Continuous Curvilinear Variable Stiffness design for improved strength of a panel with a cut-out

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Abstract

Continuous curvilinear variable stiffness (CCVS) is presented as a novel solution to improve the load carrying capacity of a fuselage panel with a cut-out. The CCVS technique allows for the tow paths to curve around cut-outs of arbitrary geometry with initial fiber angle and geometry as design inputs. An optimum CCVS design is generated using a genetic algorithm method coupled with a finite element model in NASTRAN and the results are compared with those obtained using a quasi-isotropic laminate. The optimized CCVS laminate is found to improve the load carrying capacity compared with the quasi-isotropic design by 57%.

Keywords: Continuous Curvilinear Variable Stiffness (CCVS); Finite Element Model (FEM); Genetic Algorithm (GA); Failure Index (FI); composite laminates.

1. Introduction

Automated fiber placement (AFP) allows for precise placement of fibers using robotic or gantry-based systems that help develop low-cost and lightweight optimized structures. The automated technology allows for accurate plies placement according to CAD data, which helps fully utilize the directional properties of composite materials. Tailoring fibers along a non-straight path cause the fiber orientation, and thus, properties such as stiffness vary spatially, resulting in a variable stiffness (VS) design [1]. The introduction of VS in a laminate design creates novel characteristics and the potential for significantly improving its load carrying capacity in different applications.

A major concern in the design of aircraft fuselage load bearing skin panels is the inclusion of windows and cut-outs, which introduce large discontinuities in the structure. As most of the cabin internal pressure load is carried by the fuselage skin, it is necessary to optimally design cut-out areas to reduce stress concentrations. Typically, these regions are reinforced with doublers or reinforcements, thereby locally increasing their stiffness. As such, the concept of tailoring fiber paths around a cut-out in a composite laminate can create the same effect without adding weight and is an interesting optimization problem. In composites design, these cut-outs and openings would introduce breaks in the continuity of fiber paths, thereby significantly increasing stress concentrations in their vicinities. A VS design could be used to tailor the fibers around the opening rather than cutting them, thus improving the performance of the part with these cut-outs.

Several studies investigated tailoring composite laminates around cut-outs using a VS approach under various loading conditions. Two studies completed by Jegley et al. [2, 3] are particularly interesting as a flat panel with a circular cut-out was tailored to reduce the stress concentration around the hole and improve the load carrying capacity. The results demonstrated that the buckling load was 18% higher and the ultimate failure was 15% higher relative to the baseline, i.e., a quasi-isotropic laminate. The VS concept was applied to an ovoid fuselage cut-out undergoing an axial compression by Wu et al. [4]. The cylindrical shell with cut-out maintained at 91% of the axial stiffness when tested in compression and 85% of the buckling load when compared with the case with no cut-out. Large deflections were measured radially outward in the cut-out region compared with the no cut-out case. Furthermore, there were no comparisons to a quasi-isotropic laminate. Improving the load carrying capacity of a fuselage with cut-out was further investigated by Alhajamad et al. [5]. The buckling and first ply failure were explored on a fuselage cut-out undergoing internal pressure and shear loading. A finite element analysis (FEA) was conducted in ABAQUS: the results proved that the VS design did not improve the load carrying capacity compared with a quasi-isotropic laminate.

One reason could be that in [5] the fibers break at the cut-outs and are not continuously placed around the holes leading to stress concentrations and reduced stiffness. A technique to prevent the fibers breaking at the cut-out was first demonstrated by Yau and Chou [6], who created continuous fibers around holes by inserting metal pins into woven fabric prior to curing. The resulting moulded-in laminate was shown to have a marked improvement, in tension and compression, over the one with drilled holes. A similar technique was utilized in a study conducted by Durante and Langella [7], where an improvement of 15% in bearing strength was found when the fibers curved around the pin. Although there was an improvement, the manufacturing method was complex and there were significant variations in test results. A major issue found with the inserted pin technique is that the resulting large gap around the hole leads to complex laminate behavior that cannot be accurately predicted. A preliminary design approach was undertaken by Hyer and Lee [8], in which they used a gradient search and sensitivity analysis technique with a finite element method (FEM) to improve buckling performance of a centrally located circular cut-out undergoing compression loading. A significant improvement in the buckling load was observed; however, the resulting design was not manufacturable. Huang and Haftka [9] repeated the study with a tension loading and a similar optimization approach. The results demonstrated that the fiber angles follow a concentric path around the hole, while tending to the far field fiber directions far from it. Tailoring of the fiber paths around a hole was also examined by Lopes et al. [10] to increase the buckling and first ply failure of a composite plate with a centrally located circular cut-out; however, they considered discontinuous VS paths. The results also indicated that the optimally placed tows would tend to steer around the cut-out. Montemurro and Catapano [11] used a B-Spline and a hybrid global-local optimization approach to optimize a panel with a centrally located circular cut-out undergoing a biaxial tension loading. The results of the most optimal ply demonstrated that the fiber directions tended to curve around the cut-out as well. Furthermore, a study on bolted composites by Gustafson [12] using FEM demonstrated that aligning fibers along the principal stress directions can improve the failure load from 36% to 64% when compared with a quasi-Isotropic laminate. The resulting streamline plot of the fiber paths demonstrated that they tended to continuously curve around the bolted regions.

The results of the above studies indicated that an optimal fiber path would be a continuous one steered around the cut-out. A common analogy, often used for describing stress concentrations around circular open holes, is one of a fluid flow around a cylinder as the fluid streamlines tend to flow over a surface smoothly, taking the path of least resistance. Fluid Flow can be modeled using potential theory to generate continuous fiber paths and was utilized by Khan et al. [13], where the analytical solution to the fluid flow around a cylinder generated the load paths for potential improvements in open-hole tensile strength and failure strain of specimens per ASTM D5766. The fused filament fabrication technology of pure thermoplastics was selected as the manufacturing technique. The results were promising because the improvement in strength for a larger hole diameter (W/D = 2) was 38% and that in failure strain for a smaller hole (W/D = 4) was 52.5% compared with the constant stiffness design. They mentioned that the performance improvement is expected to increase once continuous carbon fiber composites are employed.

