peak stress concentrations. A multi-objective optimization process, aimed to lower these stress peaks and the stress level in general, is proposed in this work.

Objectives

- To minimize the stress integrals inside the jacket and the insulation material, limiting, if possible, the use of SS in the jacket.
- Respecting constraints according to Tresca failure Criterion on Primary Membrane Stress (Based on *Section III of the ASME Boiler and Pressure Vessel Code).*

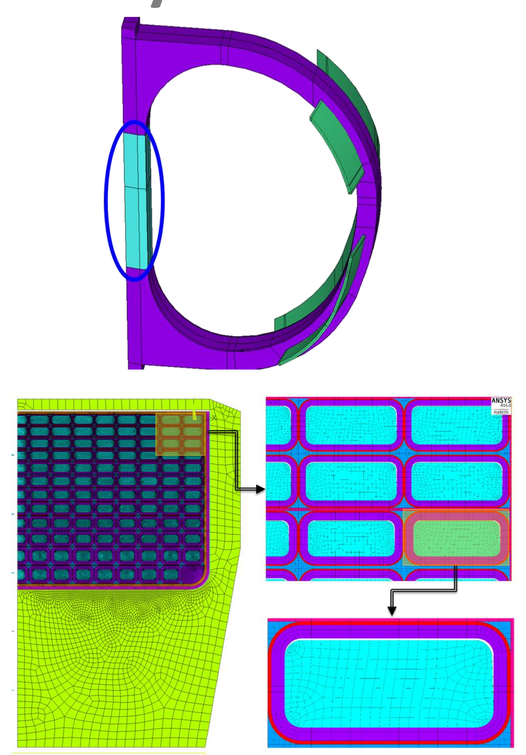
Conclusions

- The original, non-optimized, architectural configuration is not compliant in terms of Tresca stress in the Jacket and Case structural steel and in terms of shear stress in the insulation layers.
- The Jacket cross sectional area was increased of about 12%, while the stress integrals were reduced of about 3% on the jacket and about 8% in the insulation.
- At the same time, the set of Pareto optimal architectural configurations is now compliant in terms of Tresca Failure Criterion on both the casing and the jacket.
- However, it does persist a critical issue in terms of shear stress in the insulation.

