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DESIGN, STRESS ANALYSES AND LIMIT LOAD OF SANDWICH STRUCTURES
NAVRHOVÁNÍ, PEVNOSTNÍ KONTROLA A ÚNOSNOST SENDVIČOVÝCH KONSTRUKCÍ

DOCTORAL THESIS
DIZERTAČNÍ PRÁCE

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Abstract

The thesis starts with a review of design calculations of sandwich beams, plates, and complicated structures, where FEM plays an important role. Next, optimization methods are reviewed to shed light on the wide area of mathematical programming and basic topology optimization principles up to its implementation by other authors in composite design, including representative examples of analytical and numerical optimization of sandwiches. The thesis objective is defined as an implementation of mass minimization with failure constraints aiming to make the sandwich design process easier. This is done by own implementation of gradient optimization based on topology optimization principles, known as Discrete Material Optimization (DMO), which helps to find optimal layup. Approach to material interpolation and failure constraints interpolation is developed and programmed in Python, using First Order Shear Deformation Theory (FSDT) to evaluate stresses on elements, based on element loads given by the Nastran FE solver. Gradient optimizer searches for optimal materials for each layer of the sandwich face-sheet and core from the user-defined candidates. The program is tested on examples of sequential complexity from one-element beams where the true optimum is known up to a practical task of the sandwich galley from an airliner. Results have shown that the algorithm can reach a discrete solution without (significant) violation of constraints and thus can be practically used to make conceptual sandwich design more efficient.

Key words

Sandwich, Gradient optimization, Mass minimization, Sandwich failures, Stacking sequence, Constraint aggregation, Discrete Material Optimization.

Abstrakt

Tato doktorská disertační práce je zaměřena na koncepční návrh sendvičových konstrukcí pomocí metody konečných prvků za použití diskrétní optimalizace materiálu (Discrete Material Optimization – DMO), což je gradientní metoda využívající principů multimateriálové topologické optimalizace.

V první části práce jsou popsány analytické přístupy výpočtu sendvičových nosníku a panelů, které jsou již dlouho známé a používané. Široce rozšířená je též aplikace metody konečných prvků při návrhu sendvičových konstrukcí, neboť umožňuje analyzovat i složitou geometrii a vrstvení. V rámci přehledu současného stavu poznání jsou nastíněny vybrané optimalizační metody. I když se vlastní práce zaměřuje na gradientní metody, genetické algoritmy jsou zmíněné, díky svému rozšíření v optimalizaci kompozitů a tím pádem i sendvičů. Matematické programování je dále rozvinuto v podobě nejčastěji užívané metody topologické optimalizace – SIMP (Solid Isotropic Material with Penalization), která v zahraničí posloužila jako výchozí bod pro vývoj metody DMO a jejích variant, které se z užití na optimalizaci kompozitů rozšiřují i v oblasti návrhu sendvičů. Jako příklad obecného přístupu ke konstrukční optimalizaci je shrnuta optimalizace za použití metody konečných prvku v Nastranu a tří fázová optimalizace kompozitů v OptiStructu. Přímo v oblasti sendvičů je možné v omezené míře použít analytické metody, ale těžiště praktického užití je v aplikaci numerických metod.

Cíl disertační práce byl stanoven jako programová implementace optimalizační metody, která by usnadnila proces návrhu sendvičové konstrukce za použití MKP, tedy s geometrií, kterou není snadné navrhnout pomocí analytických metod tak, aby se snížil počet návrhových cyklů, které musí inženýr ručně provádět (měnit vrstvení a kontrolovat splnění požadavků).

Optimalizační úloha je formulována jako minimalizace hmotnosti konstrukce při dodržení omezujících podmínek sendvičových poruch (maximální napětí v potahu, smyk jádra, crimping – zvlnění, wrinkling – zvrásnění), kde návrhovými proměnnými jsou materiály (včetně tloušťky a orientace vrstvy) kompozitního potahu a jádra. Metoda je založená na interpolaci hustoty dílčích materiálů pomocí RAMP (Rational Approximation of Material Properties) schématu v každé vrstvě, kdy jedna vrstva obsahuje podíly více složek materiálu. Díky vhodné penalizaci matice tuhosti vrstvy a poruch se optimalizér konverguje k diskrétnímu výsledku (ve vrstvě zůstává právě jeden materiál) na rozdíl od počáteční rovnoměrné distribuce materiálových proměnných. Logistická funkce je použita pro interpolaci hustoty jednotlivých vrstev potahu tak, aby se vrstvy odebíraly z vnější strany a návrhové veličiny se plynule měnily. Pro dosažení diskrétních výsledků, které splňují předepsaná poruchová kritéria, byly stanoveny výchozí parametry optimalizace.

Vlastní softwarová implementace je naprogramována v Pythonu, kdy uživatel nejprve definuje potenciální materiály a síť MKP modelu s okrajovými podmínkami a zatížením. Program následně provede interpolaci vlastností, tak aby mohla být použita v externím MKP řešiči, kterým je Nastran. Ten spočítá lineární statickou analýzu a vypíše vnitřní silové účinky na jednotlivých elementech, které jsou už pak vlastním programem použity k výpočtu napjatosti ve vrstvách a opakovanému vyhodnocení poruchových kritérií tak, jak je požaduje

optimalizér (IPOPT) v rámci vyčíslení omezujících podmínek, cílové funkce a jejich derivací. Po konvergenci k diskrétním výsledkům vrstvení dojde k zaokrouhlení případných nepřesností a ověření splnění poruchových kritérií na finálním modelu. Za účelem snížení výpočtové náročnosti byly implementovány agregace omezující podmínek pomocí KS funkce a „patch design“, tedy sdružení elementů, které mají sdílené návrhové proměnné (vrstvení). Uživatel nakonec zkontroluje splnění ostatních podmínek, které nejsou v optimalizaci podchycení, např. deformace, ztrátu stability a konstrukční detaily.

Funkce metody byly testovány na příkladech různé složitosti, počínaje jedno-elementovým modelem sendviče zatíženého tlakem v jeho rovině, smykem a ohybem, dále série simultánně optimalizovaných nosníků sestávající z jednoho elementu. U těchto příkladů bylo řešení srovnáno se známým optimem. Příklad s vyšším počtem proměnných byly panely s trojím typem okrajových podmínek, kde je porovnána náročnost při optimalizaci každého elementu zvlášť, všech elementů se společným vrstvením, použití agregace omezujících podmínek a provázání vrstev pomocí tzv. blendingu. Složitějším příkladem je box sestávající z 25 návrhových oblastí zatížený pod tlakem na horní straně a krouticím momentem obdobně jako křídlo. Příklady z praxe jsou skříň používaná v interiéru dopravního letadla a velká kuchyňka. Na příkladech bylo demonstrováno, že optimalizace je schopna nalézt řešení, které má vysokou míru diskrétnosti a vyhovuje poruchovým kritériím nebo je jen mírně narušuje. Pro některá nastavení nebylo nalezeno skutečné minimum hmotnosti, jak lze vidět u jednoduchých příkladů. Výpočtová náročnost silně závisí na počtu proměnných a omezujících podmínek (zejména počtu elementů), takže např. vrstvení kuchyňky s hrubou sítí čítající cca 5000 elementů se optimalizovalo přibližně 14 hodin.

Přínosy disertační práce jsou v tom, že byl odzkoušen upravené postup výpočtu derivací, které umožňují snadné použití běžně používaných skořepinových MKP modelů. V rámci DMO byly zcela nově použity interpolace wrinklingu a crimpingu. Testovací příklady ukázaly, že optimalizér nekonverguje při narušení poruchových kritérií z důvodu koncentrace napětí nebo nedostatečné pevnosti využitelných materiálů, ale dobré konvergence bylo dosaženo použitím parametru, který předepisuje ignoraci malého množství poruchových kritérií. Program tedy může posloužit v inženýrské praxi pro usnadnění koncepčního návrhu sendvičových konstrukcí tím, že sníží počet ručních úprav vrstvení a přepočítávání a vyhodnocování poruch.

Klíčová slova

Sendvič, Gradientní optimalizace, Minimalizace hmotnosti, Sendvičové poruchy, Vrstvení, Agregace omezujících podmínek, Diskrétní optimalizace materiálu.

Content

1 Introduction

Sandwich structure combines a thick soft core in the middle of thin stiff face-sheets, which effectively transfers bending moments and satisfies high bending stiffness, which predetermines it to wide use in secondary structures required to be light and stiff under low or intermediate load levels. Sandwich structures are used and designed widely in the aerospace industry at least since Second World War. Since that, wide knowledge about them were collected and various design approaches were developed and described in engineering and scientific literature.

What is new in the recent years and decades is the use of calculations (mostly through the finite element method), not only in the validation of human-made designs, but also directly helping with design in the form of optimization used as a tool to find the best design parameters fulfilling design criteria given by an engineer. Such a growing tool is the topology optimization already established in the conceptual design of parts with isotropic materials. It uses gradient methods to solve tasks with a large number of design variables. Discrete Material Optimization (DMO) is a method based on similar principles as multimaterial topology optimization applied to design composite layups. Sandwiches, as a subgroup of fiber-reinforced composites, have a potential for ongoing research and the improvements of DMO.

The thesis implements DMO with a modified application of derivative evaluation combined with evolution within a given number of design cycles. The implementation is in the form of Python program intended as a tool which could be used by engineers and help them in finding a low mass design satisfying failure constraints on the level of global layup where an engineer defines geometry, loads and boundary conditions, and available material candidates so that the algorithm can search for the best suited combination of them.

