Optimisation of CFRP and aluminium honeycomb panels for spacecraft

Dipl.-Ing. L. Cabezudo Carrascal
(Airbus Defence and Space Ltd., United Kingdom)

Abstract

Spacecraft structures are often constructed of sandwich panels with CFRP skins and aluminium honeycomb core, taking advantage of their low mass, high stiffness and excellent thermal stability. The difficulty of designing structures with these materials resides in the number of design parameters to control as opposed to a monolithic material: number of plies, thickness and orientation of each ply, core density and core thickness. Also, spacecraft structures need to be simultaneously compliant with a wide range of static and dynamic requirements. Traditionally, expertise and engineering judgment are needed in a long trade-off process to achieve a final compliant design, not necessarily fully optimised. By combining free-size and parametric optimisation techniques during the analysis, both structure and material can converge together into a final design that achieves compliance with all requirements while minimizing weight, all in a fraction of the time needed for the traditional approach.

1. Honeycomb/CFRP panels. Characteristics and properties

Honeycomb panels are constructed by joining a central honeycomb core piece to upper and lower face sheets or skins using adhesive layers in between (see Fig. 1 and Fig. 2).

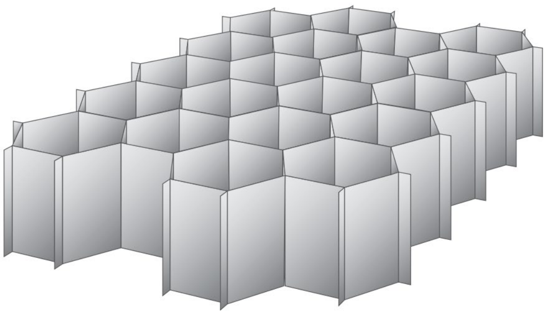

Figure 1: Honeycomb core. (Image credit: Plascore)

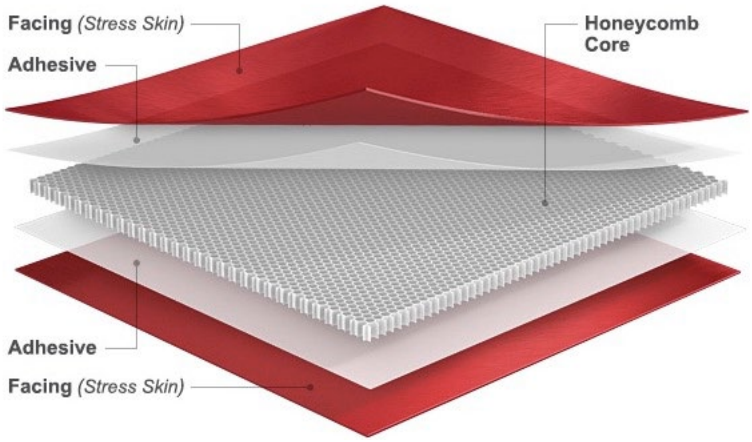

Figure 2: Honeycomb panel construction. (Image credit: Plascore)

Both face sheets and core can be made of different materials. The usual combination in the Space Industry is aluminium for both face sheets and core or Carbon Fibre Reinforced Plastic (CFRP) for the face sheets and aluminium for the core. This second option is particularly useful for applications where thermal stability is important, such as telescopes (pointing stability), due to the low expansion coefficient of CFRP materials.

Honeycomb structures achieve very high shear stiffness with low mass, which make them suitable for low-weight applications. The face sheets of the panel work similarly to the flanges in an I-beam, carrying bending stresses, with one face in tension when the other is in compression. The honeycomb cells in the core, in turn, work as the web of an I-beam, resisting shear loads. They also provide a more continuous support to the face sheets compared to the I-beam, resulting in homogeneous behaviour across the panel.

Therefore, stiffness increases exponentially with core thickness, with very little weight gain, as the effective density of the core is very low (see Fig. 3).

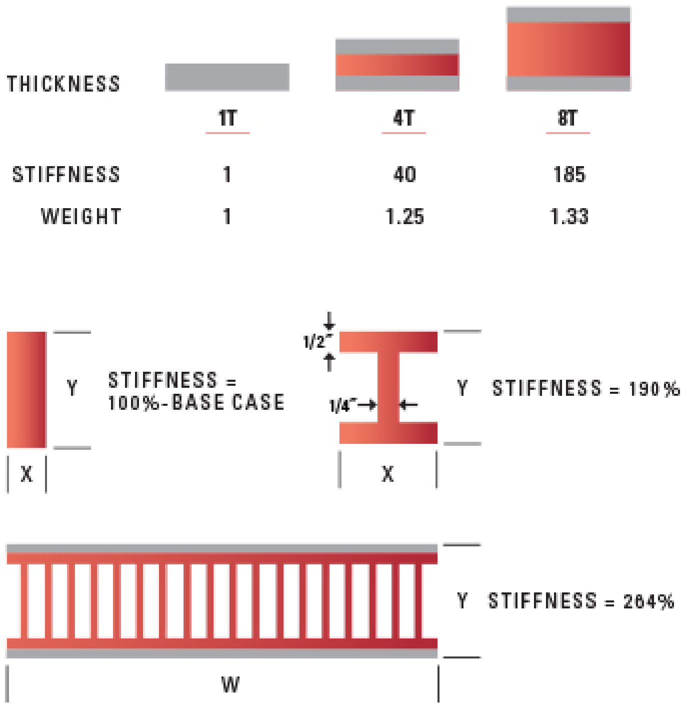

Figure 3: Mechanical performance of honeycomb panel. (Image credit: Plascore)

However, CFRP and aluminium honeycomb panels also have several disadvantages compared to monolithic materials. They are usually more expensive, both because of the cost of the raw materials and because of the complexity of their manufacture. The failure modes of a honeycomb panel are derived from its construction, and can involve the skins, the core, the adhesive or a combination of the three, making the mechanical analysis of these structures more complicated.