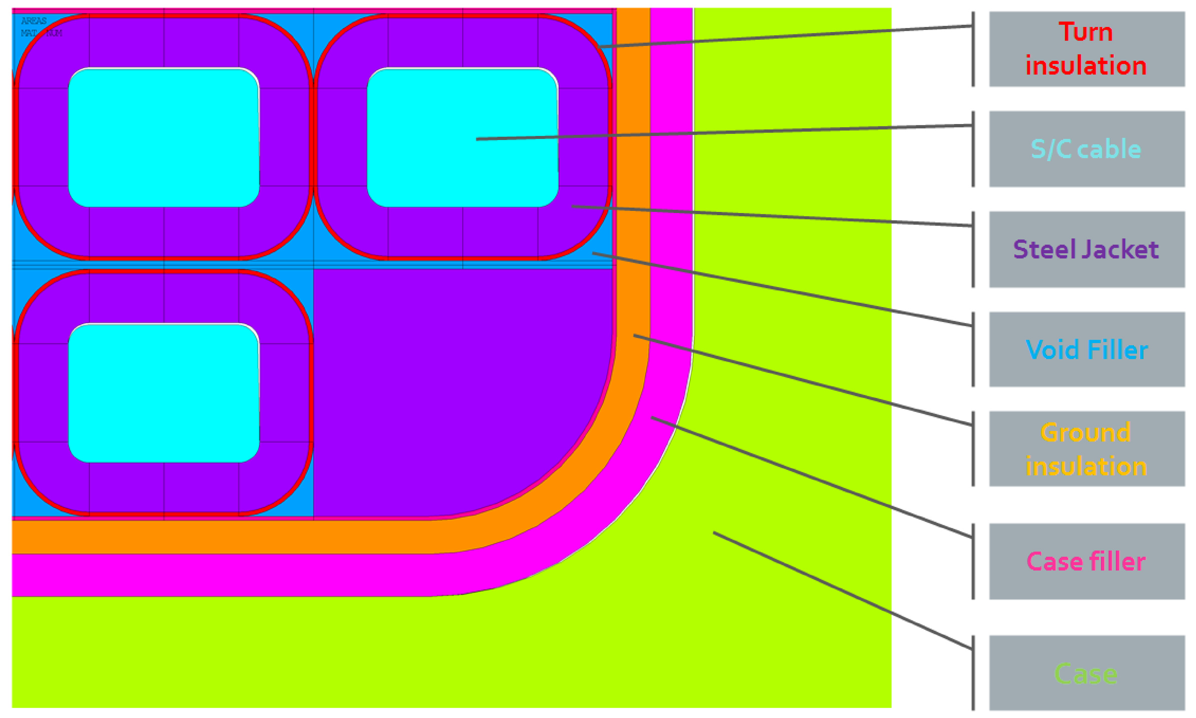
Methods

Finite Element Analysis

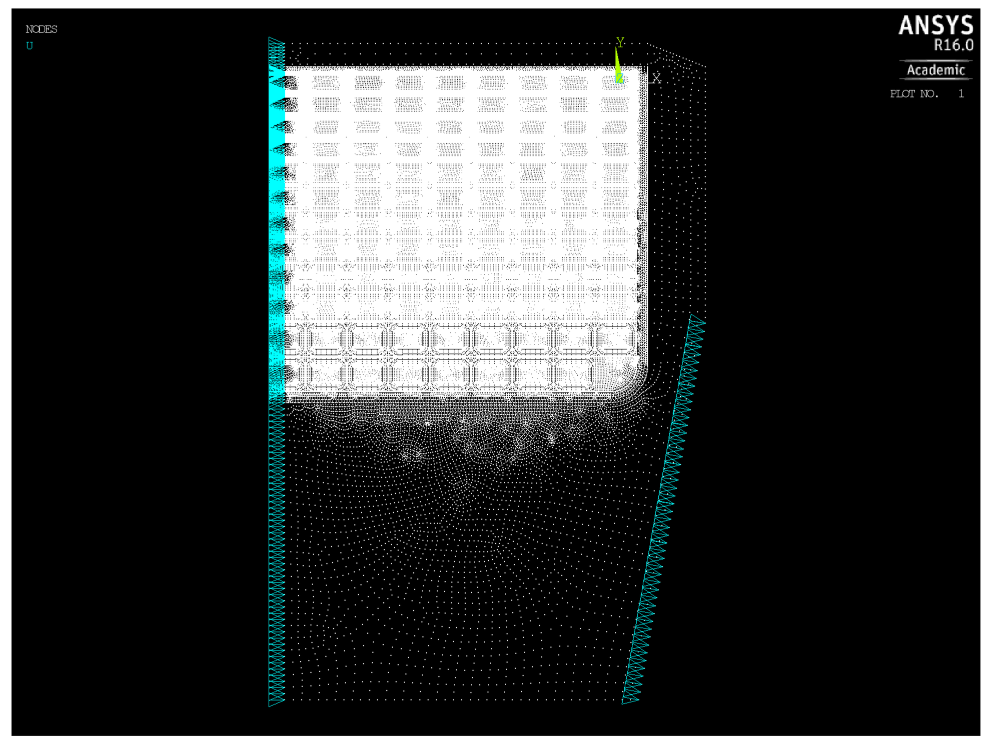
1. Thermo structural simulation – Thermal stress is due to the transition from 293 K (reference temperature) to 4.2 K (operating temperature of the magnet).
2. Mechanical simulation – The mechanical loads are generated by the Lorentz forces due to the magnetic field in the WP. The forces are applied to the centroid of each cable.