2 State of the art

The topic of sandwich structures is very wide and so the following review focuses specifically on structural design calculations, on optimization, and application of topology optimization principles to sandwich structures.

2.1 Design calculations

From the broader view, a typical development methodology of a composite structure can be found in CMH-17-6 Composite Material Handbook [1].

2.1.1 Beams and plates

Difference between the analytical calculation of the sandwich beams (plates) and homogeneous beams (plates) is that sandwiches have, due to soft core and thin face-sheets, small shear stiffness so that shear deformation cannot be neglected. Considering a typical case assuming a soft thick core between two stiff thin face-sheets, in-plane loads are transferred by the faces, whereas transverse shear is transferred by the core as drawn in Figure 1. These assumptions enable the calculation of deformations of sandwich beams and plates based on differential equations. Their precision further depends on other detailed assumptions of deformation and stresses in the sandwich layers. First Order Shear Deformation Theory (FSDT) is often used. It describes the layer stresses, based on the stiffness properties of the layers and loads of the sandwich shell.

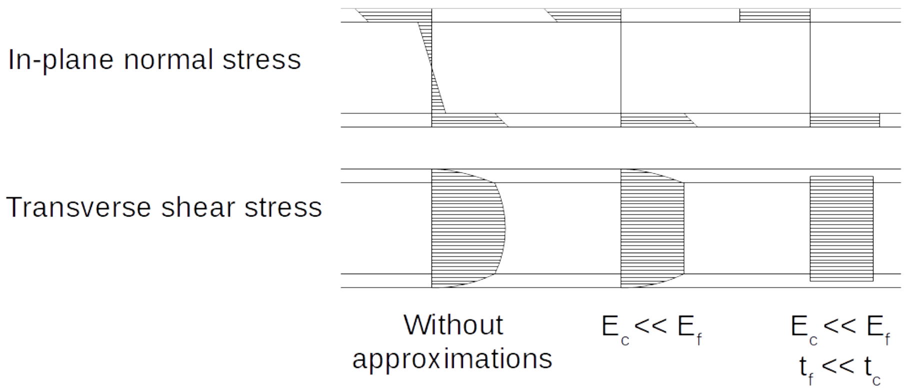

Figure 1: Simplification of the stresses across a sandwich[23].

2.1.2 Finite element analysis

Finite element method (FEM) enables several different approaches to sandwich calculations. When large structures are analyzed, the sandwiches are typically modeled by shell elements with composite layup where the special layer acts as a core. Sandwich failures are evaluated from the stresses in the core and face-sheets on each element according to analytical failure criteria. If detailed analysis is necessary (joints, inserts, etc.), the local model is used to be with 3D elements for the core and 2D elements for faces [2–6].

Real structures are often complicated so that they are difficult to describe by analytical beams and plates, so the use of FEM is necessary, such as in the case of layup design for the fuselage of a light aircraft [7, 8]. In that case, the global layup was repeatedly designed and analyzed until it satisfied stress and stability requirements, which took more than 10 laborious iterations. Structural details are made later according to technological recommendations and usually not analyzed by FEM.

2.2 Optimization methods

Extensive review papers [9–12] on composite optimization point out that genetic algorithms (GA) are often used thanks to their ability to find global extreme and deal with discrete variables, however, when a model contains large number of design variables and evaluation of constraints and goal function takes a long time, they lose the efficiency.

2.2.1 Topology optimization

If derivatives can be efficiently calculated, gradient methods can find the local optimum fast even for very large models, as the progress in topology optimization methods in isotropic materials proofs, since it was introduced by Bendsøe [13]. Design variables are element pseudo densities $x_e \in (0,1\rangle$, which are continuous so that gradient optimization can be efficiently used. Static equilibrium typical for finite element method can be written as

$$\left(\sum_{e=1}^{N} x_e^p \boldsymbol{K_0}\right)\boldsymbol{u} = \boldsymbol{F} \quad , \tag{1}$$

where the term in the parentheses is a global stiffness matrix assembled from element matrices penalized by so called Solid Isotropic Materials with Penalization (SIMP) interpolation scheme as shown in Figure 2. Alternatively, Rational Approximation of Material Properties (RAMP) can be used so the element stiffness would be

$$\boldsymbol{K}_e = \frac{x_e}{1+q(1-x_e)}\boldsymbol{K}_0 \quad , \tag{2}$$

where q is penalization parameter causing similar effect as p in SIMP scheme, $\mathbf{K}_0$ is stiffness matrix of the element with solid material. When compliance is minimized in the optimization, penalization causes that elements with intermediate properties are not effective, so that the optimization method converges to discrete solution (x_e=0 for void or x_e=1 for solid material).

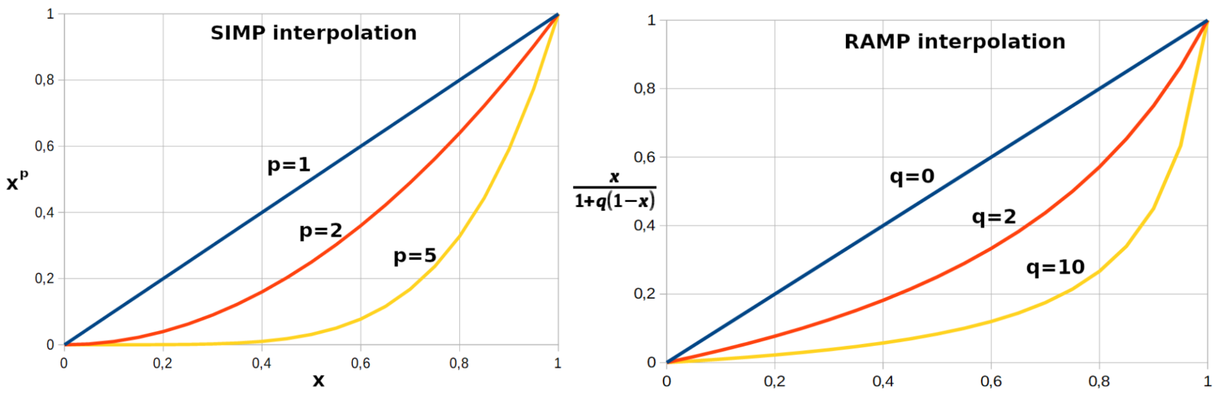

Figure 2: SIMP and RAMP interpolation.

2.2.2 Discrete material optimization

Stegmann and Lund [14] applied multimaterial topology optimization interpolation to the layer composite to minimize compliance, and in the second paper [15], to maximize the lowest eigenfrequency. Later, Lund [16] modified the method also for buckling optimization. Candidate materials include physical material as well as layer orientation, so the method is convenient for a low number of material candidates and orientations. Original Discrete material optimization (DMO) has a fixed number of layers. Søren et al. [17] included thickness new density variable $\rho_{el} \in [0,1]$ on each element e and its layer l so that laminate thickness could be varied. Authors used RAMP scheme in the form

$$\boldsymbol{Q} = \boldsymbol{Q}_0 + \frac{\rho_{el}}{1+r(1-\rho_{el})} \sum_{i=1}^{n_M} \frac{x_i}{1+q(1-x_i)} \Delta \boldsymbol{Q}_i \quad , \tag{3}$$

where $\mathbf{Q_0}$ holds properties for void layer and $\mathbf{\Delta Q} = \mathbf{Q} - \mathbf{Q_0}$, r and q are penalization coefficients. Recent study by Sjølund et al. [18] improved DMTO for sandwiches with variable thickness core and face-sheets. They used the method to minimize the mass with displacement and buckling constraints of wind turbine blades.

2.2.3 Case study

Using current software packages, it is possible to use optimization problems complexly. Velea et al. [19] described multicriteria optimization of the small car body. Multi-criteria optimization enables to reach convenient parameters not only from the mass point of view but also safety and driving properties which were quantified by torsional stiffness in the longitudinal direction, stiffness during front impact, and a few other cases.

First, the free size optimization was solved as one criterion optimization (mass minimization) with defined minimal and maximal layer thicknesses (glass fabric, PUR core, glass fabric) to find load paths. Thicknesses of other layers were found in the same way.

Second, size optimization was carried out. Based on the technological possibilities, surfaces to contain different cores were defined manually (well-shaped PUR, stronger PVC, honeycomb to prevent buckling). In this step, 7 criteria were evaluated by weighting coefficients, 42 sections were defined manually (each with constant layer thicknesses), and thicknesses were sought on them. In total, more than 5000 design points were evaluated. Final variant was selected according to minimum of the cost function made of weighted contributions of prescribed criteria.

2.3 Summary of review

The review focused on sandwich design and optimization. State of the art in this broad field can be summarized to:

1) Traditional approach to sandwich design covered in (hand)books describes the analytic design of sandwich beams and plates, so it is limited to basic geometry and boundary conditions.
2) Practical tasks are typically solved with FE models of various detail. Structures are often optimized by repeated manual modifications of layup and evaluation of design requirements.
3) Non-gradient methods (especially genetic algorithms) are used in sandwich optimization as a subtopic of optimization of fiber-reinforced composites. Such methods can reach a robust solution (close to the global optimum), but their computational demands quickly arise with the number of variables when FE model needs to be involved.
4) Optimization of some simple tasks is possible through basic optimization methods, but tasks of real complexity are designed in several phases, which can combine several types of optimization tools and manual modifications to cover all requirements from conceptual design to manufacturing.
5) In 2014, Discrete Material Optimization (DMO) was introduced. DMO is gradient method and it has been used for fixed and later variable thickness composite optimization. Goal function and constraints consist of responses on compliance, mass, natural frequency, composite failures, manufacturing rules, but not specific sandwich failures such as wrinkling and crimping.