The potential theory has proved useful for the generation of fiber paths in other studies as well. A potential theory concept, known as Circulation, was utilized by Brooks and Martins [14] to predict the existence of gaps and overlaps. Circulation is considered as the number of streamlines, or in this case fibers, passing through an arbitrary volume. Using Circulation, the authors could predict the existence of gaps and overlaps analytically by determining whether the density of fibers entering an arbitrary control volume matched the exiting volume. Hao et al. [15] investigated potential field fluid flow equations and their use for generating complex VS laminates. Potential theory can also be used to generate trajectories around circular objects as previously mentioned by Khan et al. [13]. However, not all discontinuities are circular in nature, and therefore, it is necessary to create a methodology that can address arbitrary geometries.

In this study, continuous curvilinear variable stiffness (CCVS) design is applied to a fuselage panel with a cut-out undergoing internal pressure and compressive loading to improve its total load carrying capacity compared with a quasi-isotropic laminate. A part might undergo a loading scenario which does not correspond exactly to the one used during the design and optimization stage (off-design conditions). Although improvements from VS design lessen under off-design conditions, the optimum design is found for the aforementioned design loads. The reason is twofold: This research paper focuses on deriving a numerical methodology for generating continuous trajectories around cut-outs with arbitrary geometries; and the strength (not the buckling load) is considered as the design objective, which is less sensitive to off-design conditions [16-17].

In this study, a numerical methodology derived from potential theory, known as source panel method [18], is used to generate the fiber paths around the fuselage window cut-out using MATLAB subroutines. Fiber orientation in each point is passed to a FEA code in NASTRAN to evaluate failure indices (FIs). A surrogate-based genetic algorithm (GA) developed in MATLAB will then determine the optimum trajectories for CCVS design. Finally, the performance of the optimum CCVS design will be compared with a quasi-isotropic laminate.

2. Methodology

Potential functions have shown to be powerful tools for effectively determining load paths around circular cut-outs [13]. For these cut-outs, the load paths can simply be computed using the analytical solution for a cylinder in a uniform flow [13]. For more complex geometries, it is challenging to determine an analytical solution, as none may exist. Therefore, for arbitrary geometries a numerical method, known as source panel method, can be applied to determine the flow trajectories [18].

The source panel method is a finite element (FE) formulation in which the geometry is discretized by a finite number of flat panels. The superposition of all these elements would then allow for the generation of the load paths by interpolating over a mesh. Each element is known as a source panel, which emits a potential Q[18] (Figure 1).

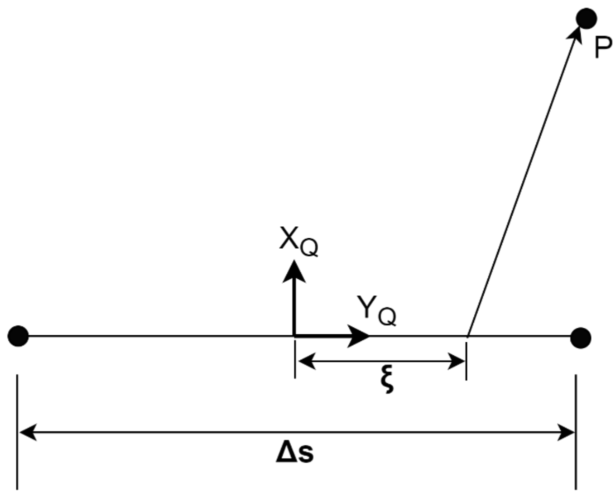


Figure 1. Schematic of a single panel in the X_Q Y_Q refrence frame [18].

The components of the trajectory can be calculated at any point, P using Eq. (1), where $X_Q$and Y_Q are the x,y axis in the reference plane of the panel of span Δs and source strength Q. For simplicity, the refrence point is always taken from the midpoint of the panel, as shown in Figure 1. Because the contribution of the total panel is necessary, the integration of the total panel is taken with each arbitrary distance along the panel represented by ξ and the midpoint. The resulting components of the trajectory components are then given by v_{Y_Q} and v_{X_Q} oriented in the reference frame of the panel (Eqs. (2) and (3)).

$$\phi_{PQ} = \int_{-\frac{\Delta s}{2}}^{\frac{\Delta s}{2}} ln\sqrt{(x_Q - \xi)^2 + y_Q^2} d\xi \tag{1}$$

$$v_{Y_Q} = \frac{\partial \phi_{PQ}}{\partial y_Q} = Q \int_{\frac{\Delta s}{2}}^{\frac{\Delta s}{2}} \frac{y_Q}{(x_Q - \xi)^2 + y_Q^2} \delta\xi = -\frac{1}{2} Q \ln \left(\frac{\left(x_Q + \frac{\Delta s}{2}\right)^2 + y_Q^2}{\left(x_Q - \frac{\Delta s}{2}\right)^2 + y_Q^2} \right) \tag{2}$$

$$v_{X_Q} = \frac{\partial \phi_{\mathrm{PQ}}}{\partial x_Q} = Q \int_{\frac{\Delta s}{2}}^{\frac{\Delta s}{2}} \frac{x_Q - \xi}{(x_Q - \xi)^2 + y_Q^2} \delta\xi$$

$$= -Q\left(\tan^{-1}\left(\frac{x_Q + \frac{\Delta s}{2}}{y_Q}\right) - \tan^{-1}\left(\frac{x_Q - \frac{\Delta s}{2}}{y_Q}\right)\right) \tag{3}$$

To pass from the X_Q, Y_Q panel reference frame to the global reference frame, a transformation function is used in Eq. (4), where θ_{xy} is the angle measured from the global x-axis. The inverse of this function is used to transform into the panel reference frame.

$$\overrightarrow{v_{xy}} = \begin{bmatrix} cos\theta_{xy} & sin\theta_{xy} \\ -sin\theta_{xy} & cos\theta_{xy} \end{bmatrix} \begin{bmatrix} v_{X_Q} \\ v_{Y_Q} \end{bmatrix} \tag{4}$$

The geometry of the cut-out can now be discretized as a series of N panels, as illustrated in Figure 2. A collocation point for each panel needs to be determined, which, for simplicity as previously mentioned, is considered as the midpoint of each panel. At the collocation point of each panel, the normal and tangential vectors, $\widehat{n_\iota}$ and $\widehat{t_\iota}$, are found with respect to the global X,Y system.

