DESIGN-OPTIMIZATION OF A CURVED LAYERED COMPOSITE PANEL USING EFFICIENT LAMINATE PARAMETERIZATION

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ABSTRACT

Layered composites have proven essential for the successful design of high-performance space structures. The aviation industry are increasingly using more and more layered composites within commercial aircraft, replacing traditional aluminum designs, to achieve weight savings. When optimizing layered composite structures it is desirable to find design solutions that satisfy global requirements early in the design phases. Particularly because of the number of design variables associated with composite layups once models become more detailed are complex: material selection, layer orientation and thickness for each ply for example.

In this paper, part of an aircraft door surround model is optimized with respect to the objectives and constraints typical for this type of component. Related load-response calculations, failure and buckling reserve factor analyses are made. The design process is built around optimization features offered by HyperStudy [1] - a solver-neutral design optimization and stochastic study software - along with ESAComp [2] – a software for design and analysis of composites - applying an efficient laminate layup parameterization approach based on sub-laminates to support manufacturing-oriented design.

Different parameterization concepts are evaluated. Both numerical results and the performance of the optimized structures are reported and compared with an aluminum baseline design.

1. INTRODUCTION

Layered composite structures can offer great benefits compared with traditional aluminum design used in the aircraft industry. In the last few decades, taking advantage of potential weight savings that can be achieved using layered composite structures the focus area has been on new aircraft designs, e.g. Boeing Dreamliner or Airbus A380.

Material selection, layer orientation and thickness, number of layers and stacking sequence influence on the performance of a structure. The amount of possible designs increases rapidly with the complexity of the structure (due to the number of design variables linked to a single laminate), which makes optimization a challenge. Having an optimized pre-design that fulfils global requirements early in a project helps decision-making before arriving at design phases where changes need a lot of effort, cause delays and costs to rise. In this paper a process applicable to pre-design optimization is presented.

2. CASE SPECIFICATION

2.1 Structure

The curved panel to be optimized is an abstraction of a generic aircraft door surround panel (Figure 1) provided by Altair Engineering. The dimensions of the lower middle part served as base for the curved panel and initial stiffener design as highlighted in Figure 1 (schematics in Figure 2).