3 Thesis objective

The goal of the thesis is to implement an automated optimization algorithm to improve the design process of sandwich structures regarding stress and load capacity. Attention should be paid to the structures with relatively low number of plies with the ability to solve tasks with geometry and loads more complicated than classical panels, which can be designed by the existing analytical approaches. Examples of the structures of interest are light aircraft fuselages or airliner interior components. The implementation should contribute to the quality of the designed structure and shorten the time needed for designing a new product. Used methods should be programmed and the workflow should be validated by comparison of theoretical and practical examples. Focus of the work is illustrated in Table 3.1.

Table 3.1: Thesis objective reasoning.

Sandwich design characteristics	**Potential improvements**
Simple sandwich panels with uniform loads and structures, which can be split to them, can be sequentially designed by the existing approaches working with separated panels.	Sandwich design of the whole structure considering nonuniform load, potentially with complicated geometry where FEM is needed.
Details (like inserts, sandwich endings), especially in the case of sandwiches with few layers, are designed according to the technological possibilities and standard processes of the manufacturer.	Put attention rather to global characteristics (number and orientation of the layers, core material, and thickness) than details.
Trend in design methodologies is to use automated optimization from the beginning according to loads, boundary conditions, and design constraints (including manufacturing) rather than cyclical intuitive design with sequential stress analysis. In the case of topology optimization with isotropic material, terms like “Design by load” or “Design for manufacturing” are used in the simulation software marketing.	Focus on the initial design phase of the layup where optimization has the biggest impact.
	Minimize design cycles where repetitive human work is needed.
Optimal results might be hard to implement in the industry.	Consider manufacturing constraints.
Need for validation.	Comparison with “optimal” results of simple examples or studies from the literature. If possible, cooperate with the industry to design a product which will be experimentally tested.

Although gradient methods contain an inherent risk of trapping in the local minimum or infeasible design, this can be partially diminished by convenient penalization. Gradient optimization also requires continuous variables to determine derivatives. Contrary, the sandwich design contains rather discrete variables (number of laminated face-sheet layers, available core materials, etc.), which requires to be transformed to continuous ones and forced to converge to discrete values or to be rounded, as performed in a classical topology optimization on solid-void material. Provided that gradients can be efficiently evaluated, this approach can efficiently reach the local optimum even with a large number of design variables.

The thesis focuses on the core functionality of the sandwich optimization regarding sandwich failure constrains. The scope of the scientific work is specified in these aims:

1) Implement gradient optimization of the sandwich structures based on DMO connected to FE model with general geometry.
    a) Minimize mass of the structure
    b) Include constrains on sandwich failures
    c) Consider manufacturing constraints
2) Demonstrate convergence to the optimum by simple examples
3) Demonstrate the application to the practical design task.

4 Methods

4.1 Optimization approach

The structure will be represented by the FE model, where each element can obtain an independent design layup if not in a patch. Optimization problem can be mathematically formulated as

$$
\begin{array}{ll}
\min M(\boldsymbol{x}) & \\
0 \le x_{ijk} \le 1 & \text{material variables} \\
\dfrac{0.99}{n_L} \le x_{Tk} \le 1 & \text{face-sheet thickness variables} \\
\sum_{i}^{n_{MC}, n_{MF}} x_{ijk} = 1 & \text{at each element layer} \\
\boldsymbol{FI}_{\sigma} < \mathbf{1} & \text{face-sheet stress} \\
\boldsymbol{FI}_{\tau} < \mathbf{1} & \text{core shear} \\
\boldsymbol{FI}_{cr} < \mathbf{1} & \text{crimping} \\
\boldsymbol{FI}_{wr} < \mathbf{1} & \text{wrinkling}
\end{array}
\quad , \qquad (4)
$$

where the material variables x_{ijk} can be between 0 (not used) and 1 (used) as in topology optimization. Indices denote i-th material candidate, j-th layer, k-th element (or patch). In the meaning of this work, term “material” includes also orientation and thickness. Sum of n_{MC} core material candidates (n_{MF} face material candidates) on the layer must be 1 to fulfill physical meaning.

Goal function

Penalized mass was selected as a goal function

$$
M(\boldsymbol{x}) = \sum_{k}^{n_E} A_k \sum_{j}^{n_L} t_{Mjk}(\boldsymbol{x}) \rho_{Mjk}(\boldsymbol{x}) \quad , \qquad (5)
$$

where n_E is the total number of finite elements, A_k is element area, t_{Mjk} is j-th layer thickness interpolated linearly from candidate materials, ρ_{Mjk} is a density interpolated with penalization as

$$
\rho_{Mjk} = \begin{cases} \rho_{Ljk}(x_{Tk}) \sum_{i}^{n_{MF}} \dfrac{x_{ijk}}{1 + q(1 - x_{ijk})} \rho_i & \text{for face-sheet} \\ \sum_{i}^{n_{MC}} \dfrac{x_{ijk}}{1 + q(1 - x_{ijk})} \rho_i & \text{for core} \end{cases} \quad , \qquad (6)
$$

ρ_i is the density of i-th material. Here, penalization coefficient is q =-0.7, so the intermediate material has higher mass as shown in Figure 3 for two candidate materials with variables x_1 and x_2, thus optimization tends to 0 or 1.

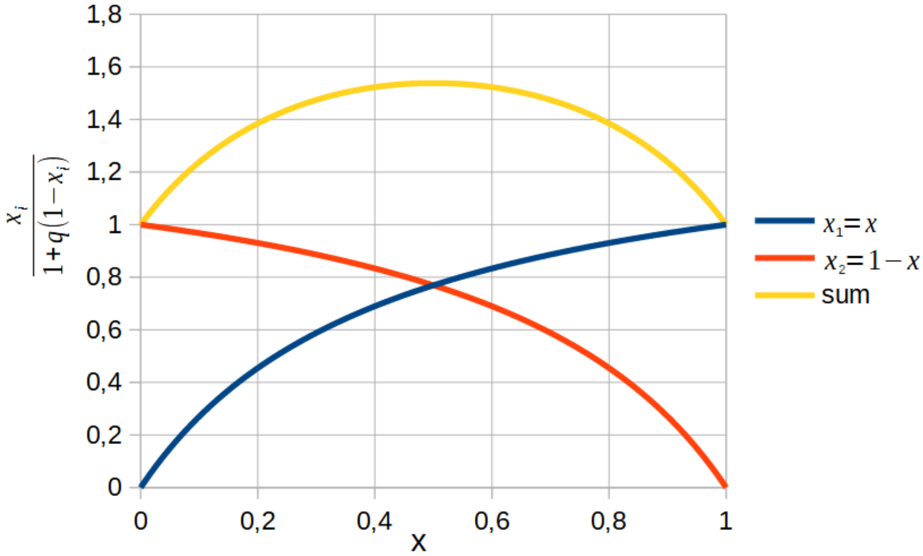

Figure 3: Penalization term for two material candidates with same densities and for q = -0.7 [22].

Layer density $\rho_{Ljk} \in \langle 0,1 \rangle$ in eq. (6) serves as a coefficient determining how much the j-th layer on k-th element is active. ρ_{Ljk} is defined by the S shape function (also called logistic function) dependent on the thickness variable x_{Tk}, for j-th layer

$$\rho_{Ljk} = \frac{1}{1+\exp[k(x_{Ljk}-x_{Tk})]} \quad , x_{Ljk} = \frac{j-1}{n_L} \quad , j=1,2,\ldots,n_L \quad , \tag{7}$$

where x_{Ljk} is the position of the beginning of the j-th layer measured from the core to the outer face-sheet surface. Figure 4 shows layer densities ρ_L for various layer positions x_L. Coefficient k controls steepness of the S shape function. The optimization starts with a low k value which gives a uniform gradient of the summary function because the layers “overlap”. At the end, k is larger which makes the summary function stair-like, which is better for final rounding to a discrete number of layers.

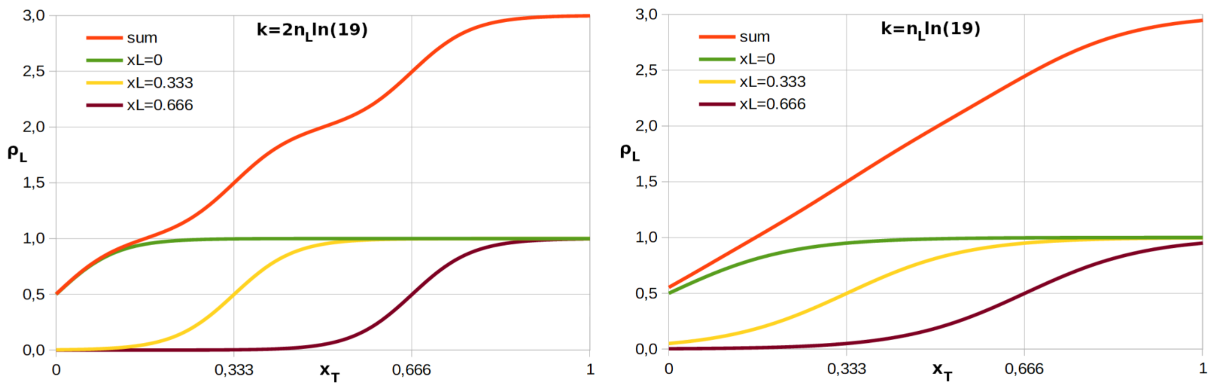

Figure 4: Layer densities of the face-sheet with three layers used in the goal function. Right graph is for k two times lower[22].

