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MULTILEVEL OPTIMIZATION OF VARIABLE THICKNESS COMPOSITE STRUCTURES MADE BY PATCHES

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Abstract

Quilted Stratum Process® (QSP®) is a multi-step fabrication process made by CETIM for high volume and production rate of thermoplastic composites. The purpose of this work is to develop a design method for structural parts made by QSP®. The proposed method is composed of three phases: a first phase to create a base optimized design, a second phase to construct a patch library, and a third phase to design the QSP® solution from this library. The method is applied to the buckling maximization of a simply supported plate under uniaxial compression. The critical buckling load of the final QSP® solution is about twice higher than the best constant-stiffness design.

1. Introduction

This study focuses on the development of a design method for the Quilted Stratum Process® (thereafter QSP®) made by CETIM. QSP® produces net-shape thermoplastic composite parts with a very short cycle time. The process is composed of four main stages. In the material manufacturing stage, unidirectional or 2D woven composite tapes are built by pultrusion. Alternately, other finished products such as organosheets, can be provided. The patch library setup: from the base material, patches are cut in different shapes by a cutting machine. The preform assembly: patches are then positioned at different assembly stores. Next, a conveyor system is responsible of carrying them in an orderly fashion to the welding station. Finally, the parts manufacturing stage: once this preform is fully assembled, the preform is heated using an aggregate of infrared and conduction heating devices. This preform is then moved by a robot to a hot press where it is thermoformed. This work focuses on stages two and three as shown Figure 1, which are directly concerned by the design of the preform..

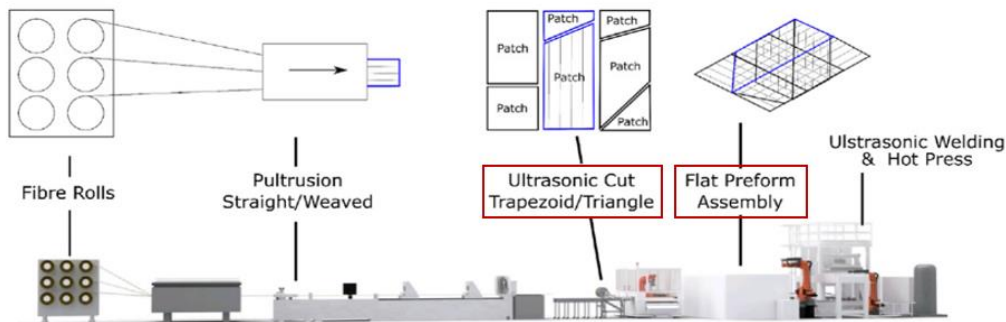


Figure 1. The QSP Process. Stages two and three surrounded in red.

The patch design problem is combinatorial and implies both discrete and continuous variables that define the number of patches, their shape and size and in-plane position, their stacking order, and their material, thickness and material orientation. These many variables define a complex optimization problem, which is very difficult to solve directly in one step only [1], [2], [3]. The multilevel framework is an efficient framework to tackle such problems [4] which is adopted in the present work. This method decomposes the original design problem into a sequence of simpler ones to. A first optimization step gives an homogenized optimized design, from which zones of similar properties are identified. The shapes and sizes of these zones are subsequently simplified to obtain an explicit description of physical composite patches and an optimized design manufacturable by QSP®.

2. General overview of the optimization method

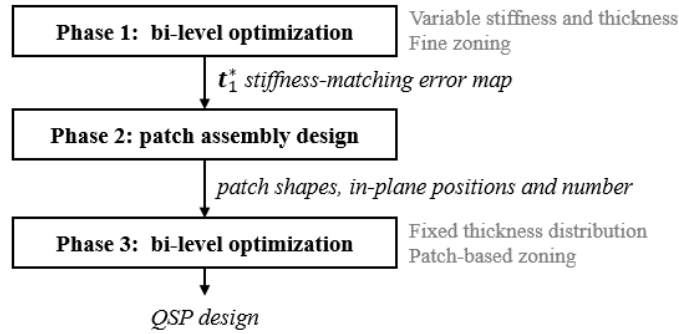


Figure 2. General diagram of the global optimization method

In its most general form, the global optimization problem considered here can be written as follows :