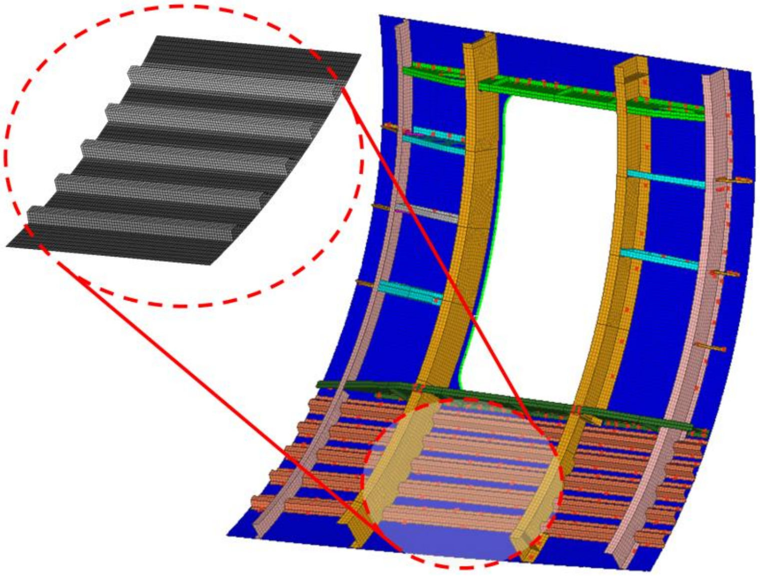


Figure 1. FE model of generic aircraft door surround panel

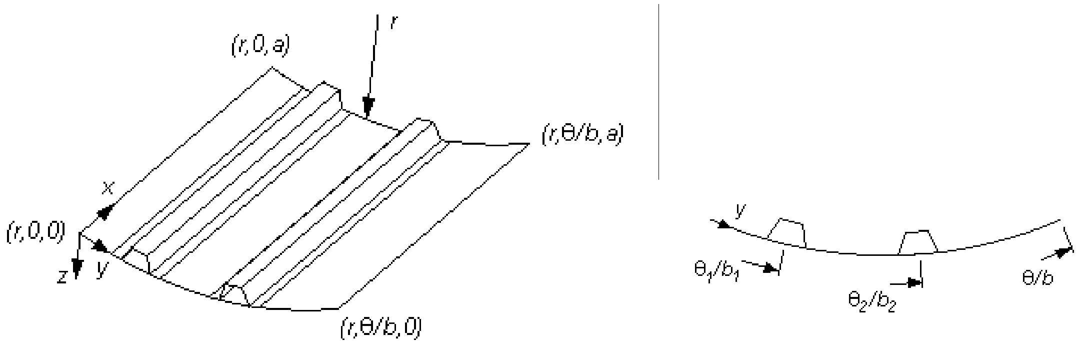


Figure 2. ESAComp curved panel coordinate systems schematics (left) and stiffener spacing (right)

The panel had a radius of curvature of r = 2,560 mm, a length of a = 1,280 mm and a width of b = 960 mm, thus covering an angle of Θ = 21.5 °. All edges are clamped and both load cases are derived from possible in flight situations. The first resembles the overpressure in the cabin when flying at high altitude. Despite the decreased pressure level of about 0.75 MPa in the cabin and around 0.28 MPa at 10 km altitude, resulting in a pressure difference of 0.47 MPa, the panel is loaded with a pressure of p = 1 MPa (approx. 1 bar) for the load response and failure analysis. For the second load case, rapid decent with malfunctioning cabin altitude system was considered. During such rapid decent, cabin pressure can reduce slower than the surrounding air pressure. At some point this results in an under pressure. To prevent damage from under pressure, airplanes are fitted with negative pressure relief valves which react at low differential pressures, for example *p_vac* = -6895 Pa (-1.0 psi) in the spring loaded flappers used in Boeing 737.[3]

To meet the stiffness requirement, the reference model consisted of a 2 mm thick aluminum 2024-T3 [4] outer skin and 5 equally spaced hat stiffeners with 1.5 mm wall thickness. Stiffener dimensions in the reference model (Figure 3) were leg width of *w_leg* =20.0 mm, base width of *w_base* = 69.5 mm, top width of *w_top* = 29 mm and core height of *h_core* = 35 mm, which leads to an angle α = 60 °. For the study, a minimum spacing of 120 mm was required with additional limitations on stiffener sizing set which allowed up to 8 stiffeners. Also stiffeners were only allowed to cover two thirds of the panel area.