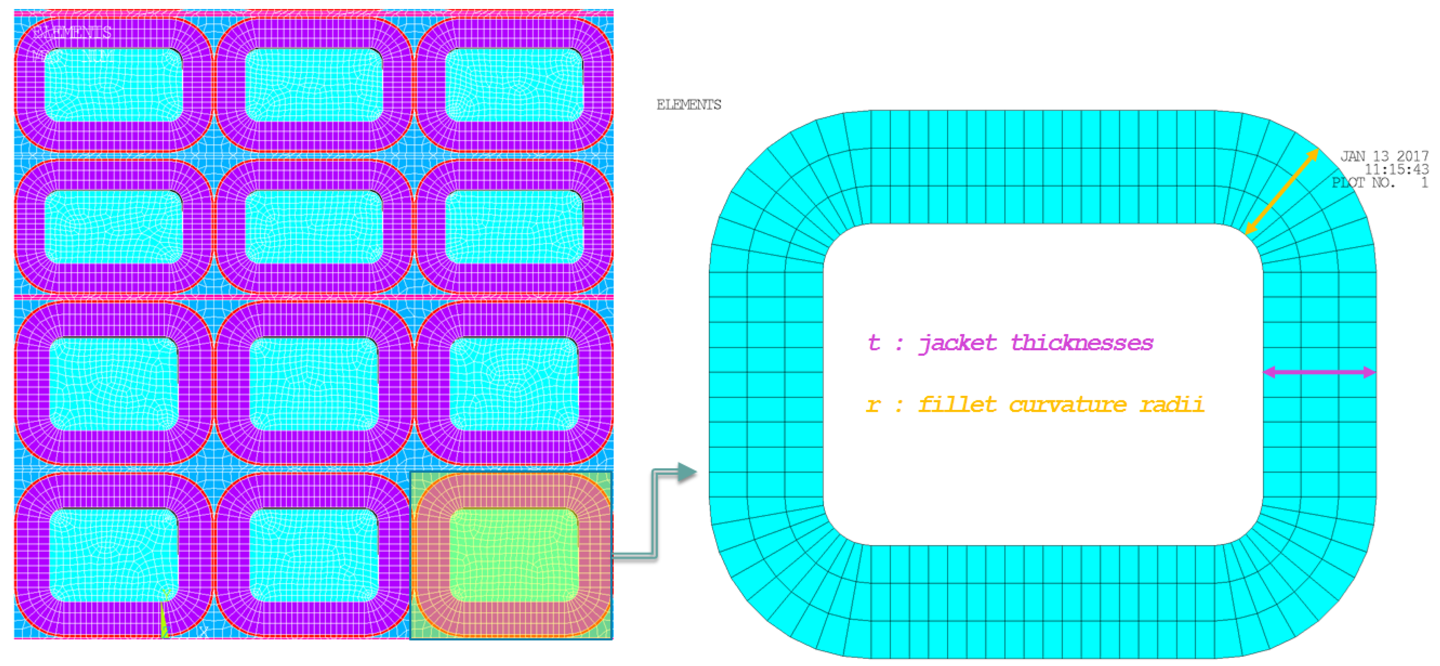
Materials distribution in the cross section