The design parameters needed to properly define a CFRP and aluminium honeycomb panel are also more than for an equivalent monolithic panel, and therefore the design process is more complex. For a given panel, and assuming the specific materials to be used have already been chosen, the design parameters to be considered are (see Fig. 4):

CFRP face sheets:

- Single ply thickness
- Number of plies
- Orientation of each ply
- Ply stacking sequence

Aluminium core:

- Core height
- Cell size
- Foil thickness

Aluminium honeycomb manufacturers provide a wide range of cell sizes and foil thicknesses to choose from.

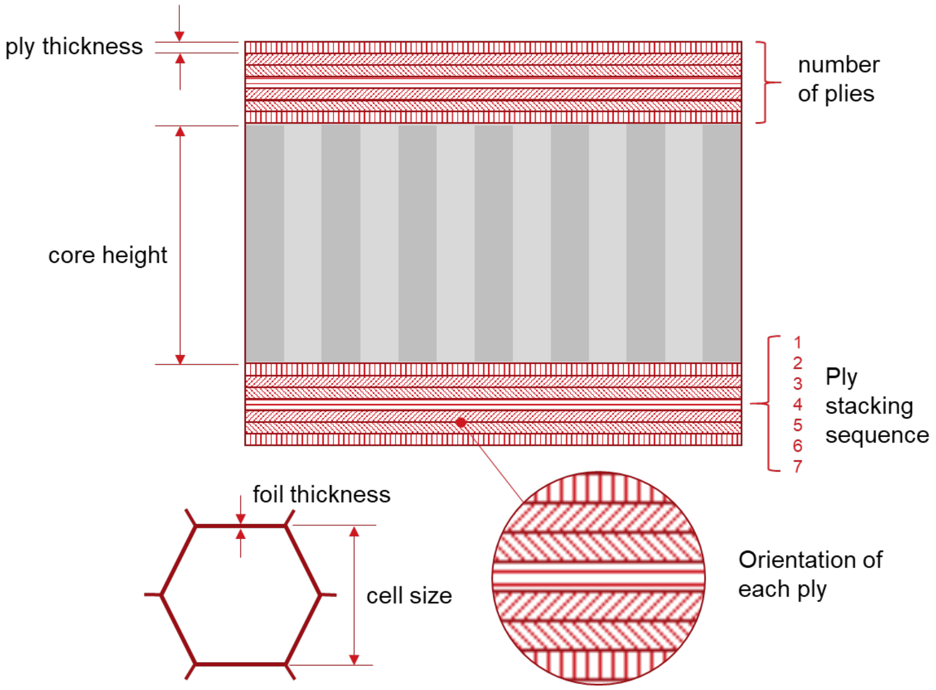

Figure 4: Design parameters of CFRP and aluminium honeycomb panel

Traditionally, producing a valid design of a structure made of CFRP and aluminium honeycomb panels is done relying on past experience and know-how, simplified hand calculations for the early design phases, and a long iterative succession of analysis, post-processing and design modifications and trade-offs, until a compliant -but not necessarily optimised- result is achieved. This is a work-intensive and sometimes imprecise process that not always delivers the best possible design (see Fig. 5).