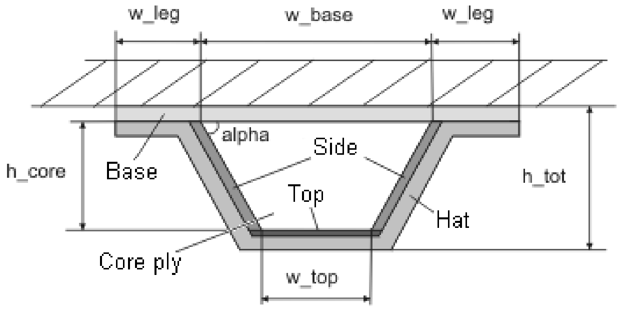


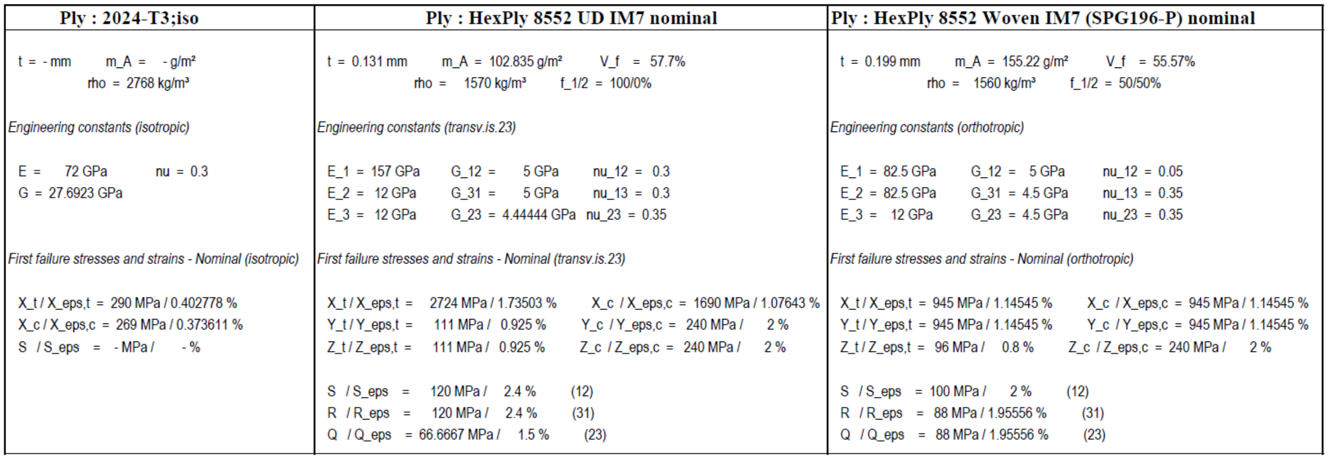
Figure 3. Hat stiffener schematics

2.2 Preliminary design

For this simple panel load response, benchmarks indicate that displacement and stress results calculated in ESAComp correlate extremely well with results presented in [5], and stability analysis are slightly conservative compared with [6]. A benchmark involving hat stiffened panels as in [7] revealed that ESAComp results are conservative with 15 % in terms of critical buckling load and mode shapes. Literature results in [8], and ESAComp results for curved panel collapse with geometrical imperfections induced by disturbance loads match very well. Based on these benchmarks no additional safety factor was added.

A mesh sensitivity analysis was conducted to keep the computational effort for solving to a required minimum while obtaining displacement and failure results that do not deviate more than 5 % from the converged case. Puck 2D was used as the failure criterion for UD materials, maximum principal strain for woven materials and von Mises for homogenous isotropic materials.

The composite materials HexPly 8552 Woven IM7 (SPG196-P) carbon epoxy material and HexPly 8552 UD IM7 carbon epoxy material were chosen from the ESAComp material database, based on the results provided by the aircraft door surround model. Figure 4 illustrates the material data for these two plies as well as the Al 2024-T3 used in the baseline model.



Ply : 2024-T3;iso	Ply : HexPly 8552 UD IM7 nominal	Ply : HexPly 8552 Woven IM7 (SPG196-P) nominal
t = - mm m_A = - g/m² rho = 2768 kg/m³	t = 0.131 mm m_A = 102.835 g/m² V_f = 57.7% rho = 1570 kg/m³ f_1/2 = 100/0%	t = 0.199 mm m_A = 155.22 g/m² V_f = 55.57% rho = 1560 kg/m³ f_1/2 = 50/50%
Engineering constants (isotropic)	*Engineering constants (transv.is.23)*	*Engineering constants (orthotropic)*
E = 72 GPa nu = 0.3 G = 27.6923 GPa	E_1 = 157 GPa G_12 = 5 GPa nu_12 = 0.3 E_2 = 12 GPa G_31 = 5 GPa nu_13 = 0.3 E_3 = 12 GPa G_23 = 4.44444 GPa nu_23 = 0.35	E_1 = 82.5 GPa G_12 = 5 GPa nu_12 = 0.05 E_2 = 82.5 GPa G_31 = 4.5 GPa nu_13 = 0.35 E_3 = 12 GPa G_23 = 4.5 GPa nu_23 = 0.35
First failure stresses and strains - Nominal (isotropic)	*First failure stresses and strains - Nominal (transv.is.23)*	*First failure stresses and strains - Nominal (orthotropic)*
X_t / X_eps,t = 290 MPa / 0.402778 % X_c / X_eps,c = 269 MPa / 0.373611 % S / S_eps = - MPa / - %	X_t / X_eps,t = 2724 MPa / 1.73503 % X_c / X_eps,c = 1690 MPa / 1.07643 % Y_t / Y_eps,t = 111 MPa / 0.925 % Y_c / Y_eps,c = 240 MPa / 2 % Z_t / Z_eps,t = 111 MPa / 0.925 % Z_c / Z_eps,c = 240 MPa / 2 %	X_t / X_eps,t = 945 MPa / 1.14545 % X_c / X_eps,c = 945 MPa / 1.14545 % Y_t / Y_eps,t = 945 MPa / 1.14545 % Y_c / Y_eps,c = 945 MPa / 1.14545 % Z_t / Z_eps,t = 96 MPa / 0.8 % Z_c / Z_eps,c = 240 MPa / 2 %
	S / S_eps = 120 MPa / 2.4 % (12) R / R_eps = 120 MPa / 2.4 % (31) Q / Q_eps = 66.6667 MPa / 1.5 % (23)	S / S_eps = 100 MPa / 2 % (12) R / R_eps = 88 MPa / 1.95556 % (31) Q / Q_eps = 88 MPa / 1.95556 % (23)