Stiffness

Layer stiffness matrix and physical thickness (different from the goal function thickness) are interpolated linearly from the candidate materials, but face-sheet thickness contains also term for S shape similar to ρ_{Ljk} in eq. (6), so that the outer layers are “squeezed” in thickness which helps to control the bending stiffness of the face-sheets as shown in Figure 5.

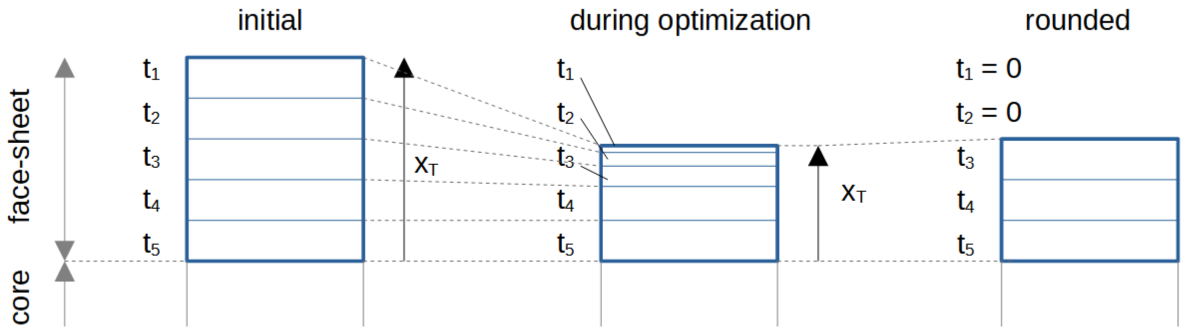

Figure 5: Thickness of the face-sheet layers controlled by the thickness variable x_T.

4.1.1 Failure constraints

Failure constraints are prescribed by the failure index FI which is required to be below 1. It is penalized to achieve a similar effect as the penalization in the goal function. Design variables in Figure 6 start in the middle (point 1 for the combination of materials α and β). When failure constraint is violated, gradient directs the optimization towards the left stronger material (red arrow). When it reaches point 2, the constraint is not active any more and the solution is directed by the goal function gradient (blue arrow) towards the discrete solution (point 4).

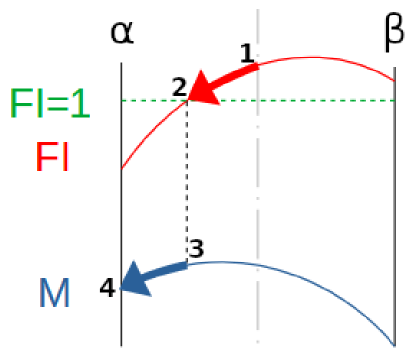

Figure 6: Schema of the mass and failure index interpolation

Max stress and core shear failure

Max stress criterion FI^i is evaluated for i-th material on the top and again on the bottom side of the layer to respect stress changes over the thickness. Final failure criteria on the layer is a maximum of candidate material failure indices penalized by the RAMP scheme (q = -0.7):

$$FI_\sigma = \sum_i^{n_{MF}} \frac{x_i}{1+q(1-x_i)} max(FI^i) \quad . \tag{8}$$

Same formula apply for the core shear failure.

Crimping

Crimping is a core failure similar to anti-symmetric wrinkling where length of the half wave approaches zero. It is caused by insufficient core shear strength. Crimping failure indices are calculated in principal directions 1 and 2 as

$$FI_1 = \frac{-N_1}{G_{c1} t_c} \quad , \quad FI_2 = \frac{-N_2}{G_{c2} t_c} \quad , \tag{9}$$

where t_c is core thickness, principal load is calculated from element internal membrane forces N_{xx}, N_{yy}, N_{xy}.

The FI penalization cannot be directly included in eq. (9) as in max stress criterion, since there is no direct design variable interpolation in eq. (9). Material properties (G_{c1}, G_{c2}, t_c) depends on the interpolation and thus they need to include penalization to follow explanation in Figure 6, however, stiffness matrix and layer thickness were defined with linear interpolation, i.e. without penalization. Stiffness penalization of the FE model would change load distribution among finite elements, which was considered undesirable. So the special layer stiffness matrix is defined $\tilde{\boldsymbol{Q}}_{jk}$ just for the crimping and wrinkling evaluation

$$\tilde{\boldsymbol{Q}}_{jk} = \sum_{i}^{n_{MF}, n_{MC}} \frac{x_{ijk}}{1 + \tilde{q}(1 - x_{ijk})} \bar{\boldsymbol{Q}}_i \quad , \tag{10}$$

where $\tilde{q} > 0$ to penalize intermediate values as plotted in Figure 7. Now, intermediate values of the stiffness matrix are decreased, including core shear modulus which is used in eq. (9). Since G_{c1} is in denominator, it will have similar effect on the crimping FI as the opposite penalization on the max stress FI.

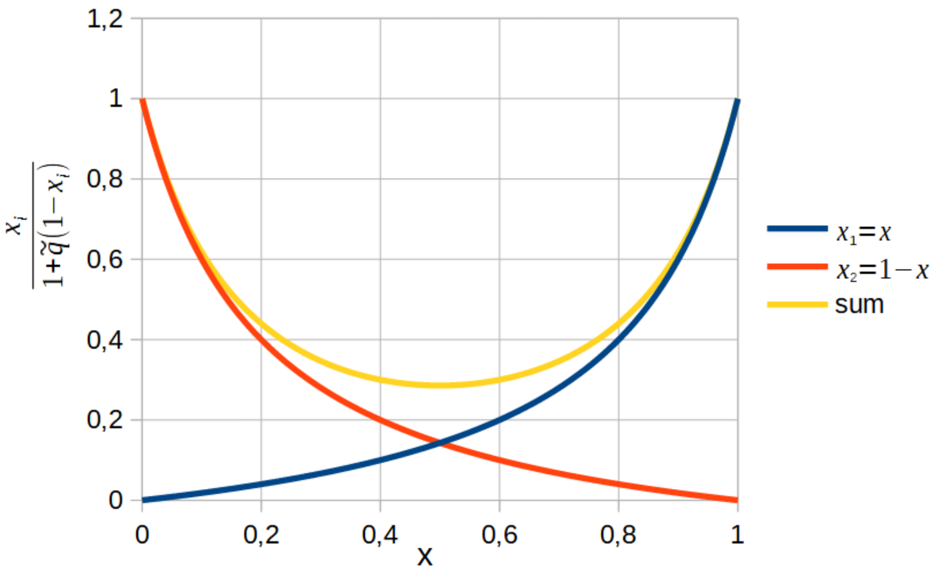

Figure 7: Penalization term for two material candidates with same densities and for $\tilde{q} = 5$ [22].

Wrinkling

Wrinkling is a local stability failure of the face-sheet loaded in compression. If only one principal load is in compression, wrinkling is evaluated as uni-axial. If both are in compression, failure index is defined by addition equation

$$FI_{wr}=\begin{cases} R_1^3+R_2 & if\ R_1\leq 1 \\ R_1^{1/3}+R_2 & else \end{cases} \quad , \tag{11}$$

where $R_1=\frac{-N_{f1}}{N_{wr1}}$ and $R_2=\frac{-N_{f2}}{N_{wr2}}$, which in fact denote separated wrinkling failure indices in the first and second principal directions of the face-sheet loads. Since critical wrinkling stress (used by Hoff and Mautner [20]) would be a vague value due to face-sheet thickness interpolation, critical wrinkling force is evaluated in principal direction as

$$N_{wri}=k_{wr}\left(E_{fiN}\,E_c G_{ci}\right)^{1/3},\ \ i=1,2 \quad , \tag{12}$$

where thickness is dropped from the effective face modulus

$$E_{fiN}=12\left(1-\nu_{12}\nu_{21}\right)D_{fi},\ \ i=1,2 \quad , \tag{13}$$

E_c, G_c are core moduli, D_f is face-sheet bending stiffness.

Sullins [21] defined the first row in eq. (11), i.e., $R_1^3+R_2=1$ to fit experimental results from bidirectionally loaded panels, so this relation just corresponds with the state of wrinkling failure. In the optimization, it is necessary to evaluate FI not only before the failure (the structure withstands the loads) but also above when FI > 1. Thus second case $R_1^{1/3}+R_2$ was added in the thesis to fulfill the intuitive requirement so that the weaker compressive load contributes less to the wrinkling failure index FI_{wr} as shown in Figure 8.

