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Multi-Fidelity Reliability-Based Design Optimization of Advanced Composite Structures

Dario ZAMANI[1,a *], Alfonso PAGANI[1,b], Marco PETROLO[1,c] and Erasmo CARRERA[1,d]

[1]MUL2 Lab, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

[a]dario.zamani@polito.it, [b]alfonso.pagani@polito.it, [c]marco.petrolo@polito.it, [d]erasmo.carrera@polito.it

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Abstract. This paper presents a Multi-Fidelity Reliability-Based Design Optimization (MF-RBDO) strategy for Automated Fibre Placement (AFP) tow-steered composite structures. The framework combines manufacturing-aware fibre-path design, uncertainty propagation and multi-fidelity structural theories based on the Carrera Unified Formulation (CUF). The composite optimization framework is posed as a mixed-integer problem, where the number of plies is discrete and the tow-steering parameters are continuous. Deterministic AFP constraints on curvature, gaps and overlaps are enforced before the structural analysis, while stochastic variability in material properties, load, thickness and fibre angles is propagated through a multi-fidelity Gaussian Process Regression (GPR). Low-fidelity Equivalent-Single-Layer models provide inexpensive exploration, whereas high-fidelity Layerwise descriptions enrich the surrogate in regions where through-thickness stresses and failure indices are critical. A benchmark tow-steered plate shows that the reliability-based solutions require only a modest mass increase, but reduce the predicted failure indices and make the design less sensitive to manufacturing-signature variability.

Introduction

Automated Fibre Placement (AFP) enables variable-stiffness composite laminates by steering the tow direction inside each ply [1]. This design freedom can improve stiffness tailoring, stress redistribution and buckling response, but it also introduces a strong coupling between the nominal fibre path and the physical manufacturing signature of the part [2]. In tow-steered laminates, gaps, overlaps, local fibre-angle deviations and thickness variations can move the final structure away from the ideal design; therefore, optimized solutions must be robust to manufacturing defects and explicitly account for their effect on structural performance [3,4]. Reliability-based design optimization (RBDO) is well suited to this problem because it embeds uncertainty directly into the design constraints [5]. However, probabilistic assessment of composite failure requires repeated evaluations of stress fields, including transverse shear and out-of-plane normal stresses that are especially relevant for delamination. Full Layerwise (LW) Finite Element (FE) analyses are accurate but too expensive to be used repeatedly inside a stochastic optimization loop. The present work addresses this limitation by combining CUF structural models [6] with an adaptive multi-fidelity Gaussian Process Regression (MF-GPR) surrogate [7]. In this framework, the Carrera Unified Formulation (CUF) is used as a generator of structural-theory, enabling node-wise variation of model fidelity from efficient Equivalent Single-Layer (ESL) descriptions to refined LW kinematics. This allows ESL models to support efficient exploration of the design and uncertainty space, while LW models are selectively introduced in regions where accurate through-thickness stress fields are required. The remainder of the paper introduces the tow-steered design parameterization, AFP manufacturing constraints, CUF-based multi-fidelity modelling strategy

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and adaptive MF-GPR reliability assessment. The proposed framework is then evaluated on a benchmark tow-steered composite plate.

Methodology

Tow-steered design variables. The laminate is described by a mixed vector x containing the discrete number of plies N and the continuous steering parameters of each independent layer. For a symmetric stack, only the half-laminate is parameterized. In the *k*-th ply, the fibre angle follows the linear law

$$\theta^k(s) = T_0^k + \left(T_1^k - T_0^k\right) s/a, \quad s \in [0, a] \tag{1}$$

where T_0 and T_1 are the centre and edge fibre angles of the *k*-th ply, respectively, and a is the half-length along the steering direction. The full stacking sequence is obtained by mirroring the half-stack through the mid-plane. This representation keeps the design space compact while allowing layerwise tailoring of variable-stiffness laminates.