Figure 4. Mechanical properties of the materials used in the study.

2.3 Optimization problem

A single objective optimization to minimize the mass of the panel was carried out. The problem can be formulated as:

$$\min_{\vec{x} \in S} m\left(\vec{x}\right) \qquad [1]$$

with the vector of design variables *x*, the mass of the structure *m* and the feasible set *S* defined by constraints as *S* = $\{\vec{x} \mid \vec{g}(\vec{x}) \leq 0,\ \vec{h}(\vec{x}) = 0\}$. For over pressure the maximum displacement must be under 5.5 mm, also provided by the reference aluminum panel, and the reserve factor (RF) for first ply failure (FPF) above 1.25. For under pressure the buckling reserve factor was evaluated, but not used a constraint. It was, however, used as an additional means to evaluate the performance of otherwise equally performing design.

The range of the design variables for stiffener sizing is given in Table 1. The sizing parameters are continuous, whereas the layup parameters are discrete. The approach for the latter is illustrated in the following section. The mixed optimization problem (13 integer and 4 real variables) was solved using the genetic algorithm (GA) available in HyperStudy. Each generation had 40 individuals and for the given problem a state after which only minor improvements could be observed was reached after 12 generations.

The angle α is calculated from the other stiffener design parameters and the corresponding constraint is set to 45°<= α<=70°.

Table 1. Optimization range for hat stiffener sizing parameters

Design variable	**Lower bound [mm]**	**Upper bound [mm]**
n_stiff	0	8
w_base	30	100
w_top	20	70
w_leg	10	40
h_core	10	50

3. LAY-UP PARAMETERIZATION

The ply thickness was pre-defined with the choice of materials. Thus material type, orientation and multiplier for individual layers of the laminate remain as design variables. In earlier studies the authors have presented layup parameterization based on elementary laminates which was successfully applied to thick laminates [9]. However, optimized layups for the panels were relatively thin, so that the method could not be applied efficiently.

Through the study the skin consisted of HexPly 8552 Woven IM7 (SPG196-P) and a minimum number of 7 layers was required, for the hat stiffener layup, 4 layers were required respectively. A constraint for the number of consecutive plies with the same orientation was not set for the layers with woven material. In one parameterization an additional reinforcement on top of the hat stiffener was allowed (see Figure 5) and consisted of the intermediate modulus unidirectional (UD) material HexPly 8552 UD IM7 with a 0° orientation. Also in the same case the “Hat” layup was formulated using the stacking sequence vector formulation [9] and could use the UD material as well, with a range of 0° to 90° in steps of 15°. The additional stacking sequence variable allows switching position of each material-orientation-multiplier combination within the stack. Skin and hat layup must be symmetric which was already taken into account in the parameterization, along with the balance of layers consisting of the UD material. The middle layer is (if existing) of only half thickness of the original ply, thus enabling the creation of symmetric odd layups. The parameterized skin laminate consisted of stacks of layers with the same orientation, where the allowed angles were 0° and 45°, and multipliers from 0 to 3.