Boundary Conditions

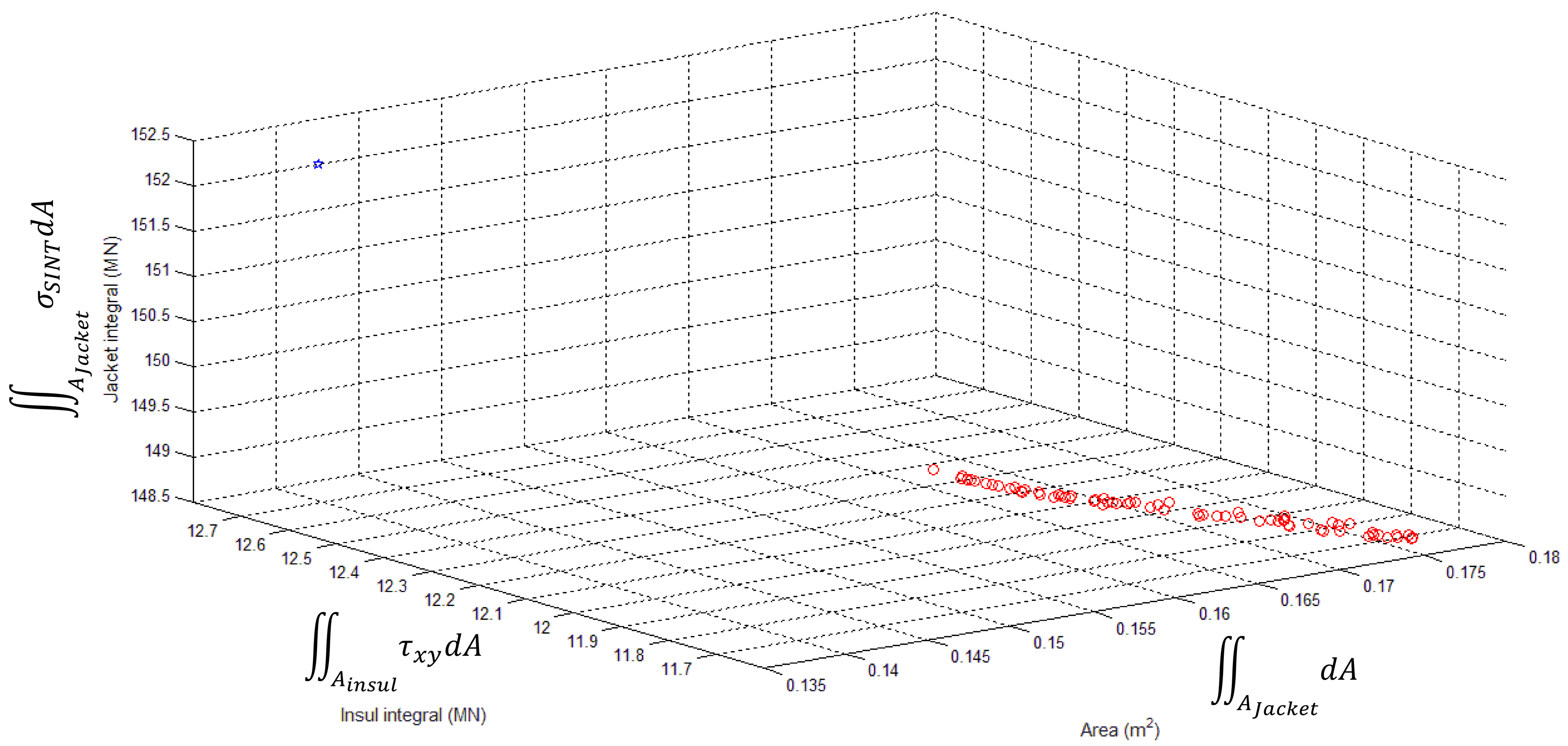


Optimization Parameters



Results

Pareto front



The Pareto front represents the infinite set of solutions for a multi-objective optimization problem.