$$\begin{aligned}
 & \max_{\mathbf{x}} f(\mathbf{x}) \\
 \text{s.t. } & m(\mathbf{x}) \leq m_0, \\
 & q_r(\mathbf{x}) \leq 0 \quad \text{with } r = 1, \dots, R, \\
 & g_l(\mathbf{x}) \leq 0 \quad \text{with } l = 1, \dots, L, \\
 & \mathbf{x} \in \mathbf{X}.
 \end{aligned} \tag{1}$$

where $f(\mathbf{x})$ represents the objective function, here related to mechanical performance, such as buckling, \mathbf{x} is a vector of the optimization variables describing the patched preform, $m(\mathbf{x})$ is the resulting mass, m_0 is a reference mass, $q_r(\mathbf{x})$ are the design rules and finally $g_l(\mathbf{x})$ represent the mechanical constraints. It is assumed in this work that all patches are cut from the same base material, thus they all share the same material properties and thickness.

The proposed design method is outlined in Figure 2. It is composed of 3 main phases. Phase 1 and Phase 3 follow a bilevel optimization scheme consisting in a first continuous optimization step followed by a discrete one. The continuous optimization step allows to define a target design with optimized structural performance. A gradient-based optimization is done, which results in an idealized target described by homogenized stiffness and total thickness distributions. This optimization step is based on the use of lamination parameters to parametrize the homogenized stiffness of the laminates. Lamination parameters are employed since they offer several advantages such as being independent of the number of layers of the laminate and defined in a convex and continuous design space. Membrane, bending and coupling behaviour can be described by 4 lamination parameters each, forming a total of 12 lamination parameters taking values in the $[-1,1]$ interval. For preliminary design optimization, the problem can be simplified by assuming uncoupled laminate behaviour with orthotropic membrane and bending properties, in which case the number of non-zero parameters is reduced to 4 (V_1^A, V_3^A, V_1^D and V_3^D):

$$\begin{aligned} V_{i=1,2,3,4}^A &= \int_{-1/2}^{1/2} (\cos 2\theta, \sin 2\theta, \cos 4\theta, \sin 4\theta) d\bar{z}, \\ V_{i=1,2,3,4}^D &= 12 \int_{-1/2}^{1/2} \bar{z}^2 (\cos 2\theta, \sin 2\theta, \cos 4\theta, \sin 4\theta) d\bar{z}, \end{aligned} \quad (2)$$

Where V_i^A , and V_i^D are the membrane and bending lamination parameters respectively, $\theta(\bar{z})$ represents the ply orientation function in the laminate thickness direction and \bar{z} is the normalized thickness coordinate. The continuous optimization problem can be defined as :

$$\begin{aligned} &\max_{\mathbf{t}, \mathbf{V}} f(\mathbf{t}, \mathbf{V}) \\ \text{s.t. } &m(\mathbf{t}) \leq m_o, \\ &\mathbf{V} \in \Omega_V, \\ &\mathbf{t} \in [t_{min}, t_{max}]^{n_z}, \end{aligned} \quad (3)$$

where \mathbf{t} is the thickness distribution of the structure, \mathbf{V} stands for the lamination parameters distribution, Ω_V is the domain of existence of the lamination parameters [5], and n_z corresponds to the number of zones into which the structure is subdivided. The main difference between the continuous optimization steps in Phase 1 and Phase 3 lies in the zoning definition. In Phase 1, the zoning is free. A zone is defined as a set of one or several finite elements. The design zones can be regularly distributed over the part surface. Their size and number results from a trade-off between the design freedom and the optimization cost. The zoning can also reflect a priori knowledge of the designer, or specific design constraints on the boundary of the part. In Phase 3, the zoning and the thickness distribution result from the patches defined in Phase 2.