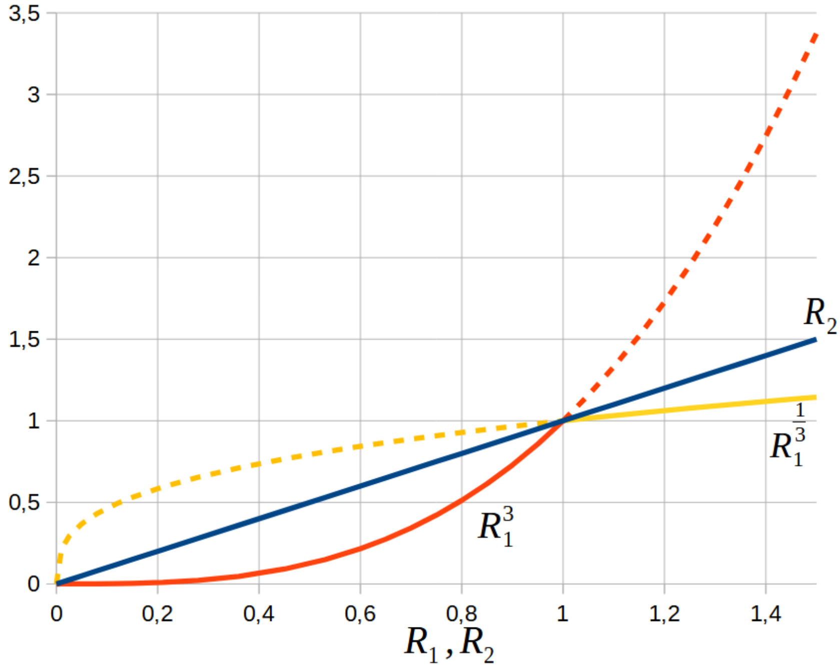

Figure 8: Members of the addition equation for wrinkling [22].

4.2 Software implementation

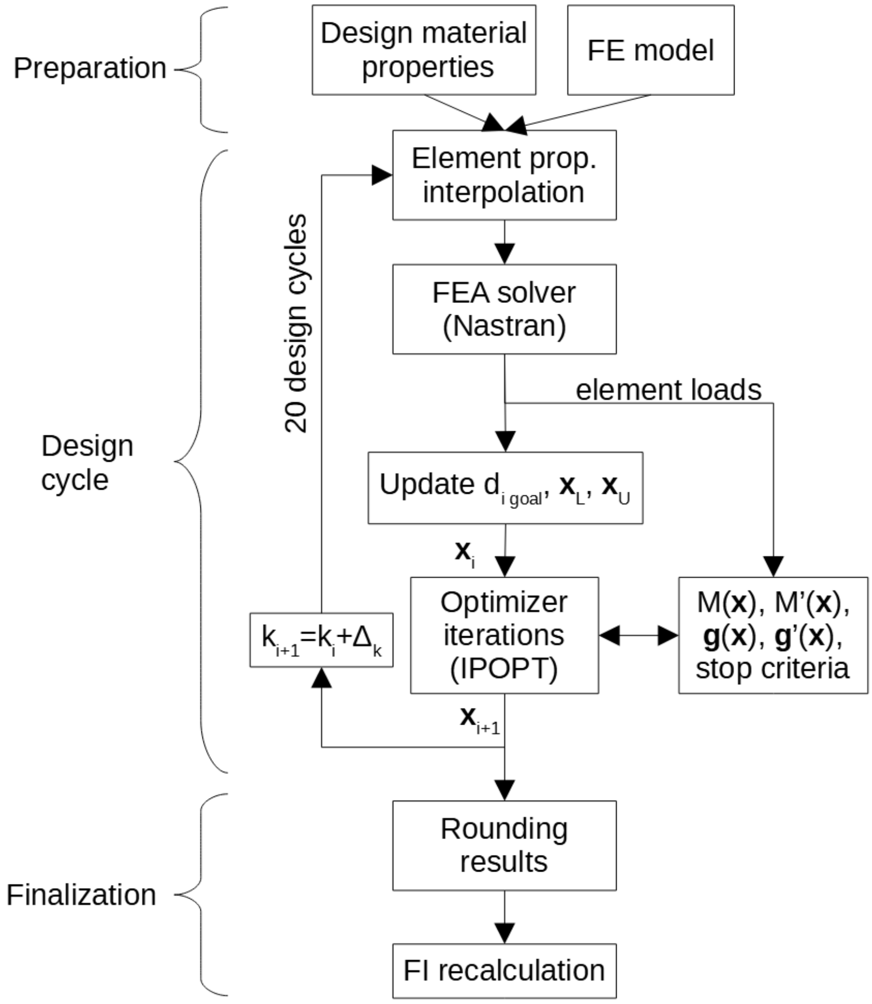

Figure 9: Algorithm flowchart [22].

Basic flowchart of the algorithm is in Figure 9. Inputs consist of candidate materials, their properties, and FE model with mesh, boundary conditions and loads. Design cycle starts with material interpolation where potential materials are combined with artificial element properties to replace properties in the input FE model. Nastran solver solves the linear static analysis to calculate element loads which are used to evaluate stresses in failure constraints during IPOPT iterations. Goal discreteness $d_{i\ goal}$, box constraints $\mathbf{x}_L$, $\mathbf{x}_U$ are updated for values in the given design cycle to prevent extensive changes. Next, IPOPT optimizer tries to improve design variables and (within its own iterations) calls subfunctions to evaluate the goal function, constraint function, and their gradients. Failure constraint derivatives are evaluated by the finite difference method on each element. Simplification in derivative calculation is that element loads are fixed during IPOPT run, so that the effect of changing stiffness of the model is considered by evolution in design cycles. Twenty design cycles repeat with the evolving coefficient k in S shape function for face-sheet thickness. Finally, design variables are rounded to discrete values and the model with rounded properties is recalculated to check its validity.

4.3 User workflow

Figure 10 summarizes the workflow during sandwich structure design when the optimization program is used (With optimization). First, the usual FE model is created. Second order shell elements with relatively large element size can be used for the optimization model to keep a low number of design variables and constraints. Boundary conditions and loads are prescribed as usual, preferably trying to avoid stress concentrations, because the optimization aims to design a global layup, so that small details (local reinforcements) are out of the scope of the optimization so the local concentrations would make difficulties in convergence. Multiple load cases can be used. Nastran input file should contain output request for internal forces acting on shell elements of the design domain.

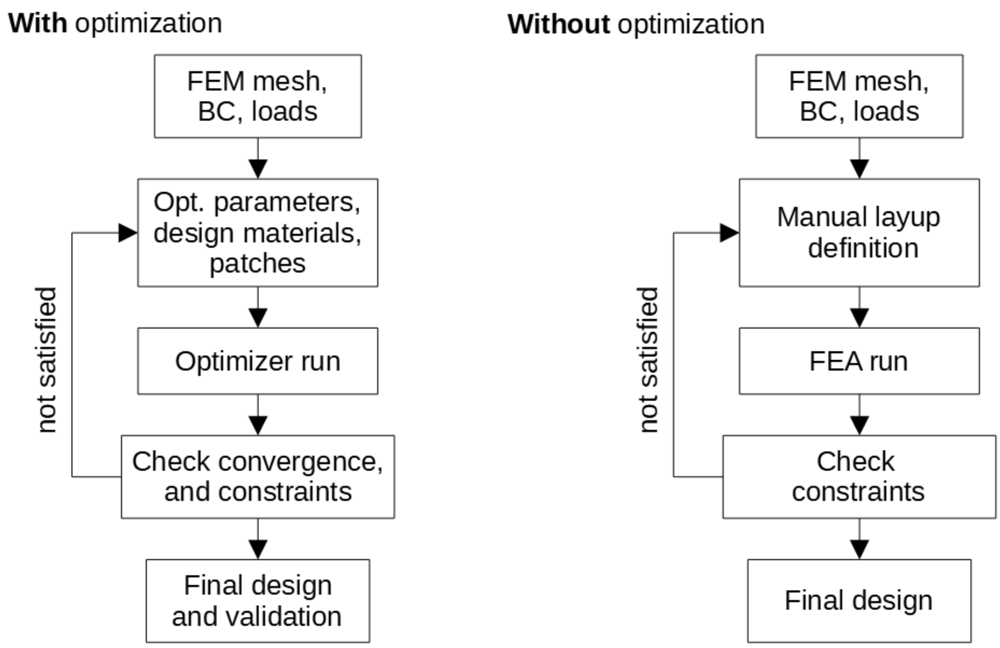

Figure 10: User workflow.

Figure 10 right shows the workflow without the optimization program, where the initial layup needs to be guessed manually according to engineering experience, including manufacturing preferences which might be missing in the optimization. Engineer needs to manually check the results from FEA and modify the layup to improve the model behavior, mostly by reinforcing the failing area or changing layer orientations. It can be seen that the workflow with optimization replaces laborious modifications. If needed, the optimization can be run more times with different optimization parameters.

4.4 Summary of the implemented method

Key possibilities and limitations which are given by the method itself and its implementation are:

1) Shell elements (CQUAD4, CQUAD8, CTRIA3, CTRIA6) can be in design domain. There are no limitations on elements out of the optimization domain.
2) Multiple design layups can be used, including laminates (without sandwich core). Limitation is that the optimization is not able to remove the core automatically.
3) Orthotropic materials are defined by engineering constants.
4) Patches can be defined (group of elements shearing layup). Blending is implemented through penalization so that the user can control how strongly the continuation of layers should be enforced.
5) Multiple load cases can be used in the Nastran file or in additional files (e.g., with additional elements out of the optimization domain).
6) Optimization aims to discrete results – choosing among predefined core thicknesses and densities, layer orientations, etc. “Continuous” options need to be approximated by many design materials, which prolongs optimization.
7) Convergence would be more difficult when materials differ dramatically in properties.
8) The method is gradient based, so it finds the local extreme, there is no guarantee to find the global extreme, even though interpolation helps to increase the chance of finding a good result.

5 Examples and results

Examples of various complexities were used to define default optimization parameters, to test the convergence and quality of results.

5.1 One element examples

Compression and bending examples test the basic ability of the algorithm to achieve optimal material selection when only one element is concerned. These examples are simple enough to check if the solution is truly optimal and aims to reveal potential shortcomings of the implemented algorithm. Examples were optimized for the sequence of loads. Material candidates were fabric composite materials for the face-sheets (0° and 45° carbon fabric) for up to 5 layers and six core candidates (foams 60, 80, and 130 kg/m^3 all with 5 and 10 mm thickness).