Manufacturing constraints. The AFP process is embedded through deterministic constraints based on the tangent vector v = [cos θ, sin θ]. The local tow curvature κ and divergence ψ are defined as

$$\kappa = \nabla \times v, \qquad \psi = \nabla \cdot v \tag{2}$$

Curvature controls the minimum steering radius, whereas divergence describes the tendency of adjacent tow paths to separate or converge. Positive divergence promotes gaps, while negative divergence promotes overlaps. The admissible design set is obtained by imposing $|\kappa| \leq \kappa_{max}$ and $\psi_{min} \leq \psi \leq \psi_{max}$, where the bounds are computed from AFP machine limits, allowable gap/overlap fractions and minimum cut/add lengths [8,9]. These checks are evaluated before the structural response, so infeasible fibre paths are discarded without expensive FE analyses. The complete MF-RBDO workflow is summarized in Fig. 1, where the manufacturing signature acts as an early feasibility filter before the CUF-based multi-fidelity reliability assessment is performed within the optimization loop.

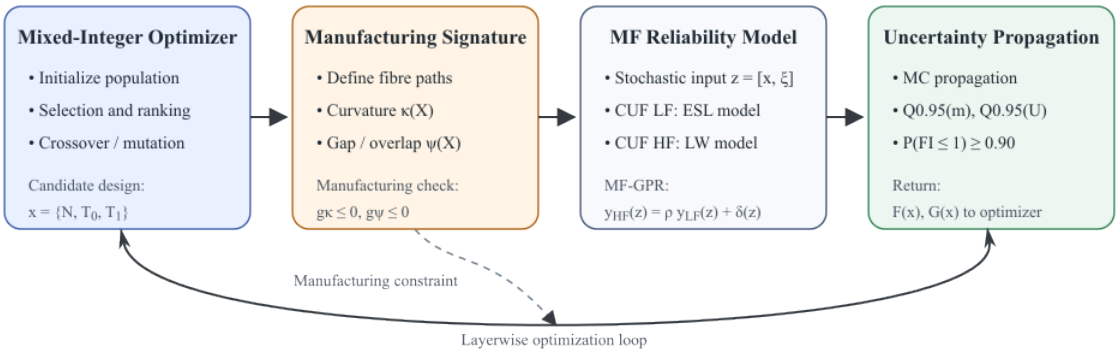


Figure 1. MF-RBDO architecture coupling AFP manufacturability filters, CUF low- and high-fidelity structural models, adaptive MF-GPR surrogate learning and probabilistic design optimization.

CUF multi-fidelity structural theories. The displacement field is expressed in CUF form as a through-thickness expansion multiplied by two-dimensional generalized unknowns [10]:

$$u(x, y, z) = F_\tau(z) u_\tau(x, y) \quad \tau = 1, \ldots, M \tag{3}$$

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The symbol M represents the number of expansion terms, and $u_\tau(x, y)$ represents the vector containing the generalized displacements, with τ indicating summation. Changing the thickness functions F_τ generates different structural theories within the same FE assembly. Taylor expansions lead to ESL models, used here as low-fidelity analyses, while Lagrange expansions generate LW models that describe each ply independently and recover more accurate through-thickness stress fields. This hierarchy is the key enabler of the proposed multi-fidelity strategy, since the same formulation supplies both inexpensive global predictions and high-fidelity failure estimates.

Reliability-based optimization. For a random vector ξ collecting material, load, thickness, density and fibre-angle uncertainties, the robust optimization problem minimizes probabilistic mass and strain-energy measures while enforcing a target probability of safe condition:

$$\min_x \left[Q_{0.95}\big(m(x,\xi)\big), Q_{0.95}\big(U(x,\xi)\big)\right], \quad \text{subject to} \quad P(\mathrm{FI}(x,\xi) \le 1) \ge 0.90 \tag{4}$$

Failure Index (FI) is evaluated through three-dimensional Hashin criteria and a quadratic delamination index [11,12]. In the present study, the target probability of safety is 90%. The deterministic design optimization (DDO) and RBDO problems are solved with NSGA-II [13] which is suitable for mixed discrete-continuous design variables.

Multi-fidelity Gaussian-process surrogate. The high-fidelity response y_{HF} is represented through an autoregressive correction of the low-fidelity response y_{LF}:

$$y_{\mathrm{HF}}(z) = \rho\, y_{\mathrm{LF}}(z) + \delta(z), \qquad z = [x,\xi]^{\mathrm{T}} \tag{5}$$

where ρ is a correlation coefficient and δ is a discrepancy Gaussian Process (GP). For any candidate design, Monte Carlo samples of ξ are propagated through the surrogate rather than through repeated LW analyses. Adaptive enrichment adds high-fidelity CUF samples close to the failure boundary and in regions of large predictive uncertainty. In the numerical database used here, 70% of the training points are evaluated with the ESL model and 30% with the LW model, reducing the number of high-fidelity analyses while preserving accuracy in the failure quantities.