The discrete optimization step aims at defining the patch stacking order and the material orientation for each patch. Thus, the total thickness distribution is fixed. A stiffness-matching optimization problem is stated as follows:

$$\min_{\mathbf{X}_1, \mathbf{X}_2} \frac{\sum_{k=1}^{n_z} d_{ABD}(\mathbf{ABD}_k, \mathbf{ABD}_k^*)}{n_z} \quad (4)$$

where \mathbf{ABD}_k represents the stiffness matrices in each zone k of the current design, and \mathbf{ABD}_k^* is the optimized target stiffness matrices from the continuous optimization step. \mathbf{X}_1 is an integer vector that defines the stacking order of the n_p patches. \mathbf{X}_2 is an integer vector that defines the material orientation of the patches. d_{ABD} is a measure of the difference between two stiffness tensors. It reads :

$$d_{ABD}(\mathbf{C}_1, \mathbf{C}_2) = \text{Tr}(\mathbf{C}_1^{-1} \cdot \mathbf{C}_2) + \text{Tr}(\mathbf{C}_1 \cdot \mathbf{C}_2^{-1}) - 12 \quad (5)$$

Patches are represented as sets of elements to make the correspondence with the finite element model used in the continuous optimization model. The discrete optimization is solved with an evolutionary algorithm.

In Phase 1, the optimized continuous thickness distribution is rounded and sliced into a finite number of plies that can cover the whole surface of the part or only part of it. Each ply is assigned a single material orientation. The optimized discrete design gives a straight-fiber blended solution which could be manufacturable, provided the shapes of the plies can actually be handled. Phase 2 makes use of the stiffness-matching error map to subdivide the plies into patches, as explained in the following section. Indeed, the optimized discrete design from Phase 1 is likely to differ significantly from the continuous target, which will often be caused by the assignation of a single orientation to a given ply, whereas in the continuous design, each element may have different stiffness.

3. Patch assembly construction

Phase 2 aims at designing the number, shape, size and in-plane position of the patches based on the results issued from Phase 1, i.e. the optimized homogenized design and the optimized discrete design. The patch is the basic element from which the flat QSP preform is assembled and then thermoformed. The patch is defined by its shape, size, material, and material orientation within the patch. In this work, all patches share the same predefined material. The shape, size and in-plane position of the patch within the preform are simultaneously designed in Phase 2 by subdividing the plies formed by the slicing operation in Phase 1. The purpose is twofold. One the one hand, the plis that only partially cover the part are subdivided into patches in order to match the target thickness distribution, while taking into account manufacturing constraints on the shape of the patches. One the other hand, plies that completely cover the part are subdivided to improve the stiffness matching by refining the zoning of the part.

The first step in defining the patches consists in forming sets of connected elements in the FE mesh of the part. Each ply that partially covers the part directly corresponds to one zone or several unconnected zones. In the case of plies that completely cover the part, the subdivision is based on the quality of the stiffness matching.

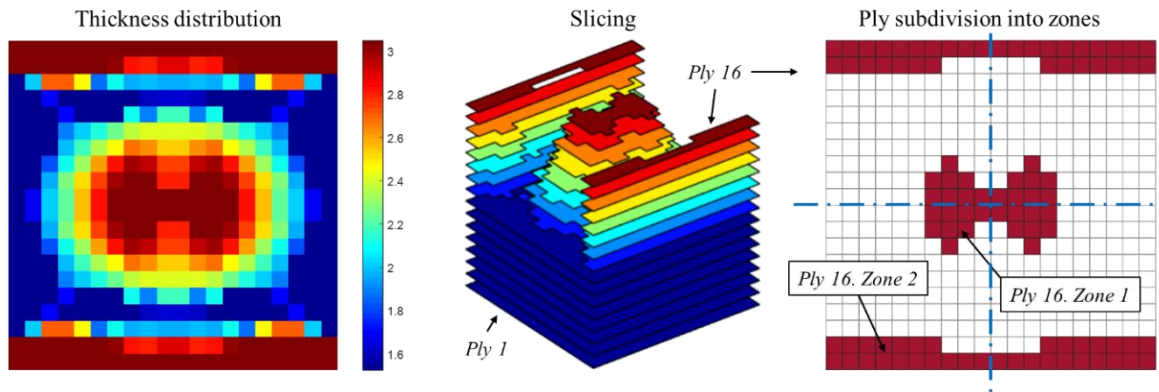


Figure 3. Slicing of a target thickness distribution (mm). Ply definition and subdivision of the plies into zones. Axes of symmetry are taken into account in definition of the zones.