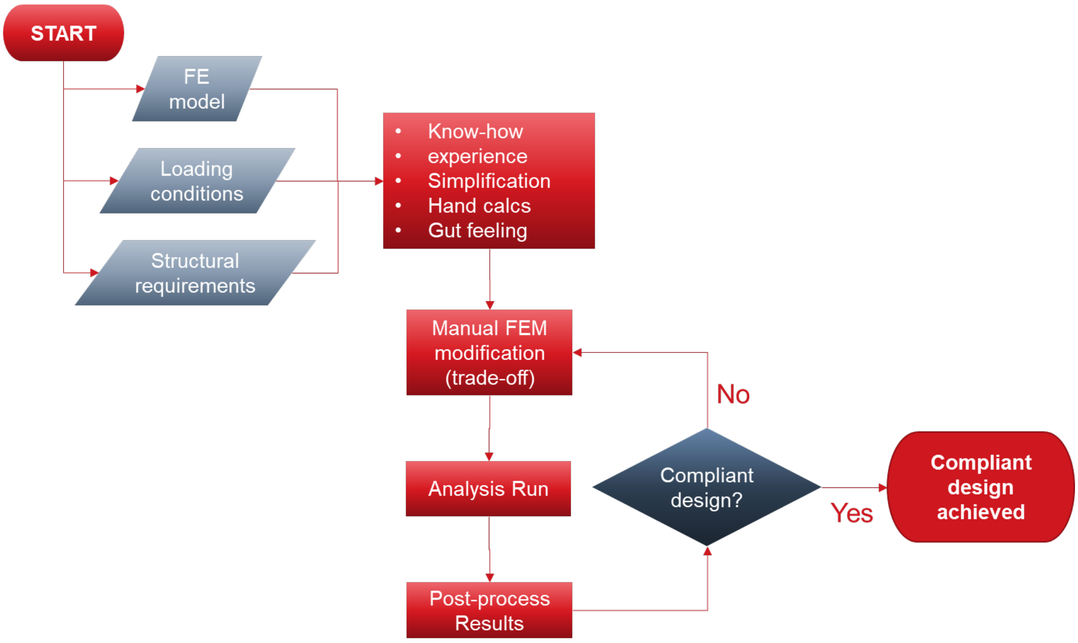

Figure 5: Traditional design process for CFRP and Honeycomb sandwich panels

2. Optimisation process

Some FEA solvers offer a solution to this design problem. They are capable of using optimisation algorithms that automatically change the design variables in a model, analyse it and evaluate the results until they converge into an optimised solution. Different types of analyses can be incorporated into the same optimisation analysis, as well as the required manufacturing constraints and performance limits, so that all the design drivers are taken into account. Many design parameters can be incorporated at once, and the optimisation algorithm will modify all of them until convergence is achieved, when possible.

An optimization problem is defined by three main concepts:

- Design objective: what do we want to optimise?

  The design objective is the magnitude that needs to be maximised or minimised. Its change will drive the optimisation in one direction or another. Normally selected responses are mass or stiffness, but many different options are possible.

- Design variables: what can we change in the model?

These are the design parameters that allow the results of the analysis to vary. The design objective needs to be a function of them. Usually, when optimising the weight or stiffness of a structure, the variables will be thicknesses, material properties, shapes, etc.

- Constraints: things the structure needs to comply with

  All the specific requirements imposed on the structure, normally a combination of mechanical performance requirements (like maximum deformation or stresses, minimum modal frequencies and acceleration responses) and manufacturing constraints (like symmetry, lay-up stacking sequence, manufacturable thicknesses, etc.)

A well-defined problem is essential to achieve a viable design. An optimised structure, while compliant with the requirements explicitly defined during optimisation, might not respond well to other load conditions, so the analyst needs to make sure that all critical cases have been taken into account during this process. If including everything is not possible or practical, additional analysis to confirm that the structure is still compliant in these conditions needs to be performed after optimisation.

There are several optimisation techniques available, depending on how the design variables are defined. For the case of CFRP and aluminium honeycomb panels, two of them are the most suitable: size (parametric) optimisation and free-size (topometric) optimisation.

<u>Size (parametric) optimisation:</u>

The optimiser uses model property values as variables in the optimisation, such as 2D thickness from shell element properties, dimensions of beam element properties, stiffness of spring elements, or any other numerical value that appears explicitly in the property definition.

Figure 6: Size (parametric) optimisation

<u>Free-size (topometric) optimisation:</u>

In this case, the variables used are the thickness of each individual element in the design area, all considered simultaneously in a single variable definition.

This allows continuous variation across the whole area, which is very useful to determine optimum thickness distributions.

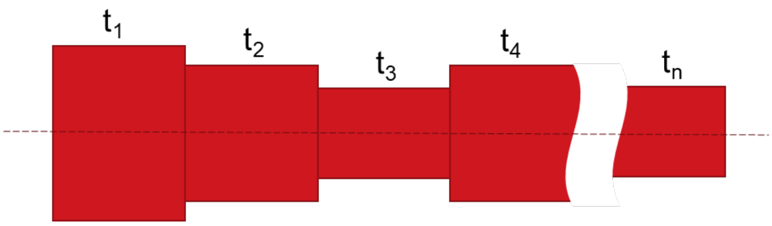

Figure 7: Free-size (topometric) optimisation

Both optimisation techniques can be applied to different areas in the model and combined during the same optimisation run.

The following figures show the same panel subject to both types of optimisation.

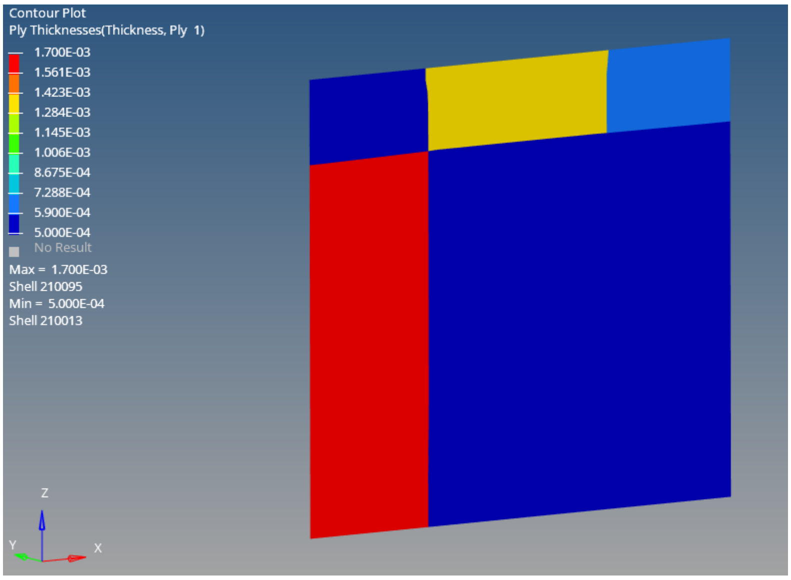

Figure 8: Size (parametric) optimisation. Property areas are individually optimised: four variables (ply thicknesses) associated to four different properties