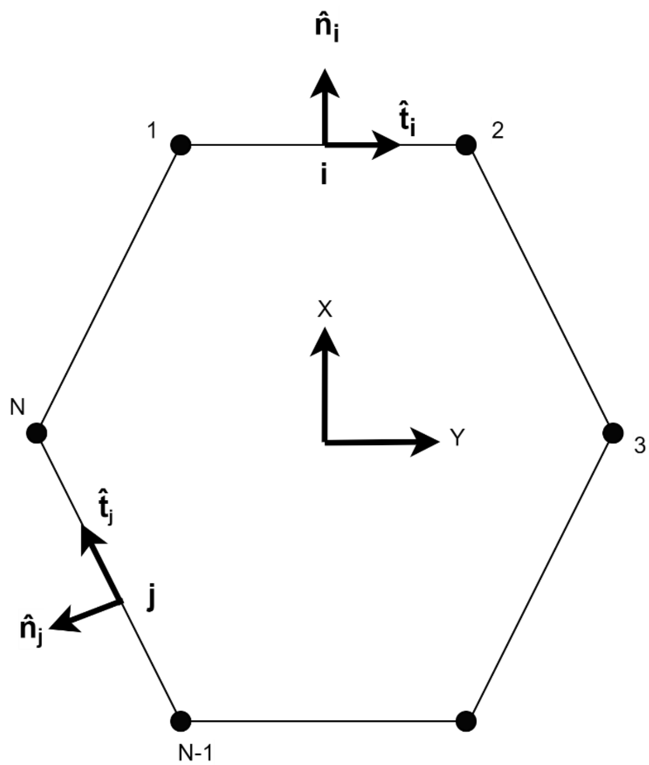


Figure 2. Discretized cut-out with Reference Frame

Because the superposition of the influences of each panel on others induces a trajectory, v_{ij}, at each corresponding panel, these influences need to be cancelled out to complete the boundary around the cut-out. To reduce the contributions of the trajectories to zero, the summation of all influences of the normal component of each panel and the summation of the ply angle, U, are considered in Eq. (5), where σ_j is the source strength Q of each panel and $\overrightarrow{v_{n_i}}$ is the total summation of the normal components of the trajectories at the collocation point of each panel.

The contribution, $\overrightarrow{v_{ij}}$, is calculated using Eqs. (2) and (3), while transformation between reference frames is completed using Eq. (4).

Setting $\overrightarrow{v_{n_i}}$ to zero results in a system of equations with N unknowns to solve for each σ_j in Eq. (7).

$$\overrightarrow{v_{n_i}} = \sum_{j=1}^{N} \sigma_j \left(\overrightarrow{v_{ij}} \cdot \widehat{n_i} \right) + \vec{U} \cdot \widehat{n_i} = 0 \tag{5}$$

$$\sum_{j=1}^{N} \sigma_j \left(\overrightarrow{v_{ij}} \cdot \widehat{n_i} \right) = -\vec{U} \cdot \widehat{n_i} \tag{6}$$

$$\begin{bmatrix} \overrightarrow{n_1} \cdot \overrightarrow{v_{11}} & \cdots & \overrightarrow{n_1} \cdot \overrightarrow{v_{1N}} \\ \vdots & \ddots & \vdots \\ \overrightarrow{n_N} \cdot \overrightarrow{v_{N1}} & \cdots & \overrightarrow{n_N} \cdot \overrightarrow{v_{NN}} \end{bmatrix} \begin{bmatrix} Q_1 \\ \vdots \\ Q_N \end{bmatrix} = \begin{bmatrix} -\overrightarrow{n_1} \cdot \vec{U} \\ \vdots \\ -\overrightarrow{n_N} \cdot \vec{U} \end{bmatrix} \tag{7}$$

Once the panel strength values are known, the trajectory of any arbitrary point can be found as the summation of influences of each panel on that point along with the contribution from the ply angle as seen in Eq. (8), where $\overrightarrow{v_{xy_{Q_i}}}$ is the trajectory induced at point (x, y) by panel Q_i and v_P is the trajectory at that point.

$$v_P = \sum_{i=1}^{N} \overrightarrow{v_{xy_{Q_i}}} + \vec{U} \tag{8}$$

3. Modeling and Analysis

In this section, the case study and mathematical formulation for calculating the fiber trajectories, FE modeling, and optimization formulation are presented.

3.1.Fiber Trajectories

A MATLAB subroutine was developed for calculating the trajectories. The inputs were the initial flow angle, representing the ply angle, and a matrix containing the element centroid coordinates. The cut-out was discretized into 100 source panels, as shown in Figure 3, after which the normal and tangential vectors were determined at the collocation point of each panel, as illustrated in Figure 4. Once this was completed, the σ_j matrix was determined to evaluate the strength value of each panel and the trajectory can be calculated at each element centroid. The examples of the load paths generated around the cut-out can be seen in Figure 5; they were generated using the methodology described by Khan et al. [13].

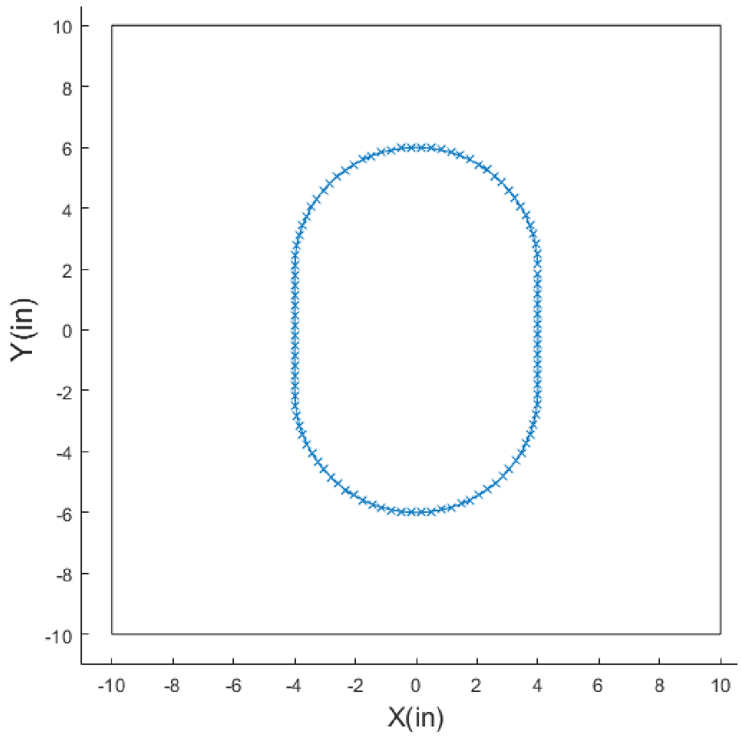


Figure 3. Discretized fuselage cut-out: panels and collocation points.