The elements with a stiffness matching error d_{ABD} (ABD_e, ABD_e^*), with e the index ranging over the elements, superior to the median value of the error over the complete model are identified and used to form a set of zones that contribute significantly to increase the global stiffness matching

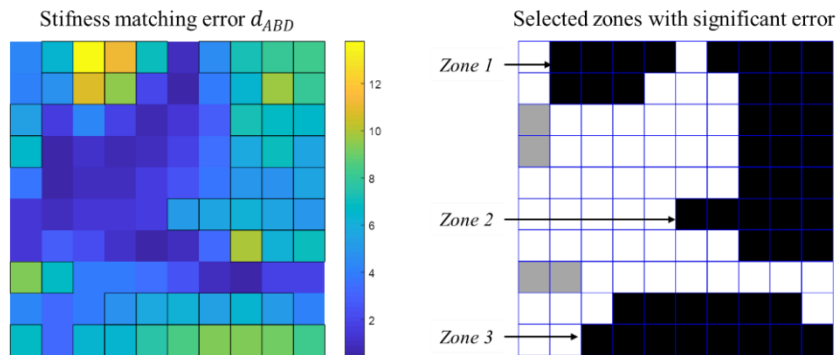


Figure 4. Clustering of the mesh based on the local stiffness matching error value (median value is 4.39). Small areas represented in grey are discarded. Focus on the lower left quarter of the plate.

Each zone is treated separately. Small zones are discarded, based on constraints on minimal area and dimensions for the patch. One patch is formed for each remaining zone, based on its bounding box. The size of the patch is then reduced to match the volume of the zone, based on the optimized thickness distribution from the continuous optimization in Phase 1. This enables to preserve the mass of the target design and avoid errors due to rounding the thickness distribution to interger number of plies. If the patch does not contain any border of the part, an homothethy is performed with respect to the center of the patch. If the patch overlaps the border of the part, these are preserved as much as possible. In this case an optimization problem is set, whose design variables are the planar coordinates of the vertex of the rectangular patch. The bounds of the design variables are defined on the one hand by the coordinates of the vertex of the bounding box of the zone and on the other hand from the coordinates of the ordered set of nodes \mathbf{B} that belong both to the patch and to the border of the part. Either the target volume can be matched within these bounds, or not. In that second case, the extremal nodes of \mathbf{B} are iteratively discarded to to increase the design space until the target volume can be reached. Finally, for each patch corresponding to a zone of high stiffness matching error, complementary patches are defined to cover the full part. These complementary patches are obtained by extending the straight edges of the patch to complete to the the edges of the bounding box of the part.

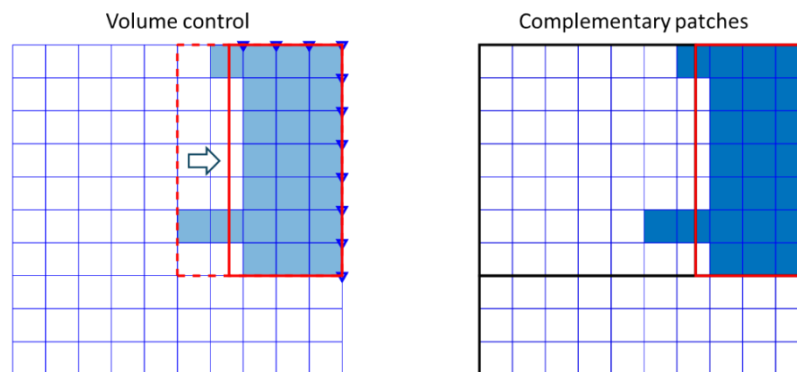


Figure 5. Illustration of the volume control process. One boundary node is discarded to match the target volume. The patches plotted in black solid lines are complementary to the one plotted in red.