Numerical Results

The framework is assessed on a rectangular tow-steered composite plate representative of a wing-box skin panel. The plate has dimensions 0.508 m x 0.508 m and ply thickness 0.1905 mm. Simply supported boundary conditions are applied along the plate edges. The structure is subjected to a uniformly distributed transverse pressure of 1000 Pa and an in-plane edge load of 1000 N/m, respectively. A 10 x 10 Q9 in-plane mesh is used after convergence. The uncertainty model includes fibre-angle perturbations, load scaling, ply thickness, density, elastic constants and strength allowables (see [7]). The representative QI, DDO and RBDO solutions are summarized in Table 1, while the corresponding deterministic and reliability-based fibre paths are shown in Fig. 2.

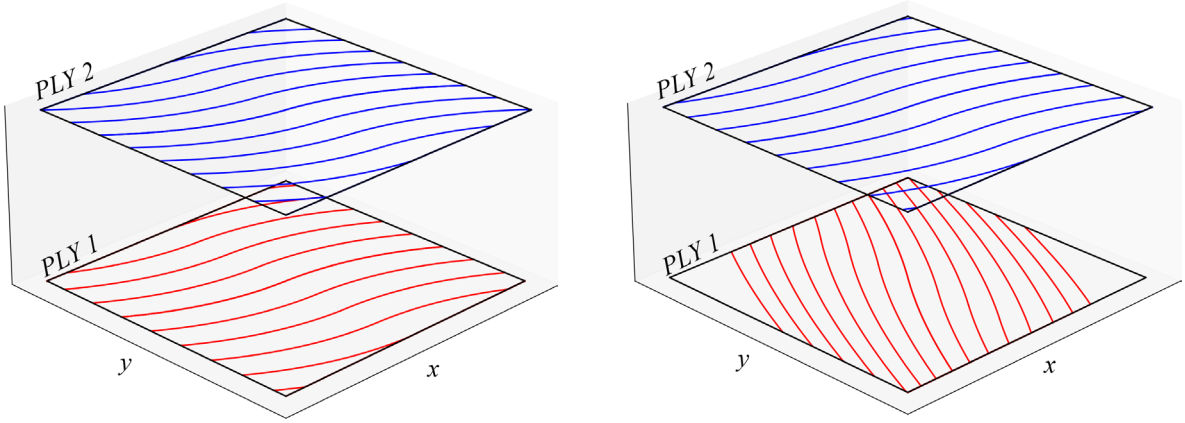
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Table 1. Comparison of Quasi-Isotropic (QI), Deterministic Design Optimization (DDO), and Reliability-Based Design Optimization (RBDO) representative solutions.

Case	N_{ply}	Mass [kg]	Strain energy [J]	Manufacturing indicators	Main reliability outcome
QI	3 / 4	0.195 / 0.260	22.12 / 9.65	–	Reference straight-fibre baseline
DDO	3 / 4	0.195 / 0.260	16.01 / 6.90	$\max \lvert\kappa\rvert / \kappa_{max} \leq 1.50/2.5$; $\max \lvert\psi\rvert / \psi_{max} \leq 0.76/2$	Lowest nominal compliance, but critical failure modes may be redistributed
RBDO	3 / 4	0.20 / 0.27	19.47 / 8.38	$\max \lvert\kappa\rvert / \kappa_{max} \leq 0.82/2.5$; $\max \lvert\psi\rvert / \psi_{max} \leq 0.44/2$	Slight mass increase, lower failure indices and improved robustness

As reported in Table 1, the deterministic optima achieve the lowest nominal strain energy, with reductions of about 38-40% with respect to the corresponding quasi-isotropic references. Nevertheless, the associated fibre paths in Fig. 2 show that deterministic steering tends to exploit more aggressive curvature and may transfer criticality from one failure mechanism to another. The reliability-based solutions are slightly heavier, by approximately 2-3%, and less compliant than the deterministic optima, but they remain more efficient than the quasi-isotropic baselines while reducing the severity of the manufacturing indicators.