All cases converged to discrete results without failure violation. Six cases reached the optimum. Seven cases finished with a heavier design than necessary, mostly due to the denser core than needed.

5.2 Separated elements

The next example contains 14 elements which are separated, so that the element forces and moments in Figure 11 will not change during optimization. Elements are fixed on one side. Eight elements are loaded with increasing compression force F, while other six elements are loaded with increasing transverse force T which cause bending moment at the element center M_{center}. Four UD carbon/epoxy candidate materials were possible for the face-sheet layers (0°, 90°, +45°, and -45°) for up to 5 layers and four core candidates (foams 80 and 130 kg/m^3 both with 5 and 10 mm thickness).

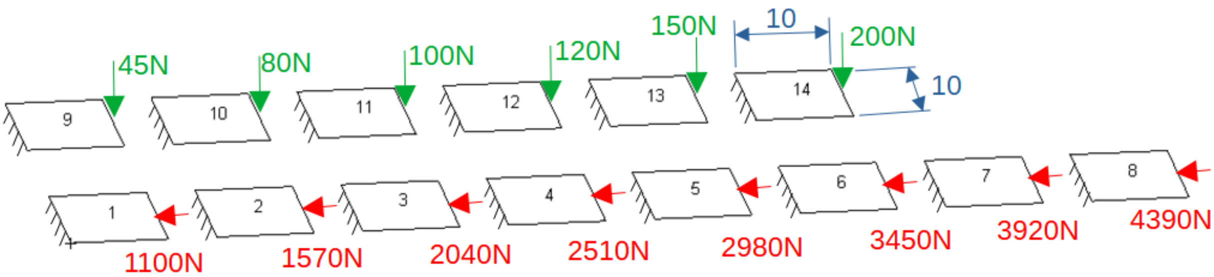

Figure 11: Separated elements with loads and boundary conditions.

The optimization converged well as can be seen in Figure 12 which shows the evolution for the selected measures. All of them stabilized after design cycle 8. Average discreteness reached the value 1.000 for all elements for the core as well as face-sheets. Mass has a small step due to the rounding of face-sheet thickness. Maximal failure indices plotted in the graph dropped from high initial values to finish close to 1 for all failure types.

This example was extensively used for selecting robust default parameters for optimization. Primary concern was to achieve discrete results without failing elements, which were achieved in this case, but with the price of some elements to be heavier than necessary. 11 elements reached the optimum, whereas 3 elements had a stronger core than necessary.

Constraint aggregation was also tested. It resulted in a heavier design by 3% and, contrary to expectation, did not shorten the optimization time.

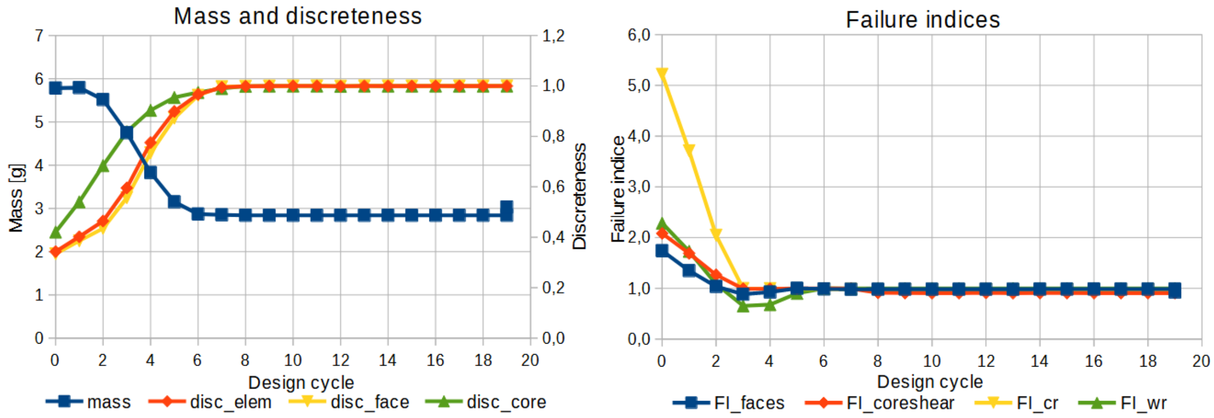

Figure 12: Mass, discreteness, and failure indices during design cycles.

5.3 Panel with pressure or side load

This example consists of a 700×1400 mm panel loaded by the normal pressure 50 kPa with fixed edges in the first variant and simply supported edges in the second variant. Third variant has one edge fixed, the middle of the opposite edge is loaded by 6000 N in each of the 9 nodes (the distribution is to decrease stress concentration). It was meshed with 16×32 quad8 elements as shown in Figure 13. This example follows the results published in the article [22]. Four unidirectional layer candidates were used for the face-sheet layers (0°, 90°, -45°, and 45° UD carbon) for up to 5 layers and 6 core candidates (foams 60, 80, and 130 kg/m^3 all with 5 and 10 mm thickness).

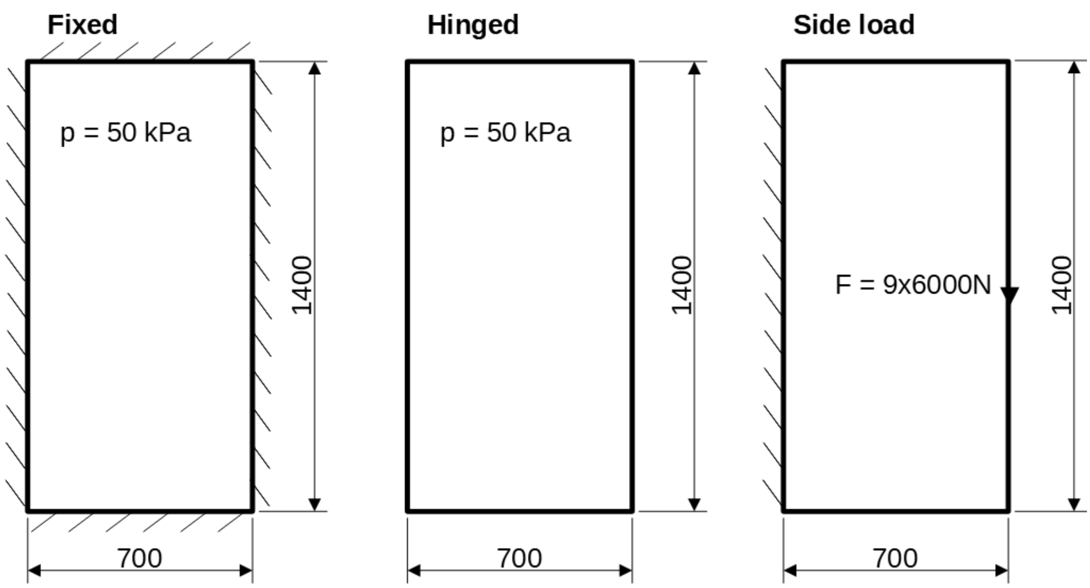

Figure 13: Panel with different boundary conditions [22].

Several optimization settings were tested on these examples. Variable stiffness, where each element has its own layup gave the results in Figure 14, which gives a symmetric pattern for the first two cases with high discreteness and maximum failure constraints violated by 1%.