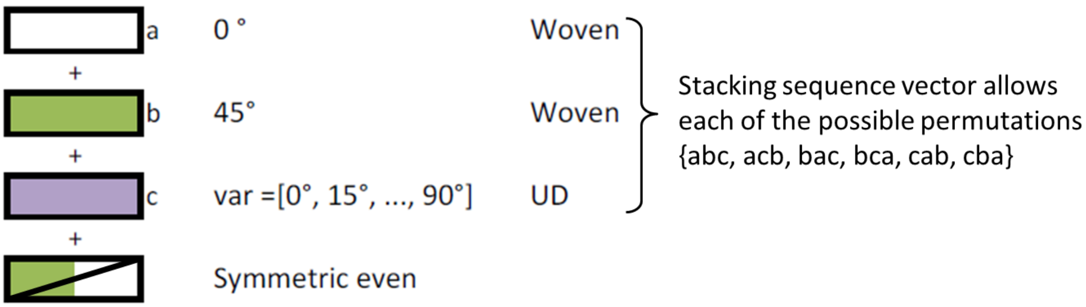


Figure 5. Example for a hat stiffener laminate coding using stacking sequence vector together with fixed and variable orientations

ESAComp uses a dedicated module to process Extensible Markup Language (XML) based scripts for describing the laminates subject to optimization. The scripting language supports various types of laminate and allows specification of constraints concerning symmetry and balance already during problem specification, so avoiding unnecessary increases of the design space. It supports sub-laminate based laminate design, which resembles the manufacturing process of the composite structure better than the traditional zone based design. After their definition, sub-laminates are connected to laminates depending on orientation and built up direction. Changes in sub-laminates are automatically mapped to the laminates applied in different zones. Furthermore, the system allows creation of material pools from which to choose materials for certain layers.

The elementary laminate approach (reduced design space, whilst retaining the result space) allows near optimal designs faster, could not be applied due to thin laminates. However, the approach of using a dedicated script language and parsing module has proven effective. Creating trade off studies between parameterization concepts is fast, due to high re-usability of building blocks. In the preliminary design phase, where model solving times are relatively short, the amount of time spent to set up the different optimization cases is very significant. And taking into account manufacturability as well as various constraints during the parameterization can save lot of time otherwise implementing such rules in the optimization environment.

4. SIMULATION AND OPTIMIZATION ENVIRONMENT

The optimization process was set up with HyperStudy and ESAComp. HyperStudy is a solver-neutral design optimization and stochastic study software. It serves as the environment for the variable and response specification. Models and the data flow between them can be easily managed. HyperStudy offers a range of design of experiments and optimization methods that suit a wide range of applications. Furthermore, various post-processing features assist in evaluating the results and reporting. ESAComp provides powerful features for laminate design and the curved stiffened panel analysis features (load response, failure, natural frequency, buckling and non-linear simulation) serve the scope of the preliminary panel optimization perfectly. Based on the design variables created by the optimization software, laminate layups and panel geometry is built by ESAComp. A dedicated optimization interface handles parameterized laminates. The newly developed Python scripting interface enables access to the ESAComp objects and the designer can utilize the full power of Python for creating customized output files. A finite element (FE) model is created automatically in ESAComp and solved with the built in FE solver ELMER [9]. Panel mass, maximum displacement, inverse reserve factor for first ply failure and the reserve factor for buckling are reported to the optimization software, which then ranks the designs and creates new ones for the next iterations.

The curved panel calculations in ELMER are based on a Reissner-Mindlin-von Kármán type shell facet model applicable to thin or moderately thick composite plates. This approach is fitted to solve large deformation problems. For the optimization static linear analysis was used, because it is computationally much less expensive than using the non-linear solver.

5. RESULTS

The optimized composite cylinders fulfilled the stiffness and strength constraints set based on the aluminum reference panel with less than half the mass of the original design. As can be seen from Table 2, the reserve factor against first ply failure was also by more than a factor of two higher. The linear buckling reserve factor, for which no constraint was set, is only at approximately one third. Composite panels with a mass of around 6.8 kg, still considerably lighter than the reference panel, reached a level of RF_B = 3.49, while providing higher strength and stiffness. For the simple case of all edges clamped and pressure load applied, the optimization algorithm steered towards using as many woven layers with 0° orientation as possible. A consecutive ply constraint should definitely be in place, when attempting similar optimization with UD materials. The displacement and inverse reserve factor results are shown in Figure 6.