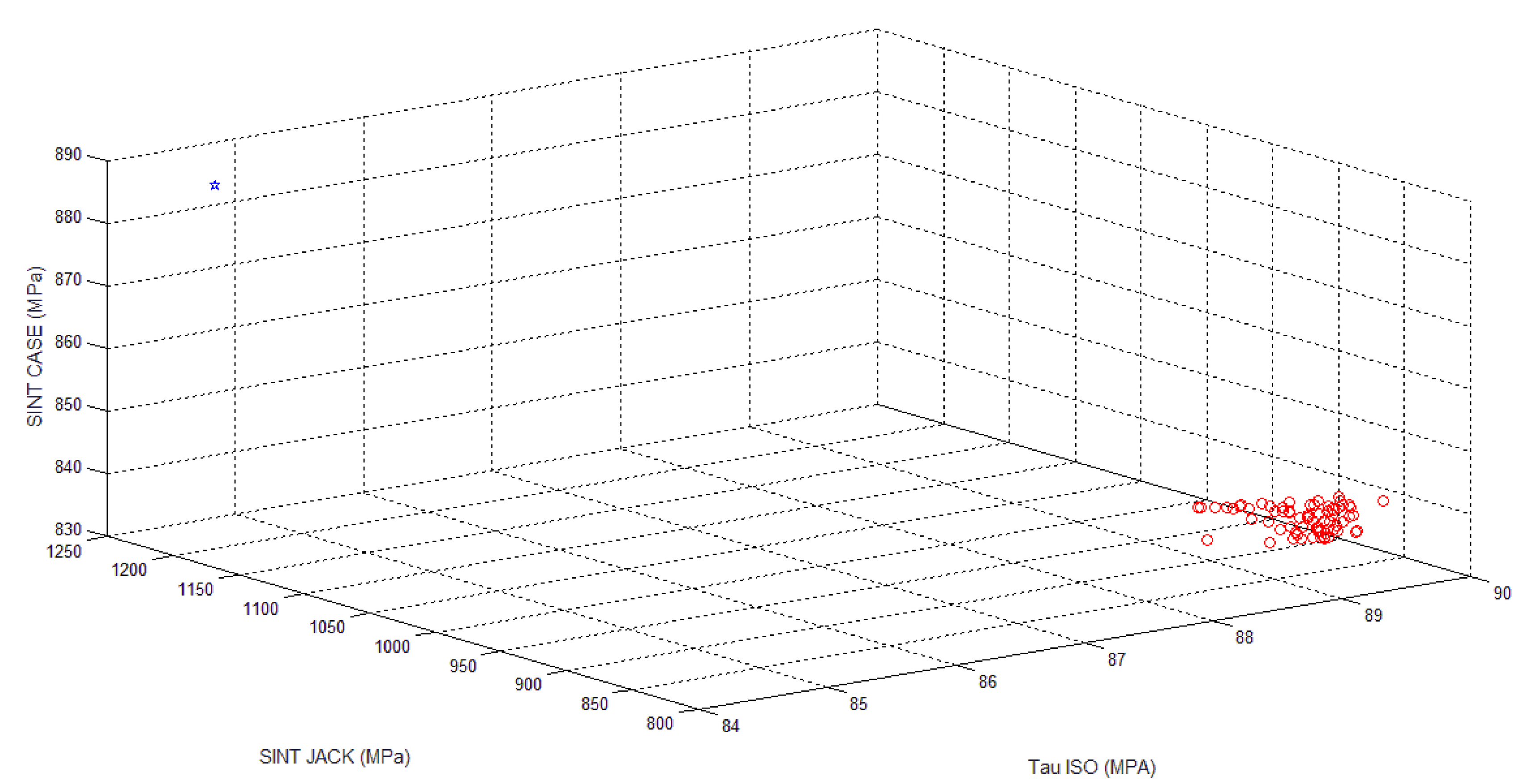
In this specific case, three objectives were set, to be minimized, for the optimization:

- the total cross-sectional area of the jacket ("Area" in figure beside);
- the integral of the Shear stress over the insulation ("Insul integral");
- the integral of the Stress Intensity over the Jacket ("Jacket Integral").

In the plot beside, the discrete set of Pareto optimal solutions for the multi-objective optimization is represented with red circles. In the same figure, the blue star represents the value of the three objectives calculated for the original, non-optimized, configuration.

From the comparison between the Pareto front and the non-optimized configuration, it is clear that the optimization process led to a significant decrease in the stress integrals, both in the Insulation and in the Jacket, by increasing the area of the jacket cross-section.

Corresponding constraints in the optimal configurations



While minimizing the objectives described in the box on the left, constraints were also posed in the multi-objective process.

In particular, constraints were set for the max value of:

- Tresca Stress intensity in the casing ("SINT CASE" in the figure beside);
- Tresca Stress intensity in the jacket ("SINT JACK");
- Shear stress in the insulation ("Tau ISO").

The effect of the optimization process on the mentioned structural outputs is represented in red circles with respect to the values achieved for the non-optimized configuration (blue star).

As the shear stress in the insulation is increased (exceeding acceptable values both in the non-optimized and optimized configurations), both the Tresca stress in the casing and jacket are reduced below acceptable values.

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