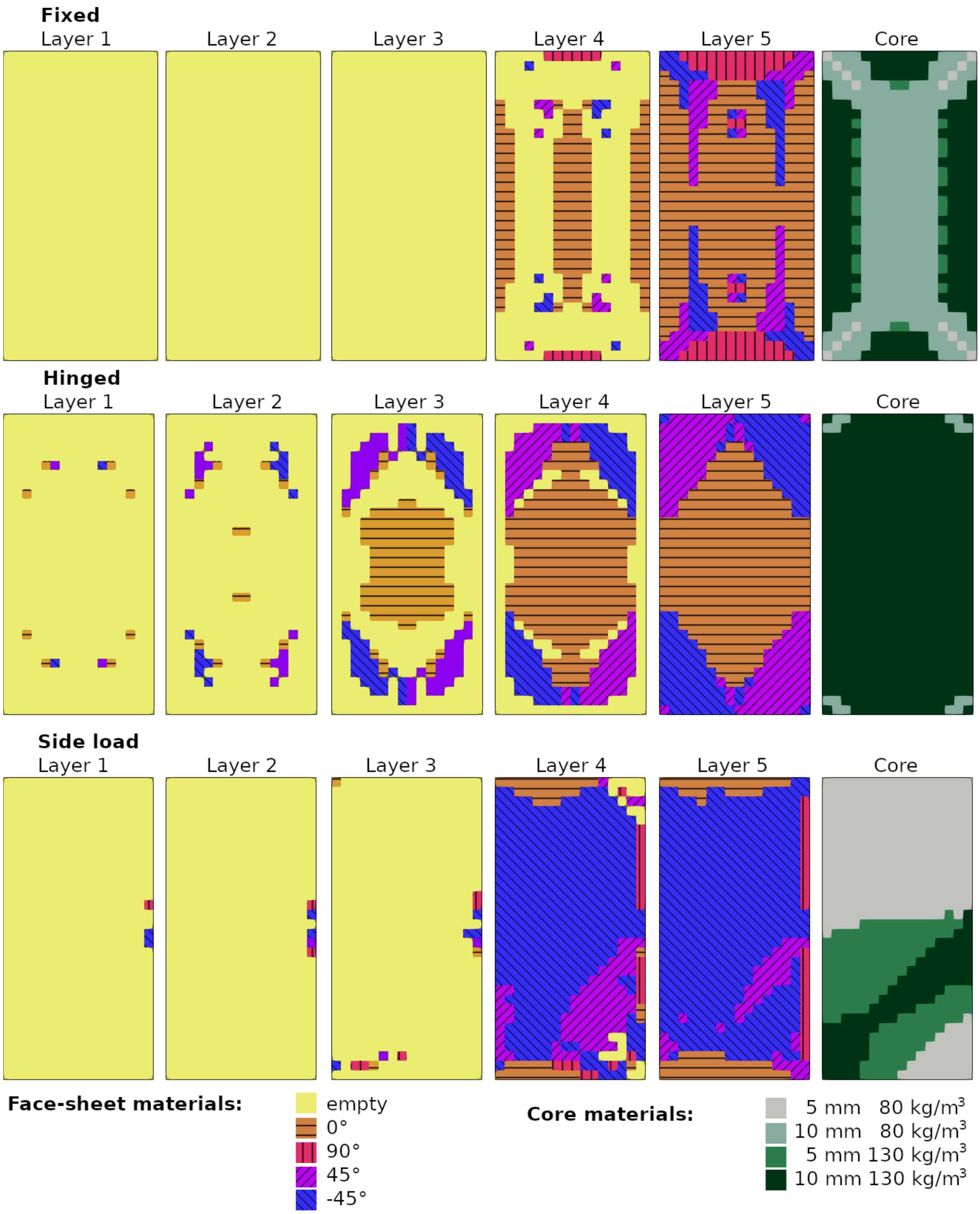

Figure 14: Layup for different boundary conditions, opposite face-sheet is symmetric [22].

Blending decreased convergence, but better results were achieved with double number of design cycles. Size of the common materials in the layer increased with the blending parameter b_0, which proved that the level of blending could be partially controlled as intended.

Effect of stress concentration was tested on the panel with side load concentrated to one node. The example demonstrated that the concentration caused that the optimization did not converge at all. However, when the parameter A_{ign} was set to ignore failures on 1.5% of the area or more, it converged well and achieved similar results to the case when the load was not concentrated.

Constraint aggregation decreased the convergence in two of three cases and led to mass increase by 12-55% for various boundary conditions. Contrary to the expectations, the optimization time increased.

When a refined mesh was used (2048 elements instead of 512), the layup was similar, max. failure index slightly increased, optimization time was 5-7 times higher.

Patch design (one patch for all elements) led to optimal layup for 2 panels, 1 panel had over dimensioned face-sheet with 45/-45$_2$/ orientations instead of 0$_2$/.

5.4 Box with top underpressure and torque

Long box example with ribs is in Figure 15. It is cantilevered on the left end and loaded by tensile underpressure 15 kPa on the top side and torque on the circumference of the ribs through RBE3 elements, 2 Nm on each. Two fabric candidates were for the face-sheet layers (0° and 45° carbon fabric) for up to 5 layers and four core candidates (foams 80 and 130 kg/m^3 both with 5 and 10 mm thickness).

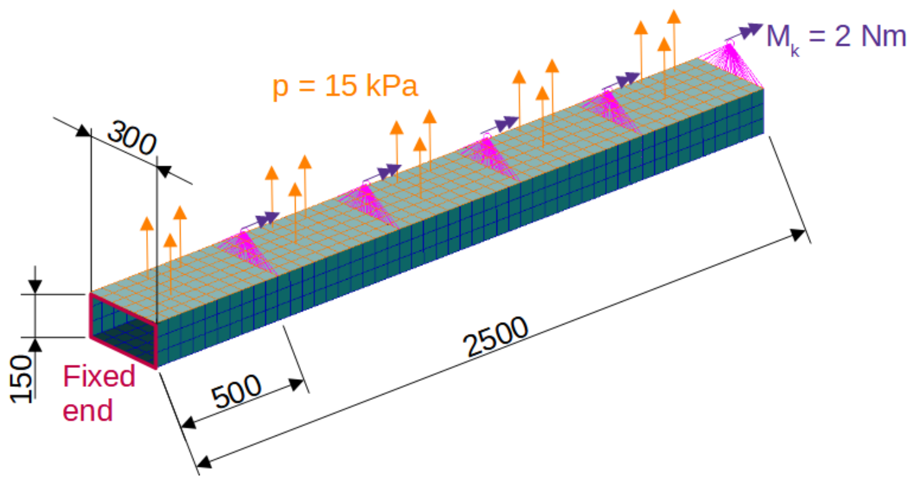

Figure 15: Schema of the box example.

This example tested multiple panels with patches. Good results were achieved with a higher number of optimizer iterations, which points to slower convergence. Constraints were satisfied. At least two panels were heavier than necessary.

Another variant of this example was with underpressure p = 50 kPa and with laminate flanges which has only one candidate material (UD) in 40 layers, so the optimization should have determine number of layers. Results shown that flanges were over dimensioned by ~50%, which means that the algorithm was far from the optimum.

5.5 Aircraft interior components – Galley

The final example represents application of the program to the conceptual design of an airliner galley. The galley covers the rear bulkhead of the passenger compartment. It serves to accommodate trolleys and equipment. Shell FE model is typically used to analyze the strength and deformation of the galley. RBE2, RBE3 elements, springs and rods mass elements are used in the model. The model contains 6 load cases.

Aim of the optimization was to select the global layup for the panels, before the application of doublers and inserts (determine if to use 2 or 4 face-sheet fabric layers, thickness and orientation of the core). Parameters were set to ignore failures on 5% of the area as an area for later reinforcement.

Figure 16 shows the color plot corresponding to the core material, i.e., thickness and orientation. Since the orientation depends on FE element orientation, black lines were added manually according to the element orientations on each panel. In this example, the optimizer had to evaluate element loads on each element of the panel for 6 different load cases, so it is difficult to evaluate specifically the correctness of the resulting core orientations and thicknesses.

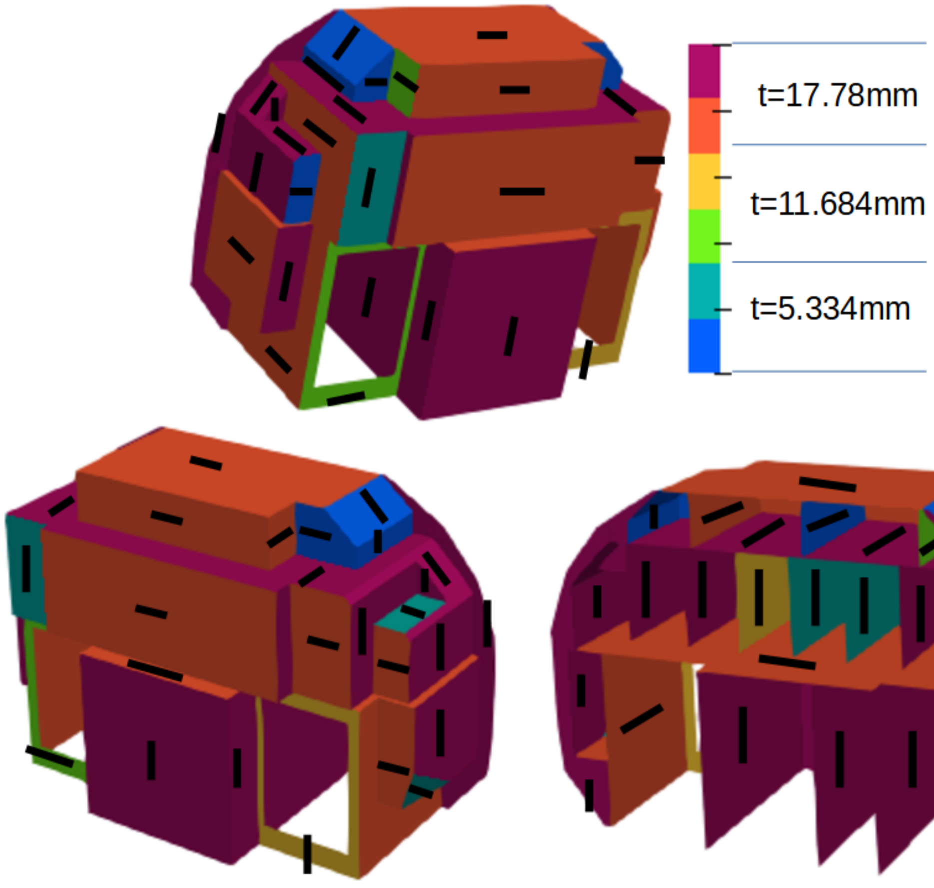

Figure 16: Galley results with panels orientations and thicknesses for A_{ign}=0.05.

Figure 17 shows the failing elements, which are mostly in the ignored area. It is a useful output for the designer so that these areas can be reinforced with doublers and inserts. Imperfections of the model can also cause failures, which might be considered because some elements might be failing just because of a poor quality of the mesh due to rough element size.