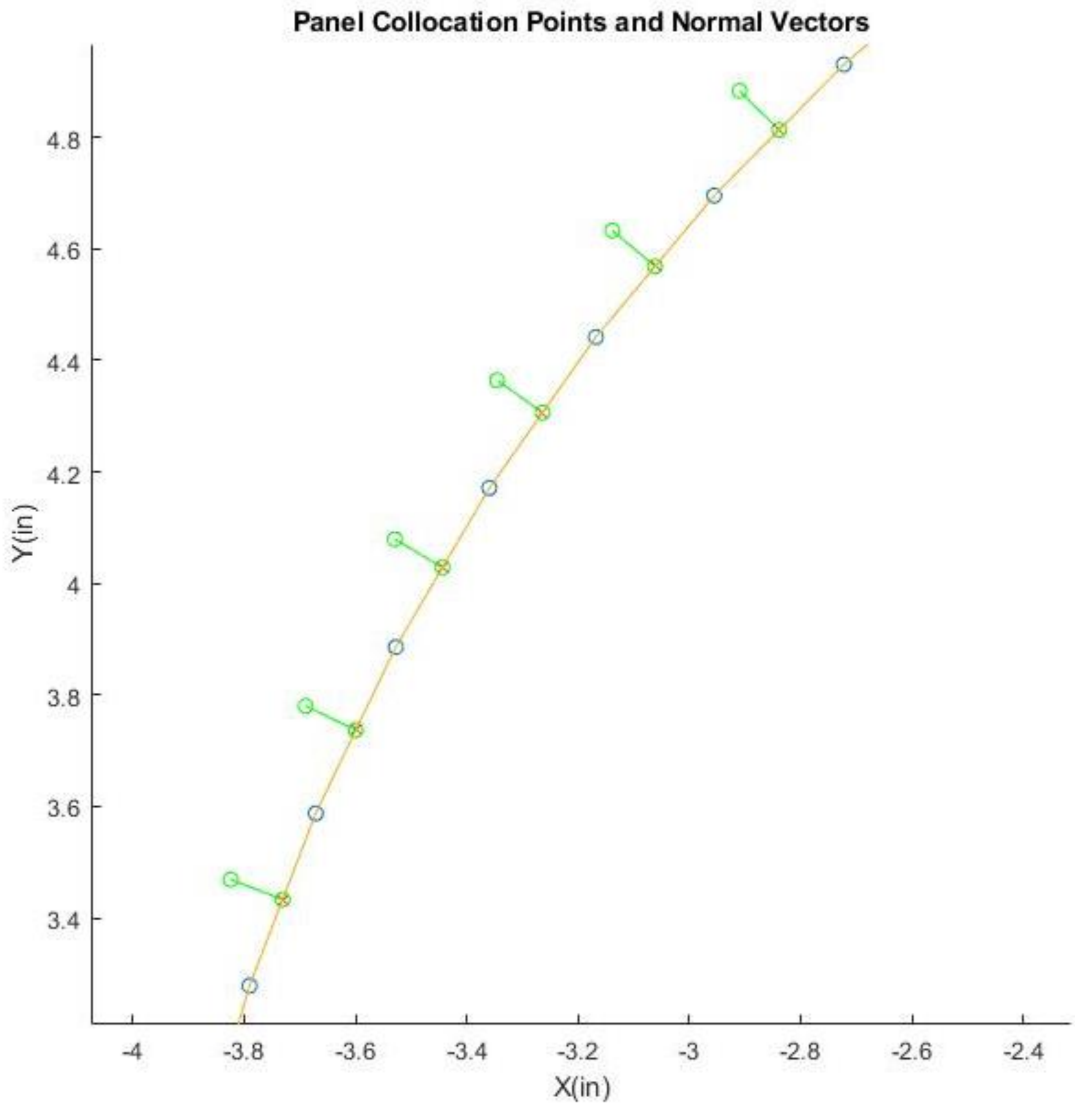


Figure 4. Normal and Tangential vectors.