4. Numerical example : plate buckling maximization of under uniaxial compression

The method is applied to the buckling maximization under mass constraint of a simply supported square composite plate subjected to uniaxial compression. The two edges where the load is applied remain straight. The x and y translations of the central node of the plate are blocked. The plate's base ply is orthotropic with the following material properties : $E_{11} = 181$ GPa, $E_{22} = 10.3$ GPa, $G_{12} = 7.17$ GPa and $\nu_{12} = 0.28$. The mesh is composed of 400 quadrangular shell elements. An offset is defined so that the shell elements bottom surface and the plane defined by the element nodes are coplanar. The symmetry of the plate is enforced through the definition of the zones, but the full plate is modeled to capture antisymmetrical buckling modes.

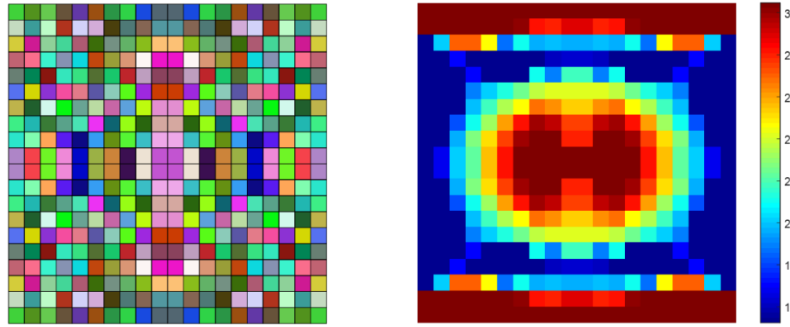


Figure 6. Initial zoning and optimized thickness (in mm) from Phase 1 continuous optimization.

Phase 1 initial zoning and the optimized thickness distribution obtained from continuous optimization are presented in Figure 6. The result of the stiffness matching optimization of Phase 1 is illustrated in Figure 7, where the values of first membrane and bending lamination parameters are shown for the elements of the mesh, sorted in ascending order of total thickness (4 lamination parameters are used in the optimization to represent orthotropic materials). Values obtained after continuous optimization are shown in red while the discrete optimized values are shown in blue. First, the figure highlights that zones of equal thickness can show significantly different values of lamination parameters in the continuous solution, which is not possible in the discrete solution since stiffness variations can only be achieved by adding or removing plies. Second, the lamination parameter values can change abruptly between zones in the continuous solution. In the discrete design, the amplitude of the transition is directly related to the variation of number of plies. The purpose of Phase 2 is thus to increase the design freedom for the discrete design by subdividing the plies into zones with different material orientations

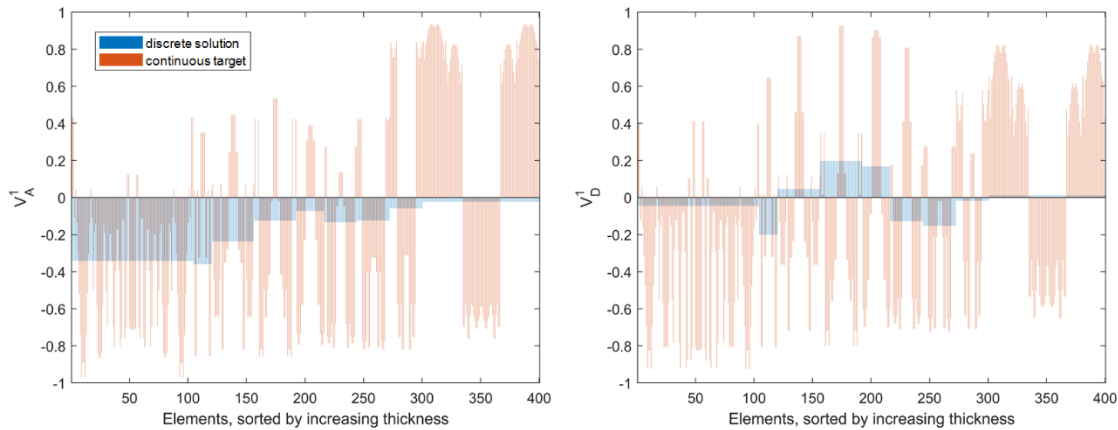


Figure 7. Phase 1. Lamination parameters V_A^1 and V_D^1 of the target solution (in red) and the discrete blended solution (in blue). Elements are sorted in ascending order of total thickness.