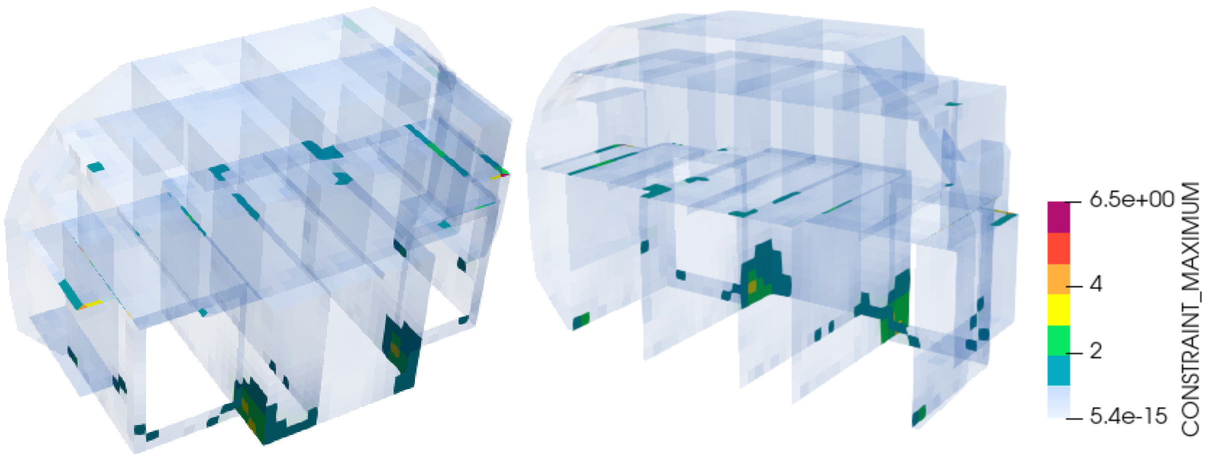

Figure 17: Elements with max FI > 1, for A_{ign}=0.05.

5.6 Summary of examples

Findings from the test examples can be summarized to these points:

1) Final discreteness and maximum failure index can be used for the first assessment of the results. In most cases, the final design was without failure constraint violation. Some examples finished with a slight violation. Final discreteness was usually close to 1, which denotes that the continuous variables converged successfully to a discrete solution which is required in the composite design.

2) The optimizer was not able to reach a discrete solution when the failure constraints could not be fulfilled by the strongest candidate materials (or) due to local stress concentration. The difficulty can be avoided by the use of A_{ign} parameter prescribing area of the elements which failure constraints are ignored.

3) Constraint aggregation did not work satisfactorily. Best solutions were achieved with ρ_{KS} lower than reported in the literature, but it still did not reach the quality of a solution without aggregation. Aggregation was expected to decrease the optimization time, but examples with aggregation required similar or even longer time due to worse convergence. These differences, compared to the literature, could be explained by a different approach to derivatives and evolution of the design cycles.

4) Although default optimization parameters were defined to achieve a robust solution in most cases, lower mass was achieved with altered parameters in some examples (the box example performed better with higher number of iterations i_{max}).

5) Simple examples revealed that the program is capable of reaching the true optimum in some cases, but not in all of them, which is not surprising when gradient optimization is used. Box with flanges, as a representative of a larger task, contained patches with a relatively low failure index, which also points to nonoptimal solution.

6) Optimization time ranged from minutes for one element to 14 hours for the galley with multiple load cases. Most of the time is spent on Jacobian evaluation, related to the number of failure constraints, thus time increases with number of candidate materials on the layup, the number of elements, and the number of load cases. Number of design variables also increases time, but not as significantly as was demonstrated by the panel where one large patch did not shorten the time as dramatically compared to the case without patches.

6 Conclusion

Theses described a new approach to sandwich optimization for the task of mass minimization with sandwich failure constraints. The method is based on Discrete Material Optimization (DMO), which applies the principles of multimaterial topology optimization to composite optimization. The method uses continuous design variables which converge to discrete values by the end of the optimization due to penalization.

Outcomes and contributions of the thesis:

1) The novelty of this approach is that it evaluates the gradients on elements separately and the interaction of the neighboring elements is carried out by the controlled evolution of the model. Gradient evaluation is separated from the FE model, which is theoretically less efficient, but enables to use an ordinary Nastran model which can contain common types of elements such as springs, RBE elements, etc.

2) Sandwich failure criteria within the concept of DMO require to deal with a combination of the candidate materials. Among sandwich failures, crimping and wrinkling were not found to be published previously in the scope of DMO.

3) The method was implemented as a Python program. It is able to deal with basic features such as: general Nastran input with shell elements in the optimization domain, multiple user-defined layups, multiple load cases, and patches.

4) Test examples were used to find robust default optimization parameters. It was shown that optimization is able to achieve a discrete solution without failure constraint violation or only slight violation.

5) Test example with concentrated load at one node revealed difficulties of the optimizer to converge due to locally high failures. This issue was successfully solved by defining a parameter which prescribes a small portion of the element failures to be ignored.

6) Examples demonstrated potential of the program for conceptual design of the sandwich structure layup. As a result, the workflow of a designer can change as shown in Figure 10, where the comparison with and without optimization is shown. Running the optimization program takes longer machine time, but modification of the optimization parameters is quick compared to manual layup modification and checking the results each time to satisfy requirements when the optimization program is not used.

The method can be further improved to fit a wider scope of engineering tasks. New manufacturing constraints can be added as they will be required by specific components. Implementation of the adjoint method for derivative calculation could help with additional requirements on displacement and buckling. Other potential for scientific work is in combination with different methods, such as GA, to decrease the risk of reaching a local minimum.

7 Literature

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8 List of symbols and abbreviations

A, A_{ign}	element area, relative ignored area
D	bending stiffness
DMO	Discrete Material Optimization
E, E_f	elastic modulus, effective face-sheet modulus
F	force vector
FE, FEA, FEM	finite element, finite element analysis, finite element method
FI, $FI_{\sigma, \tau, cr, wr}$	failure index for face-sheets, core shear, crimping, wrinkling
FSDT	First Order Shear Deformation Theory
GA	genetic algorithm
G_c	core shear modulus
i, i_{dc}, i_{max}	i-th candidate material, number of design cycles, number of optimizer iterations
IPOPT	Interior Point Optimizer
j	j-th layer, design cycle
k	k-th element, coefficient in the logistic function
k_{wr}	wrinkling coefficient
K	stiffness matrix
M	penalized mass in the goal function, bending moment
n_E, n_M, n_{MF}, n_{MC}, n_L	number of elements, materials, face-sheet materials, core materials
N, N_{cr}	linear load, critical load
p	penalization coefficient
PUR	polyurethane
PVC	polyvinyl chloride
q, $\tilde{q}$	distributed load, penalization coefficient
Q	shear force
Q, $\bar{\boldsymbol{Q}}$	layer stiffness matrix, layer stiffness matrix in element coordinate system
RAMP	Rational Approximation of Material Properties
RBE2, RBE3	Rigid Body Element
SIMP	Solid Isotropic Materials with Penalization
u	displacement vector
UD	uni-directional composite
t_c, t_f	thickness of the core, face-sheet
t_M,	thickness in goal function
x_{ijk}, x_{Tk}	material variable, thickness variable
Δ_{max}	allowable change of design variable per design cycle
ν	Poisson’s number
ρ, ρ_L, ρ_M	material density, layer density, density in goal function

9 Publications

Publication related to the thesis

Paper published in the journal with IF

- LÖFFELMANN, František. Discrete material optimization with sandwich failure constraints. *Structural and Multidisciplinary Optimization* [online]. 14 July 2021. [Accessed 30 August 2021]. DOI 10.1007/s00158-021-03006-x. Available from: https://link.springer.com/10.1007/s00158-021-03006-x

Other publications not directly related to the thesis:

Conference papers indexed in Scopus

- LÖFFELMANN, F. Failure Index Based Topology Optimization for Multiple Properties. In *Engineering Mechanics 2017. Engineering mechanics 2014.* 1. konference Engineering Mechanics 2017, Svratka, ČR: Brno University of Technology, 2017. s. 590-593. ISBN: 978-80-214-5497-2. ISSN: 1805-8248. Available at: https://www.engmech.cz/improc/2017/0590.pdf
- LÖFFELMANN, F.; ŠPLÍCHAL, J. Design Study of the Heat Switch Base Plate with Single and Multi-material Topology Optimization. In *13th Research and Education in Aircraft Design Conference.* 2018. s. 85-97. ISBN: 978-80-214-5696-9. Available at: https://dspace.vutbr.cz/bitstream/handle/11012/137297/READ-2018-09.pdf?sequence=1&isAllowed=y

Conference paper

- LÖFFELMANN, F. Stress Distribution Investigation at the Tapered Sandwich Endings. *Transactions of the Institute of Aviation*, 2018, roč. 2017, č. 4(249), s. 62-79. ISSN: 0509-6669. Available at: http://ilot.edu.pl/eng_prace_ilot/?list_of_transactions/249_2017/5.html

10 Curriculum Vitae

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Year of birth: 1989

Education

2014-2021	Ph.D. study Brno University of Technology, Faculty of Mechanical Engineering Institute of Aerospace Engineering Subject: Design, stress analysis and limit load of sandwich structures
2012-2014	Master’s degree Ing. Brno University of Technology, Faculty of Mechanical Engineering Institute of Aerospace Engineering Specialization: Aircraft Design
2009-2012	Bachelor’s degree Bc. Brno University of Technology, Faculty of Mechanical Engineering Specialization: Mechanical Engineering
2005-2009	Technical lyceum VOŠ a SPŠE Plzeň

Internships

2017	3 month, Alkmaar, The Netherlands Zodiac Galleys Europe
2016	6 month, Stockholm, Sweden KTH, Lightweight Structures, Aeronautical and Vehicle Engineering
2014	5 weeks, Kunovice 5M s.r.o.
2013	7 weeks, Hradec Králové TL-Ultralight s.r.o.