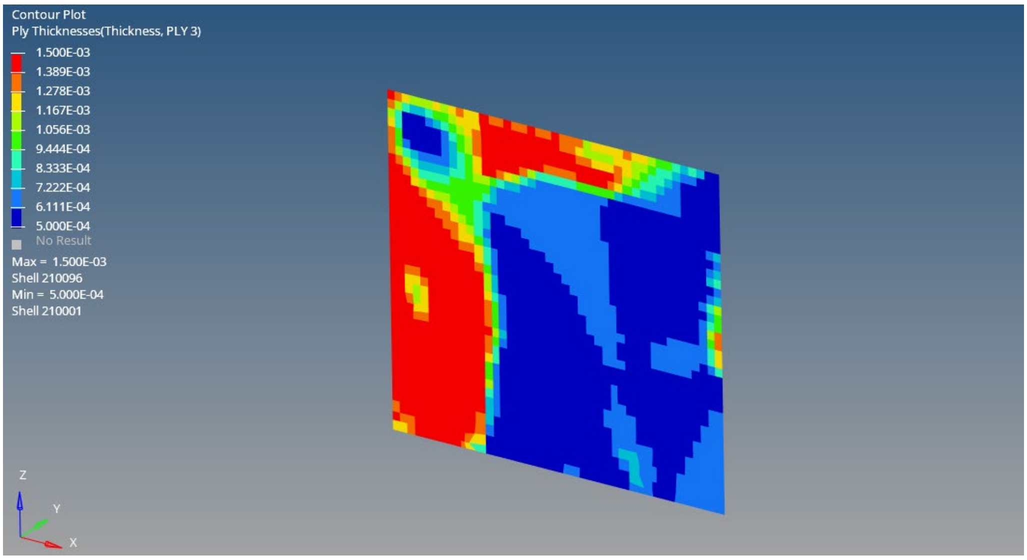

Figure 9: Free-size (topometric) optimisation. Thickness distribution is continuously optimised across the whole panel: as many design variables as individual elements, condensed into a single free-size variable definition.

Many commercial FEA solvers have optimisation capabilities. Both Nastran and Optistruct, which are widely used in the Aerospace Industry, are able to perform size and free-size optimisations. Optistruct has additional capabilities particularly related to laminates, that help in the optimisation of the stacking sequence, number of plies and ply orientations of a laminate.

<u>How to optimise a CFRP and aluminium honeycomb panel: full process</u>

The optimisation process of a CFRP and aluminium honeycomb panel can be divided into three phases.

Phase I – Concept

At this point, the number of layers and their orientations are undefined. A single ply is defined in the model for each of the allowed fibre orientations and another for the honeycomb core (see Fig. 10). A free-size (topometric) optimisation is performed, subject to the applicable manufacturing constraints, among others:

- Bounds on total thickness of laminate
- Bounds on thickness of each individual orientation
- Constant thickness of particular ply or orientation (e.g. core)
- Thickness balancing between two given orientations (e.g. +45^{o} and -45^{o})

The final result is a continuous thickness distribution for each ply across the panel (see Fig. 11).

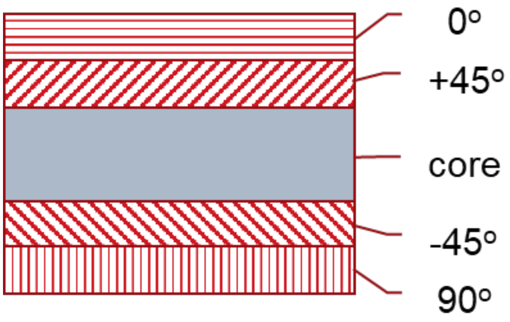

Figure 10: Phase I: Each orientation including the core is optimised as a whole (free-size optimisation)

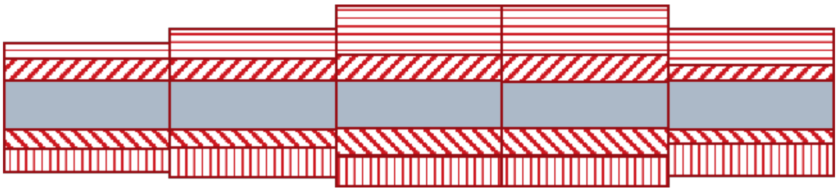

Figure 11: Result after free-size optimisation: optimum thickness for each orientation, by element

Phase II – System

From the result of the previous phase, the continuous thickness variation is discretised into different laminate properties, grouping elements that fall into the same layer thickness bracket into the same property (see Fig. 12).