In Phase 2, the plies are subdivided into patches of rectangular shapes. The stacking of the patches defines a new global zoning of the part, shown in Figure 8. In this case, the proposed method results in 42 patches that form 8 types of plies that partially cover the plate. 16 plies form the plate. 8 plies completely cover the plate. In the following, 3 of these plies are subdivided and 5 plies are kept uniform to ensure the structural continuity of the part. The stacking of these plies form 47 zones with different laminates at the global scale of the part. The symmetry of the plate is taken into account in the definition of the zones.

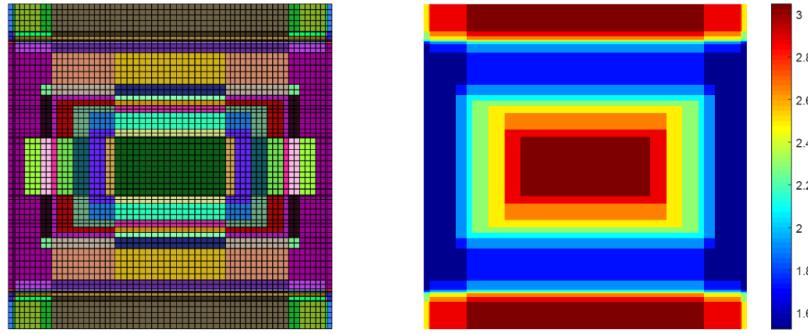


Figure 8. Resulting zoning and thickness distribution (in mm) from Phase 2.

In Phase 3, in the continuous optimization step, the thickness distribution is fixed and completely defined by the stacking of the plies. The subsequent discrete optimization step aims to find the ply stacking order and the orientations of the patches. Figure 10 presents the obtained lamination parameter distributions. Compared to Figure 7, the matching is significantly improved. By subdividing the plies into patches of different orientations, the discrete design shows variations of lamination parameters between zones with the same thickness. The amplitude of the variations depends on the fineness of the subdivision of the plies into patches. There is a trade-off between the accuracy of the stiffness matching and the complexity of the preform. More patches of smaller areas will result in a better matching, but the continuity of the laminates in the part will be degraded and the preform will be more complex to assemble and manipulate.

The final design is illustrated in Figure 11. It is encoded in the evolutionary algorithm by the interger vectors shown in Figure 9, where X_1 refers to the type of plies and X_2 refers to the orientations of the patches, taken in the set $\{-75, -60, \dots, 90\}$. The summary of the optimization phases is presented in Table 1. Optimization evolution summary. The discrete designs are evaluated using a layerwise description of the shells, so that all material couplings are taken into account, whereas the continuous model is based in the simplifying assumption that the material is orthotropic and does not take into account the transverse shear stiffness. The reference design is the best constant stiffness design for the considered test case. The discrete solution at the end of Phase 1 uses ply shapes that would be very difficult to manufacture. The critical buckling load of the final QSP solution is about 96 % higher than the reference design.

$$X_1 = [5 \quad 6 \quad 11 \quad 1 \quad 12 \quad 1 \quad 1 \quad 3 \quad 1 \quad 2 \quad 9 \quad 1 \quad 10 \quad 4 \quad 8 \quad 7]$$

$$X_2 = \begin{bmatrix} 15^\circ & -15^\circ & -15^\circ & 60^\circ & 90^\circ & -45^\circ & -75^\circ & 0^\circ & 60^\circ & -75^\circ & 0^\circ & -60^\circ & 30^\circ & 0^\circ & 15^\circ & -30^\circ \\ 60^\circ & -60^\circ & -60^\circ & 0^\circ & 45^\circ & -30^\circ & 15^\circ & 60^\circ & 90^\circ & 45^\circ & 60^\circ & 15^\circ & 60^\circ & -45^\circ & 60^\circ & -75^\circ \end{bmatrix}$$

Figure 9. Optimal design. Ply stacking order and patch orientations within the plies.