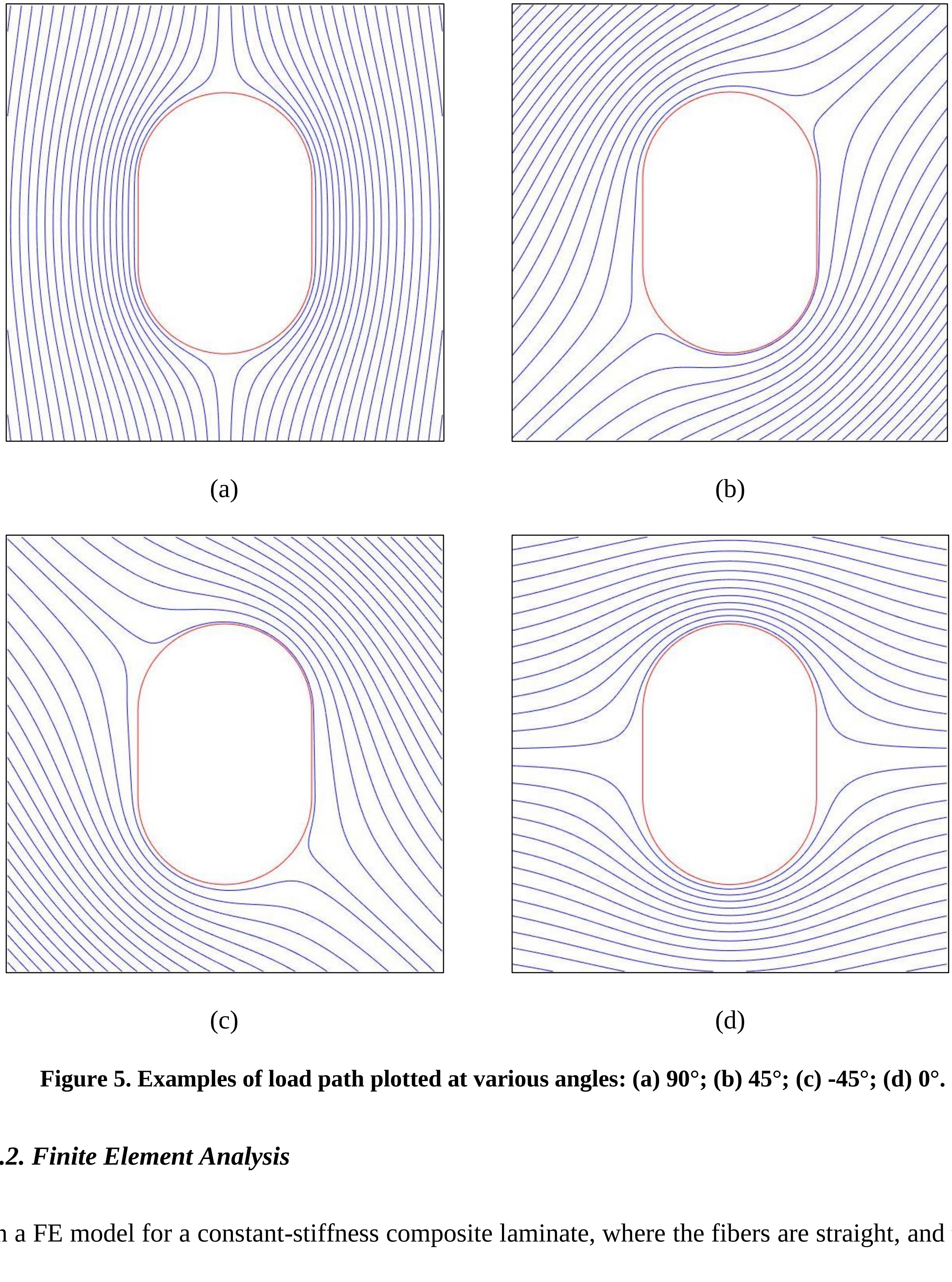


Figure 5. Examples of load path plotted at various angles: (a) 90°; (b) 45°; (c) -45°; (d) 0°.

3.2. Finite Element Analysis

In a FE model for a constant-stiffness composite laminate, where the fibers are straight, and their orientations are constant within each ply, a single property set with a specified layup is sufficient to define the material properties for all elements. However, in a VS design, the fiber orientation varies spatially; thus, each element may have a different fiber orientation and layup. Because the fiber path is discretized by the mesh size, the fiber orientation and layup for each element need to be recalculated. Therefore, MATLAB subroutines that connect the FE solver to the fiber path generator code are developed (Section 3.1). At each step, the subroutine obtains the mesh data from the FE solver, extracts the element centroids and transfers them to the path generator code, which calculates the fiber angle in each element based on the source panel method described in Section 3.1. Having the fiber angle at each element and assuming the fiber angle is straight within each element, the MATLAB subroutines then update the PCOMP card (layered shell property), defining the element layup in the NASTRAN FE input file. Because the ply angle within each element can be different for each ply, this process must be repeated through the thickness. The geometry is discretized with a mapped mesh using CQUAD4 (quadrilateral plate) elements, and a convergence study is conducted to ensure sufficient refined mesh is used in the study. It should be noted that these elements might not be suitable for cases where transverse normal and shear stresses play a significant role [19-21]. This might happen for geometries with free edges and cutouts, where in elements close to those regions failure index values can be severely impacted.

To evaluate the performance of the design, the first ply failure is considered by calculating the FIs using Tsai-Wu criteria. It should be recalled that for a VS design, the fiber angle is changing within each ply meaning that the FI will be different for each element. As a result, FI values vary spatially and all elements require inspection to determine the critical FI for the whole laminate.

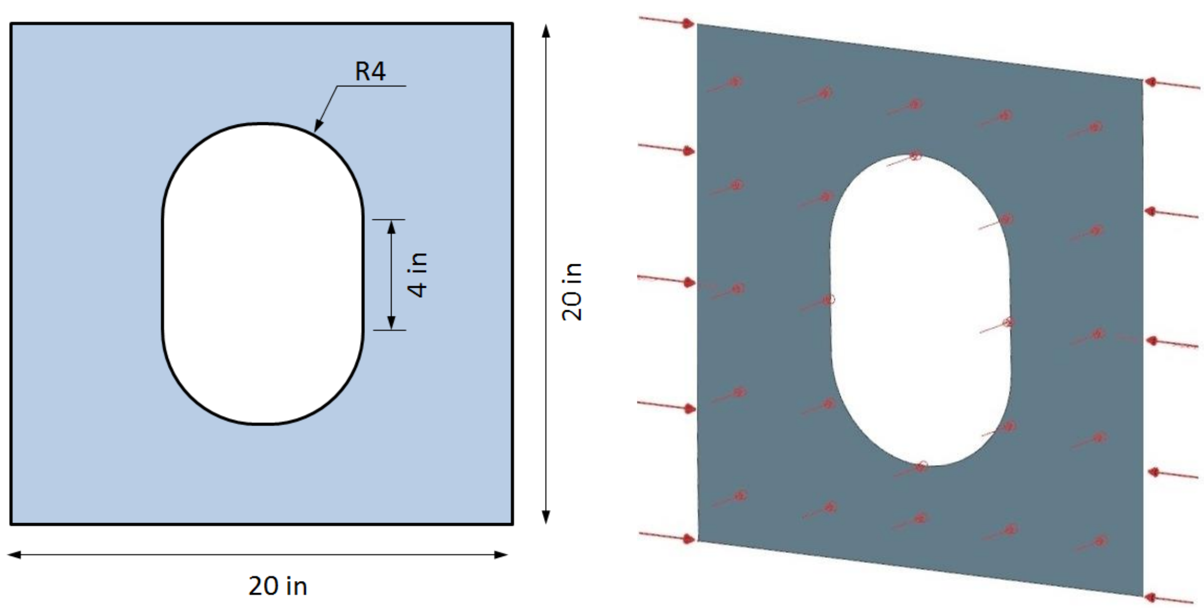
3.3. Case Study

A window opening in a pressurized fuselage skin modeled as a plate with a cut-out located at the plate center is considered as a case study (Figure 6). As suggested by Alhajahmad et al. [5], the applied pressure (P) is translated to axial (F_x) and hoop (F_y) tensile loads, calculated as follows:

$$F_x = \frac{PR_f}{2} b \qquad\qquad F_y = PR_f a \tag{9}$$

where a and b are the length and the width of the plate, respectively. The internal pressure is P = 15 psi (103.4 kPa), the length and width are a = b = 20 in (0.508 m), and the fuselage radius is R_f = 100 in (2.54 m) [5].

All the exterior edges are constrained with simply supported boundary conditions and the internal opening edges are free. In addition to the internal pressure, an external compressive force of F_x^B, representing the contribution from fuselage bending, is applied to the side edges. This study aims to demonstrate the effectiveness of CCVS design with the fiber path defined using the source panel method; therefore, the interactions from adjacent fuselage panels are ignored for the sake of simplicity.