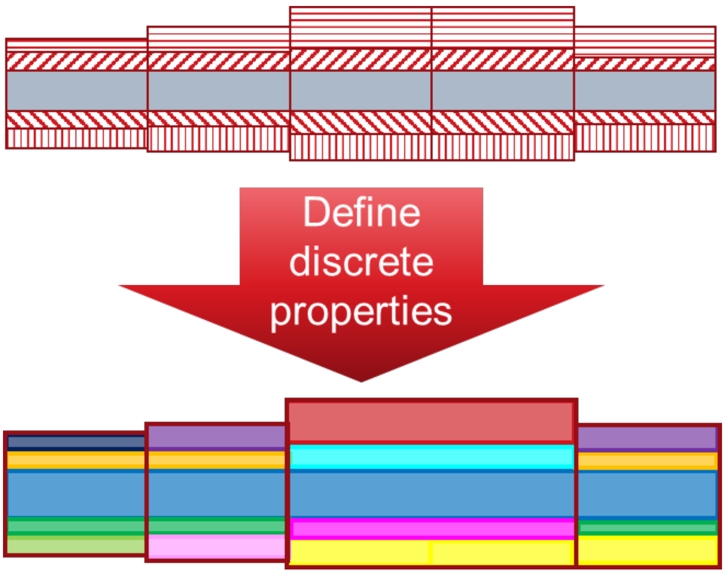

Figure 12: Grouping of elements into different laminate properties according to their layer thicknesses

The model is subject to a size optimisation where the variables are the thicknesses of the different plies in each property. Manufacturing constraints are inherited from the previous phase, and they are imposed along with the requirement that the variables only take discrete values that are multiples of the manufacturable ply thickness.

The result of this optimisation is the optimum total thickness ($n \times t_{ply}$) of each orientation per laminate property (see Fig. 13).

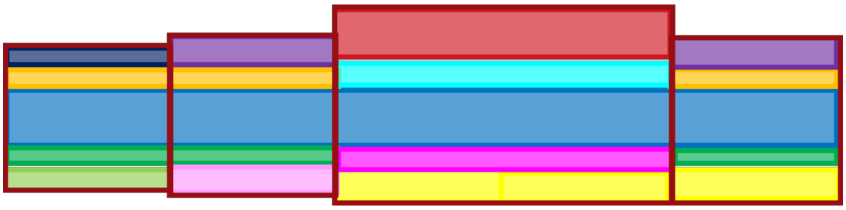

Figure 13: Result after size optimisation: optimum ply thickness and total property thickness in multiples of t_{ply}.

Phase III – Detail

From the previous result the final number of plies for each orientation is already known, but not their stacking sequence (see Fig. 14). This can again be optimised according to a set of manufacturing constraints, such as

- Limit on the number of successive plies of the same orientation
- Pairing of +45° and -45° plies
- Predefined stacking order for certain plies (e. g., core in the middle)

The model is subject to the same size optimisation as before, adding this last set of constraints (shuffling). The result is the optimized final stack for each property (see Fig. 15).

Figure 14: Un-shuffled optimised layer thicknesses

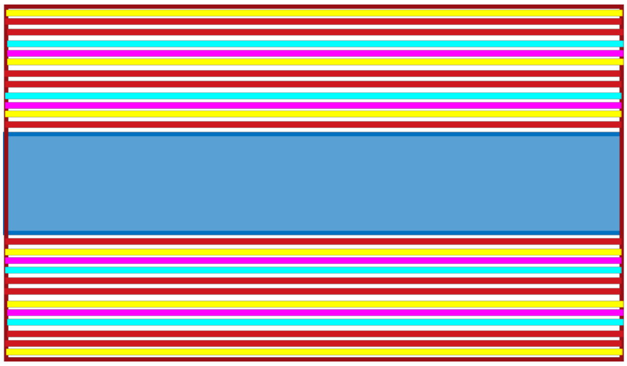

Figure 15: Optimised stack after application of stacking constraints

This process can be simplified in some cases. If the stacking sequence is already predefined, for instance, there will be no need of going through Phase III. If the laminate is also quasi-isotropic, the lay-up characterization can be further simplified by calculating the equivalent isotropic properties and working with them instead.

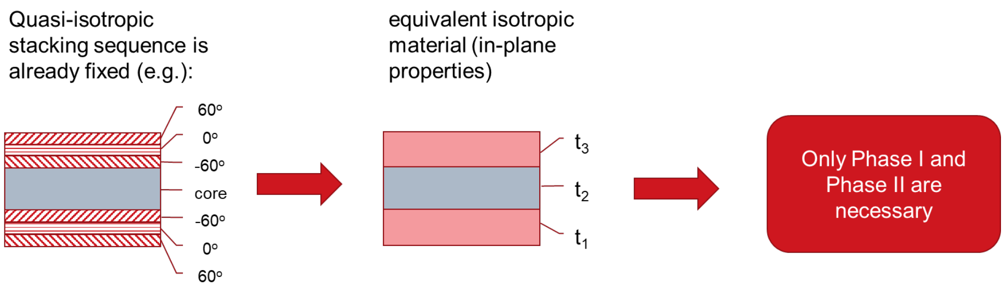

Figure 16: Quasi-isotropic laminate simplification

The sandwich panel can then be approximated by a laminate of only 3 layers (see Fig. 16): upper skin, core and lower skin, where each skin ply represents the whole lay-up to each side of the core, using an equivalent isotropic material. Some membrane-bending coupling effects will be lost, but the behaviour of the panel as a whole will be close enough to reality that the optimisation will be effective. A manufacturing constraint of discrete thickness increments equal to the thickness of the basic lay-up is imposed for each skin.

The final step after optimisation is the confirmation of results by performing a complete analysis loop on the new design. At this stage it is particularly important to consider any loading condition, analysis or response that was not included during the optimisation process.

The full process is summarized in Fig. 17.