The failure-index comparison confirms the benefit of the RBDO formulation. For the three-ply case, the RBDO design reduces fibre tension, fibre compression and matrix tension by about 62%, 69% and 72%, respectively, compared with the quasi-isotropic reference, while the delamination index decreases from 0.05 to 0.003. For the four-ply case, the robust design also lowers the fibre and matrix failure indices and keeps delamination at a low level. These trends indicate that reliability-based optimization does not merely shift the critical mode; instead, it improves the global failure margin across several mechanisms.



(a) DDO optimized fibre paths *(b) RBDO optimized fibre paths*

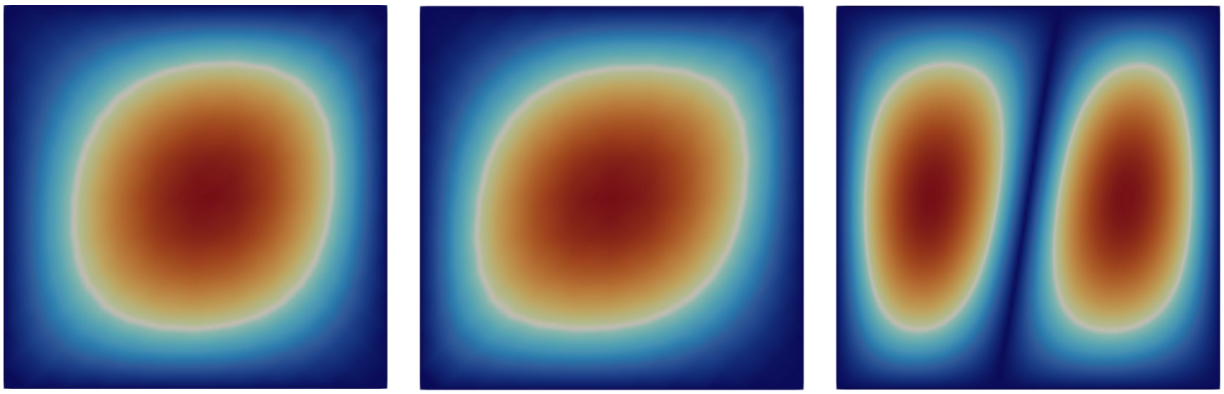
Figure 2. Comparison of representative optimal fibre paths for the tow-steered laminate.

The ESL and LW comparisons further justify the multi-fidelity framework. ESL-TE1 analyses are approximately 52-60% cheaper than LW-LD2 analyses for the representative configurations, but the largest discrepancies appear in delamination and through-thickness failure indices. The surrogate therefore uses ESL evaluations for inexpensive exploration and reserves LW evaluations for the response regions where layerwise accuracy is necessary.

As an additional structural check, the optimized plates are evaluated through linear buckling analysis. The corresponding first buckling mode shapes are reported in Fig. 3 for the QI, DDO,

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and RBDO configurations. Tow steering substantially improves the first critical load of the deterministic designs. The robust designs exhibit a more complex behaviour, including mode switching, because the stiffness field is redistributed to satisfy reliability constraints rather than only to maximize nominal stiffness. This observation is important for future extensions in which buckling metrics are included directly in the RBDO formulation.



(a) QI *(b) DDO* *(c) RBDO*

Figure 3. First buckling mode shapes for the three-layer optimal designs: (a) reference QI laminate, (b) DDO solution, and (c) RBDO solution.

Conclusions

A MF-RBDO framework has been presented for tow-steered composite plates manufactured by AFP. The method combines mixed-integer fibre-path optimization, deterministic manufacturability signature, CUF-based ESL/LW structural theories and adaptive MF-GPR uncertainty propagation. The benchmark results show that reliability-based solutions require only a small mass penalty compared with deterministic optima, while providing lower failure indices and less severe manufacturing indicators. The multi-fidelity surrogate is essential because delamination and 3D failure metrics require layerwise accuracy, but a full high-fidelity stochastic optimization would be computationally prohibitive. Future work will extend the formulation to explicit gap/overlap FE modelling, more complex geometries and direct probabilistic buckling constraints.

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