(a) **(b)**

Figure 6. Case study: (a) geometry of the plate with a central cut out; (b) applied loading (pressure and external compressive force) and boundary conditions.

It is assumed that the plate is flat laminate made of 16 layers: A symmetric balanced stack is considered with a variable-stiffness layup $[\pm CCVS_1/\pm CCVS_2/\pm CCVS_3/\pm CCVS_4]_s$. The material properties of the constitutive tow within the lamina are listed in Table 1. A quasi-isotropic laminate, $[45/0/-45/90]_{2s}$, with the same material is considered as the baseline for analysis.

Table 1. Material properties of the tow taken from [5].

Material Properties	Values			
E_1	30	msi	207	GPa
E_2	0.75	msi	5.17	GPa
ν_{12}	0.25		0.25	
G_{12}	0.375	msi	2.59	GPa
X_t	150	ksi	1.03	GPa
Y_t	6	ksi	41.4	MPa
X_c	100	ksi	689	MPa
Y_c	17	ksi	117	MPa
S	10	ksi	68.9	MPa

3.4. Optimization

An important benefit of the proposed source panel method is that it offers the great flexibility of placing the material along a curvilinear path with only one design variable, i.e., initial ply angle

(IPA), for each ply. Therefore, similar to a straight fiber layup, there will be one design variable for each ply angle resulting in an equal computational cost of optimization for both VS and straight fiber cases. This benefit will be significant, particularly for designing large and thick laminates.

Here, the maximum strength, which is equivalent to a minimum FI, of the laminate is considered as the objective function. The goal is to determine IPAs (design variables) that minimize the maximum FI. Therefore, the optimization problem is written as follows:

$$\min_{\mathrm{x}}\{\max(\mathrm{FI}(\mathrm{x}))\}; \mathrm{x} = (T_1, T_2, T_3, T_4)$$
$$s.t. \{T_1, T_2, T_3, T_4 \in [-90^{\circ}, +90^{\circ}]\} \quad (10)$$

where **x** is the vector of design variables, i.e., T_1 to T_4 that are the IPAs for each of distinct plies, respectively. It is worth mentioning that the design variables should be integers to respect the manufacturing accuracy of a typical AFP for placing the fiber in a specified angle. Because the fiber angle varies along a curvilinear path, the relation between the design variables, i.e., ply angles and the objective function, i.e., the FI, is a nonlinear complex function that needs to be calculated via FEM. The structural response of a composite laminate when it is a function of ply angle has several local optima [22, 23]. As a result, evolutionary strategies such as GA have been widely used and recommended for optimizing laminated composites [24, 25]. However, GA is a population-based algorithm requiring a large number of function evaluations to reach the optimum solution. To improve the efficiency of the optimization process, a surrogate-based algorithm suggested by Arian Nik et al. [26] is used in this study.

4. Results and discussions

In terms of FE modeling, the entire plate is modeled, rather than just a quarter of the plate. This is because for any angle except 0° and 90°, the design is not symmetric with respect to the Y-axis (Figure 5). A quasi-isotropic laminate is considered as the reference baseline design and the optimization problem is solved to obtain a VS design. The optimum design for maximum FI is calculated as $[\pm 1/\mp 87/\pm 88/\pm 1]_s$, which has a FI of 0.29 compared with 0.68 for the quasi-isotropic laminate. It shows that a CCVS design can significantly increase the failure strength of the design by 57%. Figure 5 shows the fiber paths for the optimum CCVS laminate.

Figure 7 shows the explored designs during the optimization process, where each line represents a design and the final design is marked with a thick line. Several explored designs are near the final optimum design, i.e. the angle for $CCVS_1$ and $CCVS_4$ is 1°, the angle for $CCVS_2$ and $CCVS_3$ is -87° and +88°, respectively. It means that the last iterations of the optimization tried to fine-tune the ply angle within a few degrees range that demonstrate the stability of the final design.

One might consider the optimum design with $[\pm 1/\mp 87/\pm 88/\pm 1]_s$ stacking sequence equivalent to a $[0_2/90_4/0_2]_s$ design. Note that even the $[0_2/90_4/0_2]_s$ represents a CCVS design, where the angles represent the IPA and should not be confused with a regular straight-fiber layup. The CCVS fiber path for IPA of 0° and 90° can be seen in Figure 5.