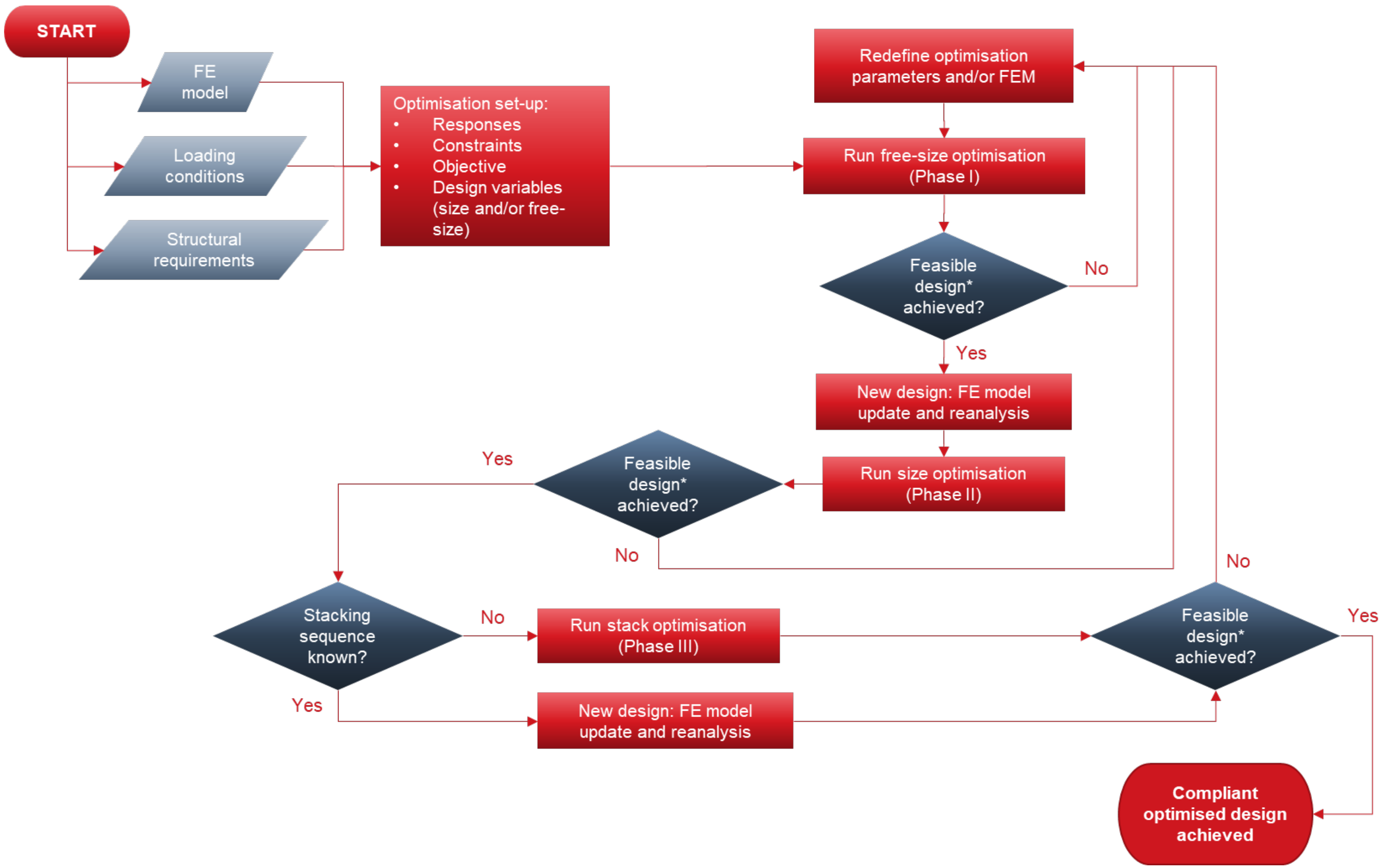

Figure 17: Full optimisation process for a CFRP and aluminium honeycomb panel

3. Practical example

The following example shows the optimisation of the central shear wall of a satellite (Fig. 18) to make it compliant with a set of structural requirements while reducing its weight.

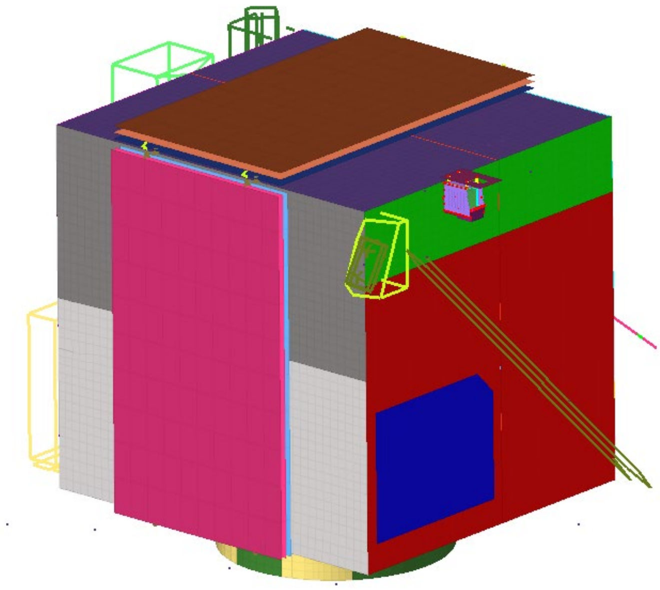

Figure 18: General view of the spacecraft

The initial design of the internal central shear wall (see Fig. 19) is a panel of uniform skin thickness (1.35 mm for upper and lower skins) of quasi-isotropic laminate 3×[60/0/-60/-60/0/60], where each ply has a thickness of 75µm. The engineering properties of the basic laminate [60/0/-60/-60/0/60] are (in Pa):