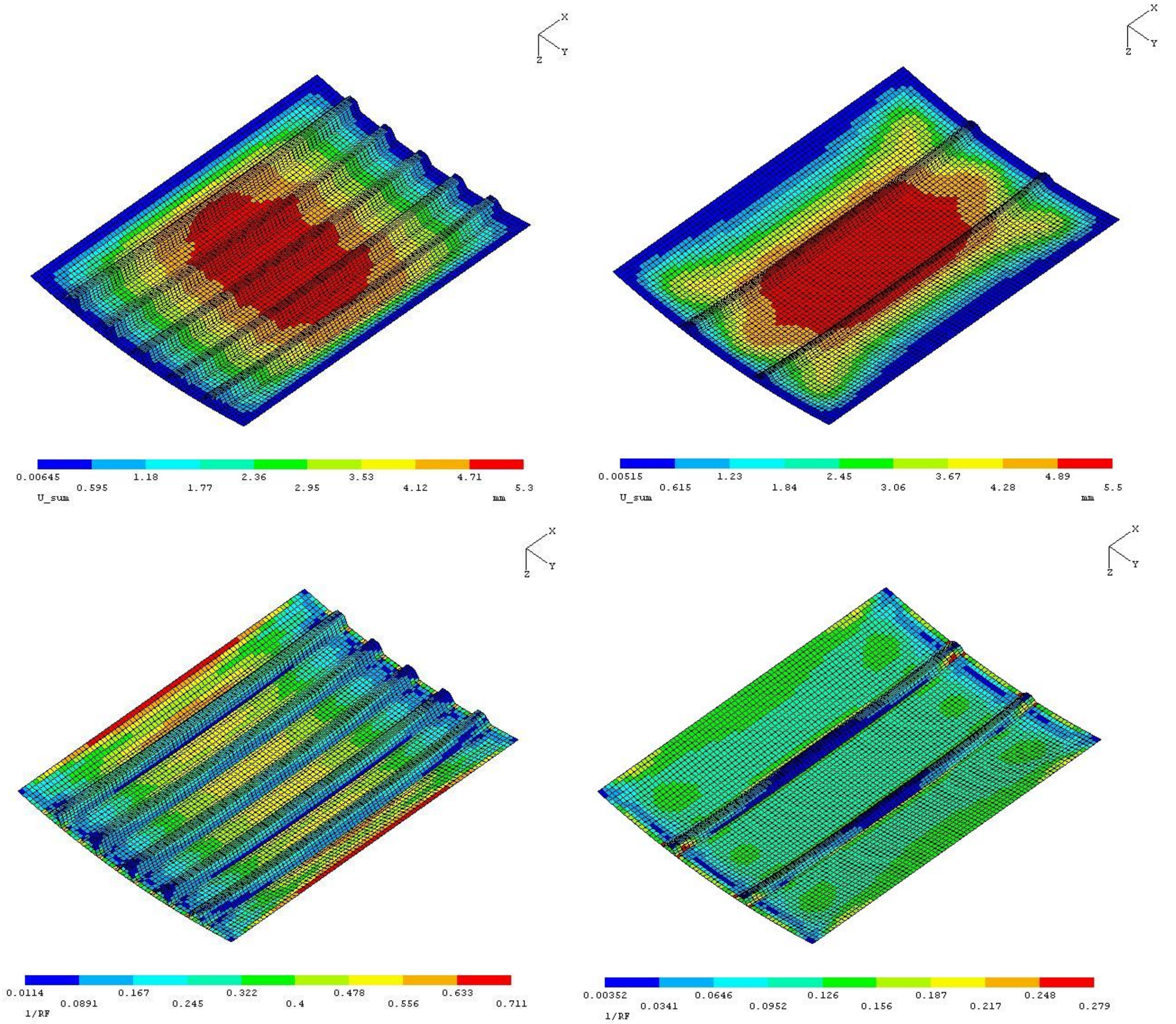


Figure 6. Displacement and inverse reserve factor results for aluminum reference panel (left) and optimized composite panel (right).

The reduced number of stiffeners in the composite panel has a big influence on the shape of the field with highest deflection. Similarly, the bigger area between the stiffeners makes the structure more sensitive to buckling.