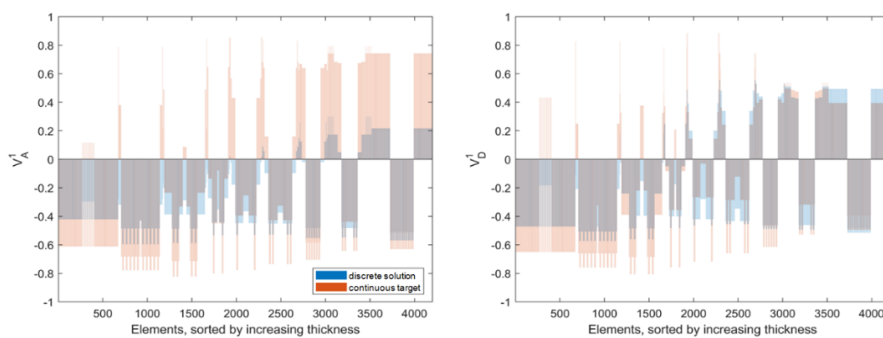


Figure 10. Phase 3. Lamination parameters V_A^1 and V_D^1 of the target solution (in red) and the discrete blended solution (in blue). Elements are sorted in ascending order of total thickness.

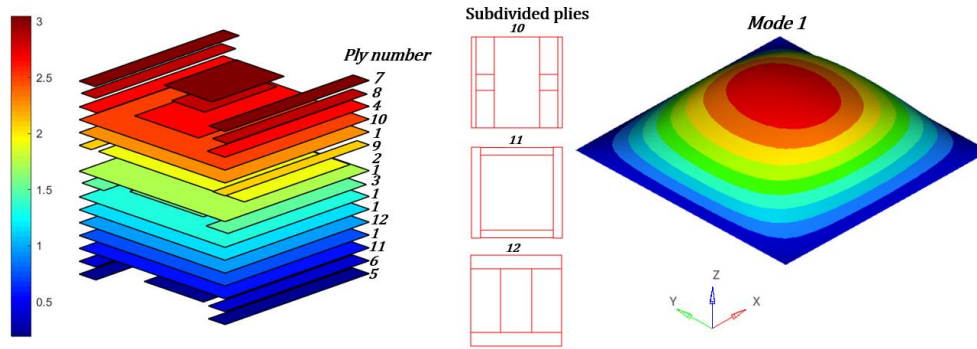


Figure 11. Final QSP design: patch assembly (left) and shape of the critical buckling mode (right).

Table 1. Optimization evolution summary.

Optimization step	λ^*/λ_0	m/m_0
Reference 12 plies solution $[(\pm 45)_3]_s$	1.00	1.00
Phase I. (homogenized solution)	3.90	1.00
Phase I. (Discretized solution)	1.46	1.00
Phase III. (homogenized solution)	3.39	1.00
Phase III (final QSP design)	1.96	1.00

5. Conclusions

This paper presents an optimization method for the design of patched composite laminates for the QSP® manufacturing process. The design problem is decomposed and solved in a succession of simpler optimization problems. In Phase 1, a continuous target design is computed and sliced to form a first set of plies with free shapes. In Phase 2, these plies are simplified to form a patch library arranged in layers. Phase 3 returns a QSP design defined by a stacking of rectangular patches, with their sizes, positions and material orientations. The method is applied to the buckling maximization of a simply supported plate under uniaxial compression, with promising results. Some of the limits of the presented method concern the shape of the patches. Even though rectangular shapes are adapted to QSP®, other forms could be included such as trapezoids, which could be useful for building complex geometry shapes, while minimizing the number of patches and the material waste. Strength-related design guidelines could also be introduced to constraint the patch layout.

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