Sequence	[60/0/-60/-60/0/60]
Thickness	0.00045
Number of layers	6

	E_x	E_y	E_z	G_{xy}	G_{xz}	G_{yz}
In-plane	+1.057E+11	+1.057E+11		+3.997E+10		
Bending	+8.386E+10	+3.757E+10		+1.309E+10		
Zero-Curvature	+1.057E+11	+1.057E+11		+3.997E+10		

	ν_{xy}	ν_{yx}	ν_{xz}	ν_{zx}	ν_{yz}	ν_{zy}
In-plane	+0.322	+0.322				
Bending	+0.273	+0.122				
Zero-Curvature	+0.322	+0.322				

This laminate has been replaced by an isotropic layer of 1.35 mm thickness taking only the in-plane properties above to simplify the optimisation process.

The core is made of aluminium honeycomb 3/16-5056-001p, and it is 19 mm thick with a density of 50 kg/m^3.

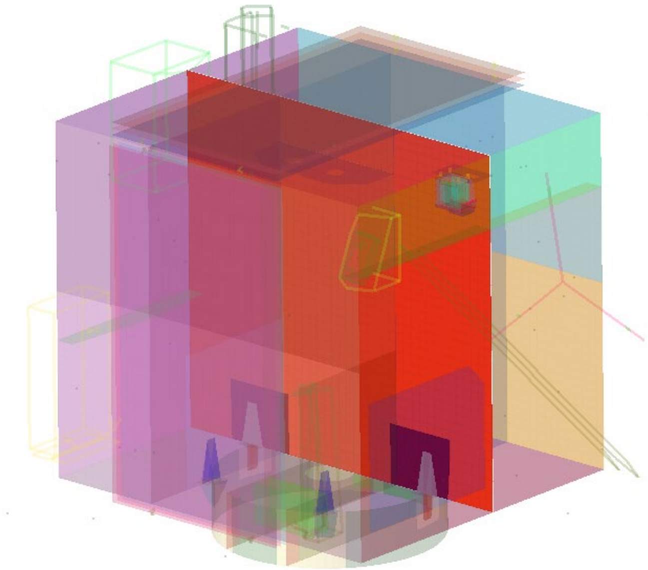

Figure 19: View of internal central shear wall to be optimised

The total spacecraft mass with this configuration is M = 2015.1 kg.

The first normal mode frequency is f_1 = 23.17 Hz.

<u>Phase I - Concept</u>

The optimisation problem definition is as follows:

1. Optimisation objective: minimize mass
2. Optimisation variables: thickness of skins and core of central shear wall (free-size optimisation)
3. Optimisation constraints: structural requirements and manufacturing constraints

   The requirements that the structure needs to comply with are:

   - The first modal frequency needs to be above 16 Hz
   - Not to exceed maximum specification accelerations for equipment units under dynamic load (see Table 1)

   The manufacturing constraints imposed are:

   - Symmetric skins (paired)

- Minimum skin thickness of 0.45 mm (basic lay-up)
- Maximum skin thickness of 1.8 mm (4× basic lay-up)
- Minimum core thickness of 10 mm
- Maximum core thickness of 50 mm
- Constant core thickness across the panel

Instrument	S/C X axis (g)	S/C Y axis (g)	S/C Z axis (g)
INST 1	20	18	18
INST 2	20	18	18
INST 3	20	18	18
INST 4	20	18	18
INST 5	23	18	18
INST 6	25	25	25
INST 7	18	18	18
INST 8	18	18	18
INST 9	18	18	18

Table 1: Maximum acceleration responses for equipment units in the model under dynamic load

The optimisation converges in 6 iterations into a feasible design (all constrains satisfied), with the following results:

- New spacecraft total Mass = 2005.7 kg (ΔM = -9.35 kg)
- First normal mode frequency f_1 = 22.79 Hz (Δf_1 = -0.38 Hz)
- All unit responses under the limitations in Table 1
- Panel honeycomb core thickness: 19 mm (unchanged)
- The new CFRP skin thickness distribution is shown in Fig. 20