Table 2. Design data and results for aluminum reference panel and the optimized panel based on the parameterization that allows UD material

Data	**Aluminum**	**Composite 2 (woven and UD)**
Skin layup	2 mm	$[0_{5\text{-Woven}}]_{SE}$ (1.99 mm)
Hat layup	1.5 mm	$[90_{UD}, 0_{Woven}]_{SE}$ (0.66 mm)
Top reinforcement	-	$[0_{UD}]$ (0.131 mm)
Mass [kg]	10.81	4.8
Max displacement [mm]	5.3	5.5
RF_{FPF}	1.41	3.59
RF_B	3.49	1.12
n_stiffener	5	2
w_base	69.5	58
w_top	29	20
w_leg	20	10
h_core	35	17

6. POST PROCESSING

Owing to the high computational cost in conjunction with non-linear analysis, it is not well suited to design optimization. For perfect structures such as the panels defined, the linear buckling calculation can be of limited meaning. Therefore, the linear buckling reserve factor has not been used as a constraint, but non-linear calculations have been conducted for the best designs, to evaluate stability performance. Also their sensitivity to imperfections was studied. For this purpose the first mode shape of the eigenvalue analysis was superimposed on the perfect panel structure with amplitude of 1 mm. For cylindrical shells of similar scale as the panel amplitudes of this level have been experimentally verified in [10].

ESAComp utilizes a modified version of Elmer FE solver based on the Riks' method with Crisfield's elliptical constraint for arc length [12, 13, 14, 15, 16]. Depending on the pre-defined number of steps, the load is increased piecewise and the FE model updated accordingly.

The aluminum reference panel had a buckling reserve factor of 3.49 for the under pressure load case and for the perfect structure non-linear calculation indicated very low maximum displacement of 0.37 mm at a reserve factor for FPF of 18.4. With superimposed first buckling shape at amplitude of 1 mm (already half the skin thickness), the result does change slightly shifting to 0.87 mm and RF_{FPF} = 13.7, so no catastrophic failure to be expected. The load displacement curve is still fully linear, also for higher amplitudes. In comparison the composite panel presented in Table 2 shows already some weakening in the perfect structure. Here switching from the perfect to the imperfect structure raises the maximum displacement from 0.42

mm to 10.2 mm. Even with the lowest available step size for load increase (3 steps), the change of behavior is obvious in Figure 7. These findings indicate that it is recommended to add safety factors during the calculation. For the given optimization case the scatter plot in Figure 8 shows a quite strong trend between panel mass and achievable reserve factor against buckling.