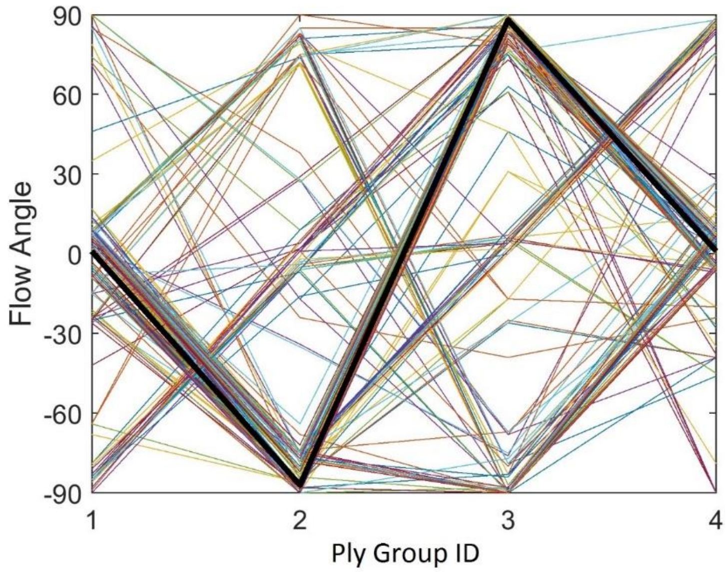
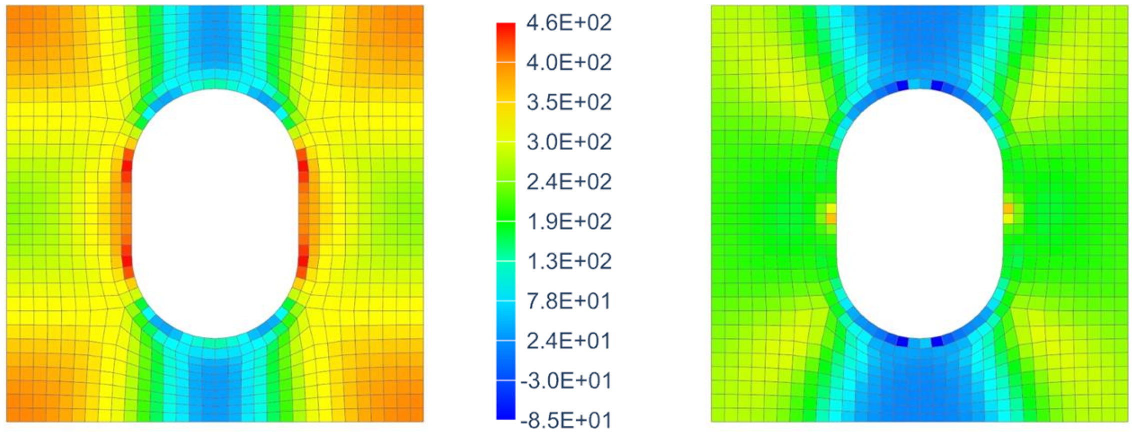
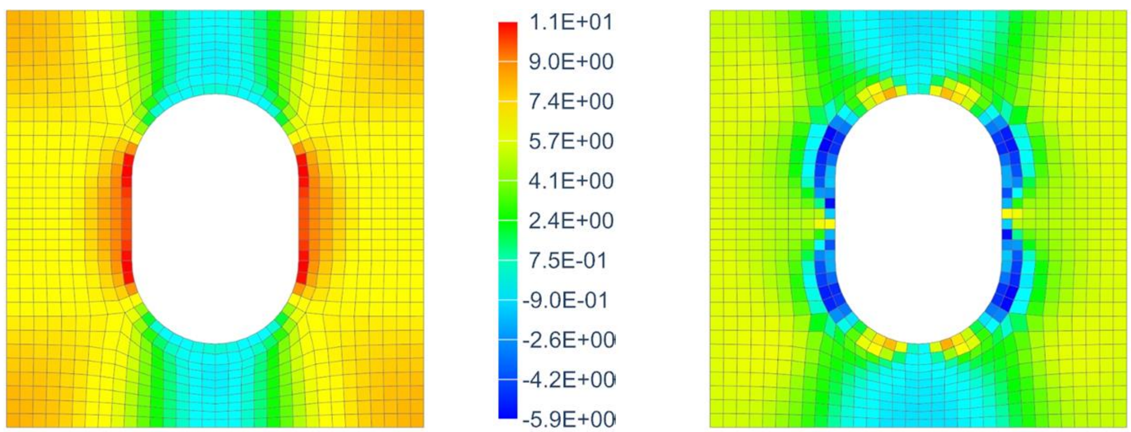


Figure 7. Explored designs during the optimization.

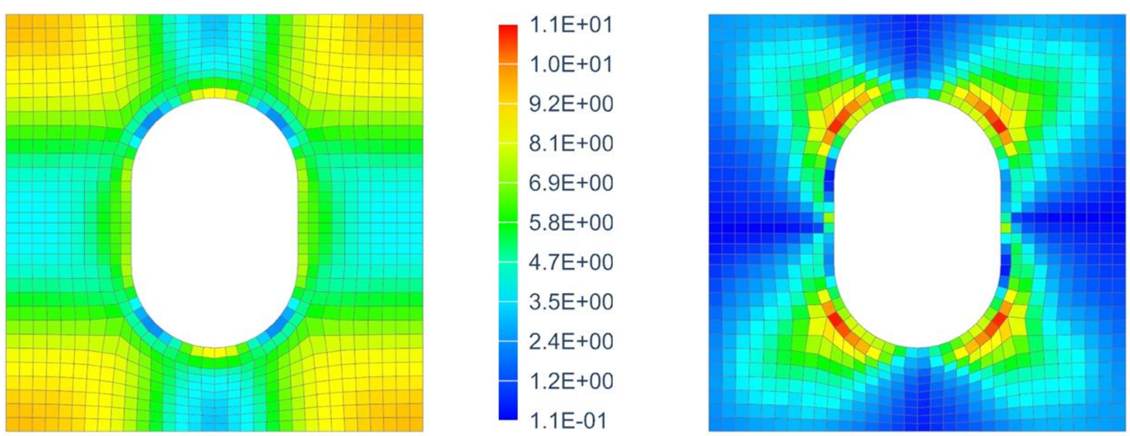
Figures 8 and 9 show the stress contours and failure index plots for the quasi-isotropic and the optimum CCVS designs, respectively. Note that the plots show the envelope of the results over all plies. Compared with the quasi-isotropic design, the CCVS design reduced the normal stresses σ_{xx} and σ_{yy} all over the plate particularly around the cut-out, thereby increasing the strength of the panel. The σ_{xy} in the CCVS design is 15% higher than that in the quasi-isotropic design. Comparing the FI plots (Figures 8d and 9d), the CCVS design generally redistributes the stress all over the panel and there is much less stress gradient compared with the quasi-isotropic design. Therefore, it can be concluded that a CCVS design allows for a significant reduction in the stress concentration around geometrical discontinuities such as cut-outs.



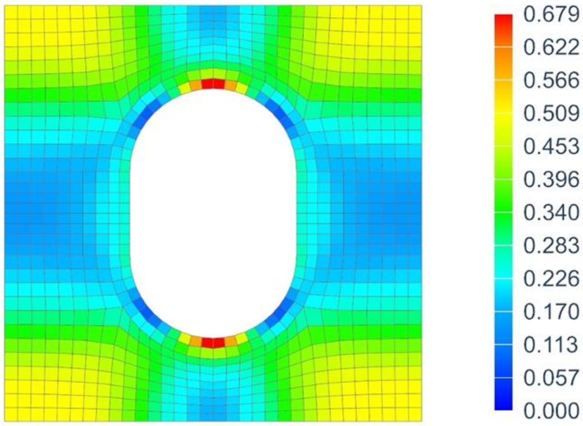
a) σ_{xx} (MPa) a) σ_{xx} (MPa)



b) σ_{yy} (MPa) b) σ_{yy} (MPa)