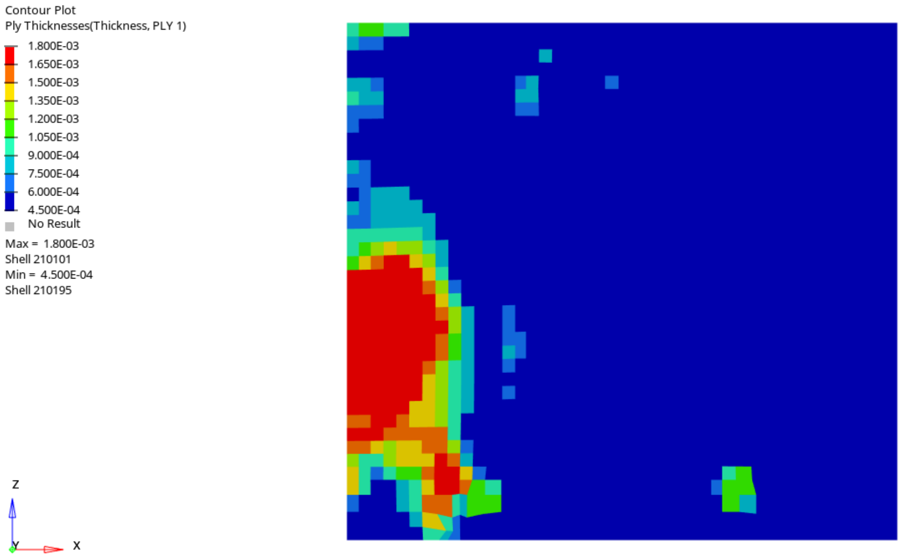

Figure 20: Skin thickness distribution after Phase I free-size optimisation

<u>Phase II -System</u>

The ply geometry of the new thickness distribution obtained from Phase I is simplified into rectangular areas for ease of manufacture.

Figure 21: Discretization of thickness distribution into 6 rectangular property areas

The optimisation problem is the same as in Phase I, with an additional manufacturing constraint: the skins can only take thickness values of 0.45, 0.9, 1.35 or 1.8 mm (multiples of the thickness of the basic sequence, 0.45 mm).

The optimisation converges in 2 iterations into a feasible design (all constrains satisfied), with the following results:

- New spacecraft total Mass = 2006.6 kg (ΔM = -8.53 kg)
- First normal mode frequency f_1 = 22.83 Hz (Δf_1 = -0.34 Hz)
- All unit responses under the limitations in Table 1
- Panel honeycomb core thickness: 20 mm (+1 mm)
- The new CFRP skin thickness distribution is shown in Fig. 22

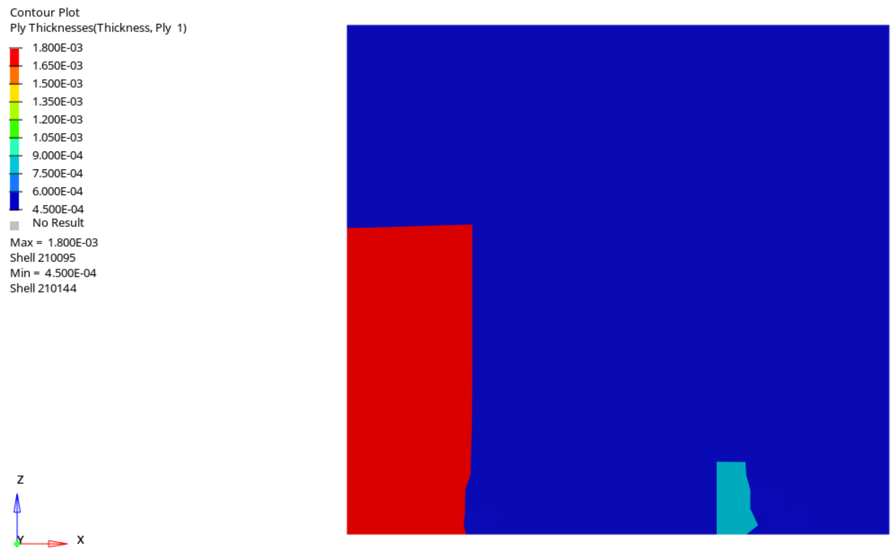

Figure 22: Skin thickness distribution after Phase II size optimisation

According to the optimisation, only three different laminate thicknesses are necessary. In this case the basic lay-up is known and the final stacking sequences are just repetitions of the basic lay-up until the total thickness obtained from the optimisation is achieved.

Instrument	**S/C X axis (g)** **Spec**	**S/C X axis (g)** **Optim**	**S/C Y axis (g)** **Spec**	**S/C Y axis (g)** **Optim**	**S/C Z axis (g)** **Spec**	**S/C Z axis (g)** **Optim**
INST 1	20	16.9	18	6.5	18	11.9
INST 2	20	18.4	18	11.6	18	9.8
INST 3	20	12.0	18	9.3	18	7.9
INST 4	20	6.9	18	16.5	18	12.5
INST 5	23	15.5	18	8.9	18	14.3
INST 6	25	18.7	25	10.9	25	15.1
INST 7	18	11.8	18	11.3	18	7.5
INST 8	18	10.4	18	8.8	18	7.0
INST 9	18	13.8	18	8.2	18	6.3

Table 2: Maximum acceleration responses for equipment units in the model under dynamic load

A full analysis loop has been performed on the new design to confirm these results. All units are compliant with the specification (see Table 2), the first frequency of 22.83 Hz is above the requirement and the final design of the panel is 8.5 kg lighter than the initial design.

4. References

Gibson, Lorna J. and Ashby, Michael F. (1988). *Cellular solids, structure and properties*. Cambridge University Press.

Hexcel Composites (2000). *Honeycomb Sandwich Design Technology.* Hexcel Composites.

Altair Engineering Inc. (2021). *Altair Optistruct 2021 User Guide*. Altair Engineering Inc. Design Optimistation, Optimization of Composite Structures.

MSC Software Corporation (2018). *MSC Nastran 2019 Design Sensitivity and Optimisation User's Guide*. MSC Software Corporation.