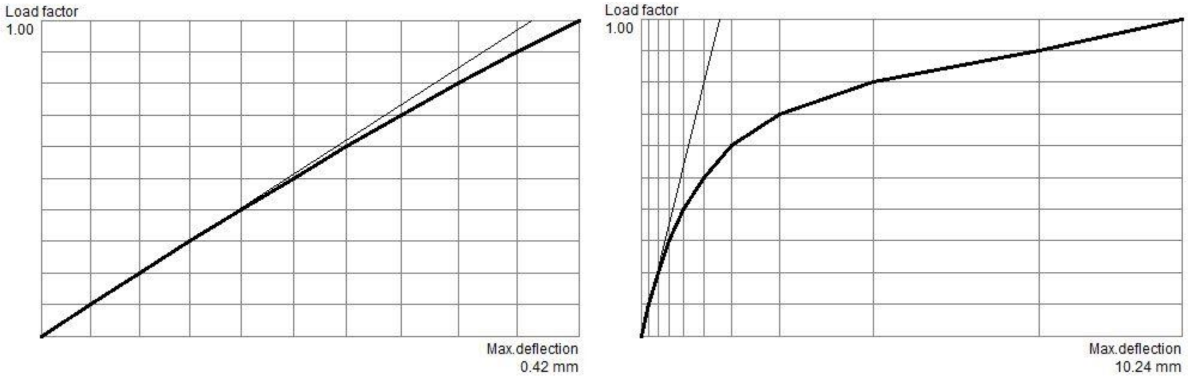
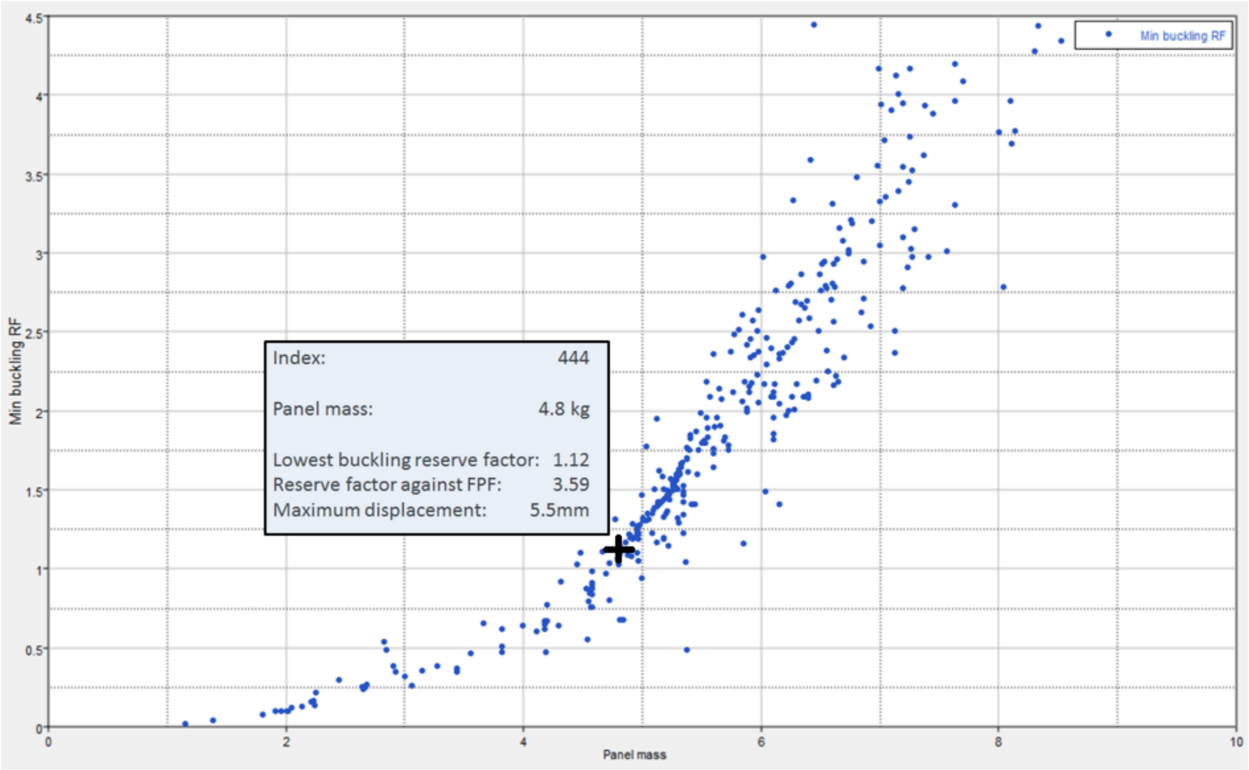


Figure 7. Load displacement plot for non-linear analysis of curved composite panel without imperfections (left) and with imperfections (right).



Index: 444

Panel mass: 4.8 kg

Lowest buckling reserve factor: 1.12
Reserve factor against FPF: 3.59
Maximum displacement: 5.5mm

Figure 8. Scatter plot for panel mass and lowest reserve factor against buckling.

7. CONCLUSIONS

The work was focused on optimization of a preliminary design, where it is essential to be able to set up optimization problems quickly, to modify them easily and to assess various design concepts within the same framework, rather than the analysis of details. The process described, using HyperStudy as optimization engine and ESAComp for model parameterization and solving, fits the requirement mentioned above with easy integration of models and high re-usability that saves time when setting up additional iterative optimization runs. Although currently the non-linear analysis in ESAComp is too time-consuming to be incorporated into the preliminary design loop effectively, it does prove far more valuable in later design phases. With increased solver performance, the influence of non-linear analysis on the optimal design can be investigated in further studies.

8. REFERENCES

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