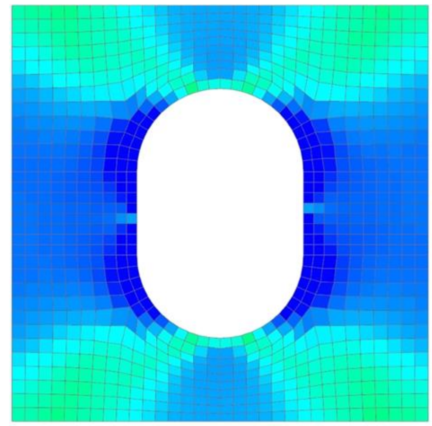


c) σ_{xy} (MPa) c) σ_{xy} (MPa)



d) Failure Index

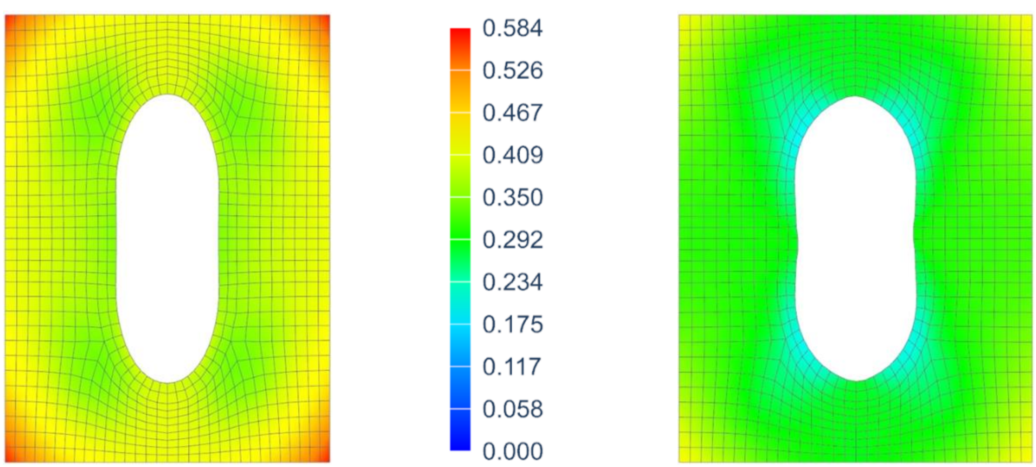
Figure 8. Envelope of stress distribution and FI plots for the quasi-isotropic design.



d) Failure Index

Figure 9. Envelope of stress distribution and FI plots for the optimum CCVS design.

A closer look at the optimum design $[\pm1/\mp87/\pm88/\pm1]_s$ and the fiber trajectories depicted in Figure 5d shows that for the exterior plies with an IPA of close to 0°, there is a relatively sharp change of the fiber angle around the centerline of the opening (see Figure 5d). It causes the local regions to be relatively less stiff compared with the quasi-isotropic design, thereby relieving stresses. This is evident in the total displacement distribution plots (in mm) for the CCVS compared with the quasi-isotropic design in Figure 10, where they are bulging towards the cut-out.



(a) (b)

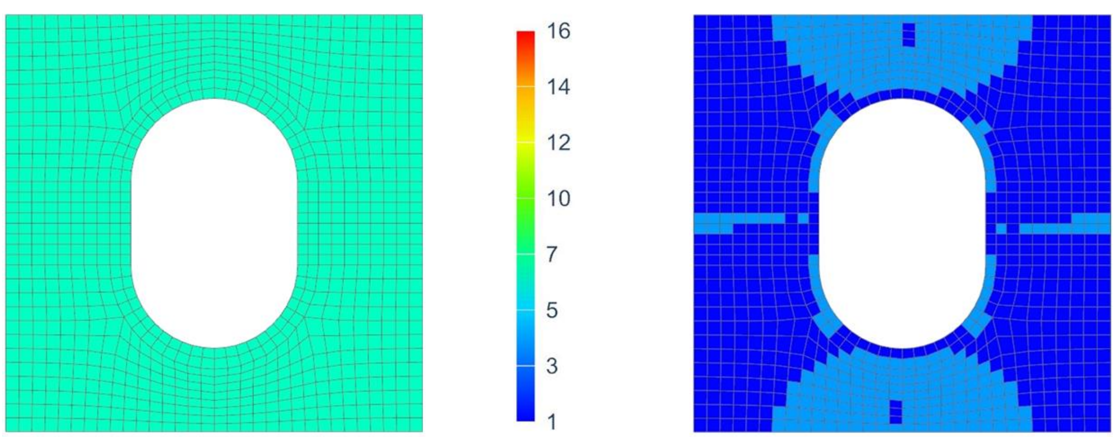
Figure 10. Total displacement distribution plots in mm (deformed shape with a factor of 100); (a) quasi-isotropic laminate; (b) CCVS design.

Failure index, maximum stresses, and displacement values discussed above for the optimum CCVS and the quasi-isotropic laminates are summarized in Table 2. It should be noted that maximum values for each component of stress happen in different elements and/or plies for both laminates, so there is no direct relation between these stress components and FI.

Table 2. Comparison of the optimum CCVS and the quasi-isotropic laminates.

Laminate	Failure index	Maximum stresses (MPa)			Displacement (mm)
		σ_{xx}	σ_{yy}	σ_{xy}	Total Translation
$[\pm1/\mp87/\pm88/\pm1]_s$	0.29	375.05	8.13	11.48	0.47
$[45/0/-45/90]_{2s}$	0.68	459.28	10.68	9.98	0.58

Another aspect of the CCVS design is that the maximum failure index varies spatially within each ply and through the thickness in contrast with the straight fiber design where a whole ply fails (Figure 11). It will potentially improve crash worthiness of the design as the laminate might withstand much more load, which can be evaluated by future studies using a progressive failure analysis.



(a) (b)

Figure 11. Layer number where maximum FI occurs: (a) Quasi-isotropic laminate (layer #7); and (b) CCVS design (layer #1 and 4).

5. Conclusions

In this work, a CCVS design was presented as a novel solution to improve the load carrying capacity of a fuselage panel with a cut-out. The CCVS was designed by defining fiber trajectories using the source panel method. The proposed trajectory formulation was demonstrated to represent the CCVS design for each ply with only one design variable, which reduces the computational cost of optimizing a CCVS design to that of a conventional constant-stiffness design. Further, the optimal CCVS design could improve the first ply failure strength of the design by 57%. In addition, the CCVS design has the benefit of distributing the failure over the laminate and potentially increasing the last ply failure strength of the design.

Future studies are required to investigate the potential improvements from CCVS under off-design conditions. Multi-directional loading, the addition of ±45° layer to the VS layup, and the change in loading direction/scenario can be investigated as well. In addition, the progressive failure analysis of a CCVS design can be completed to explore the full potential of this design. Continuous tow shearing and additive manufacturing of continuous carbon filaments can be used to fabricate CCVS designs. Certain defects, gaps, and overlaps will emerge during manufacturing and future work will also include modeling defects in the FEM using a defect layer method.

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