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MULTI-OBJECTIVE OPTIMIZATION OF FREQUENCY AND DAMPING OF VERTICAL STABILIZER SKIN STRUCTURE PLACED WITH VARIABLE-ANGLE TOWS

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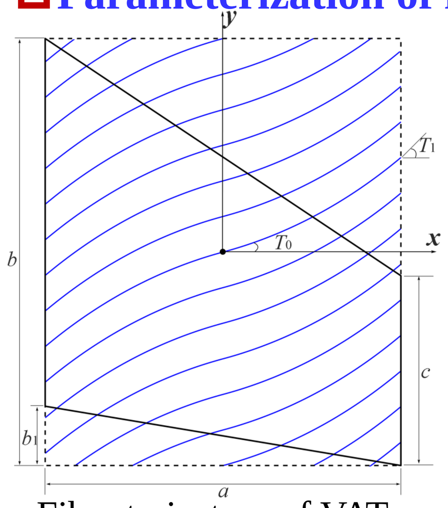
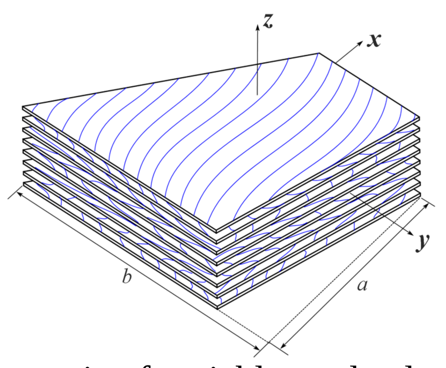
Theoretical development of optimization model

Parameterization of fiber trajectories

$$\theta(x) = \frac{2}{a}(T_1 - T_0)x + T_0$$



Fiber trajectory of VAT vertical stabilizer skin structure



Schematic of variable-angle ply and spatial coordinate system of vertical stabilizer skin structure

Damping modelling

$$\varphi = \frac{\Delta U}{U}$$

$$\Delta U = \sum_{q=1}^{n}\sum_{i=1}^{3}\sum_{j=1}^{3}\frac{1}{2}\int \psi_{ij}\sigma_{ij}^{q}\varepsilon_{ij}^{q}\mathrm{d}V_q$$

$$U = \sum_{q=1}^{n}\sum_{i=1}^{3}\sum_{j=1}^{3}\frac{1}{2}\int \sigma_{ij}^{q}\varepsilon_{ij}^{q}\mathrm{d}V_q$$

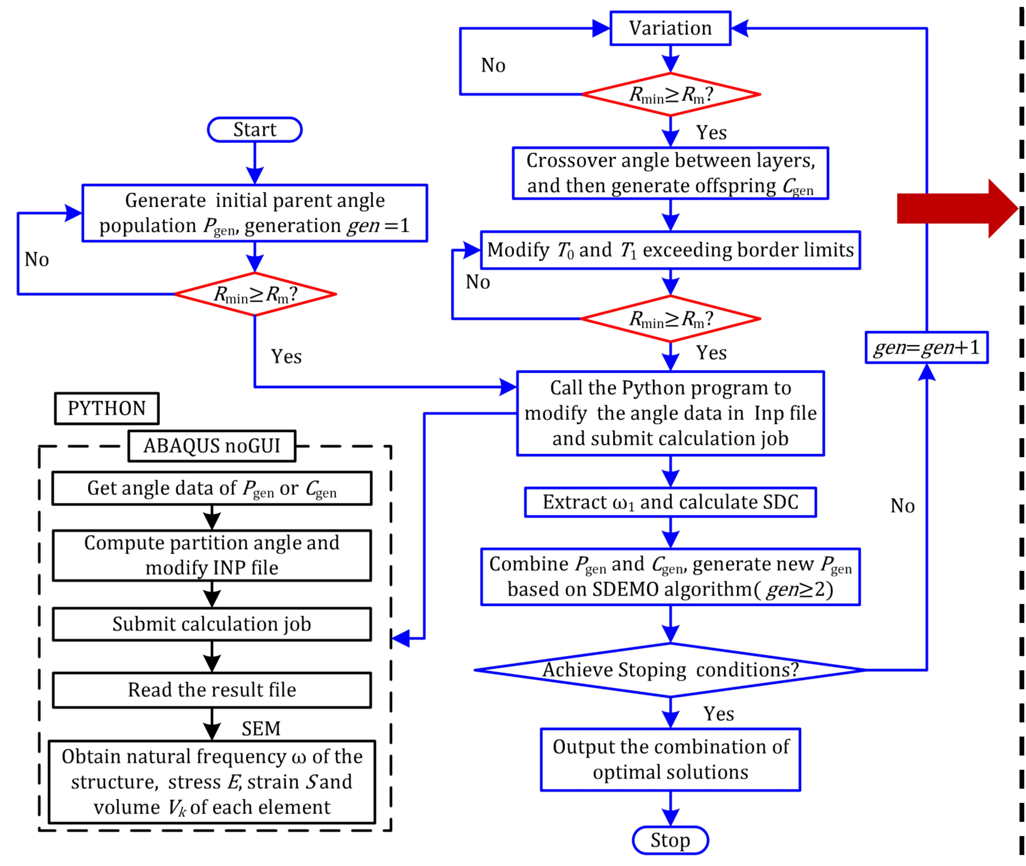
Multi-objective optimization model

$$\begin{cases}\text{maximum } f(\boldsymbol{x}) = [f_1(\boldsymbol{x}), f_2(\boldsymbol{x})] \\ \boldsymbol{x}\epsilon \boldsymbol{X}\end{cases}$$

$$\begin{cases} f_1(\boldsymbol{x}) = \omega_1 \\ f_2(\boldsymbol{x}) = \varphi_1 \end{cases}$$

$$x^{(k)} = \left[T_0^{(k)}, T_1^{(k)}\right] \quad k = 1,3$$

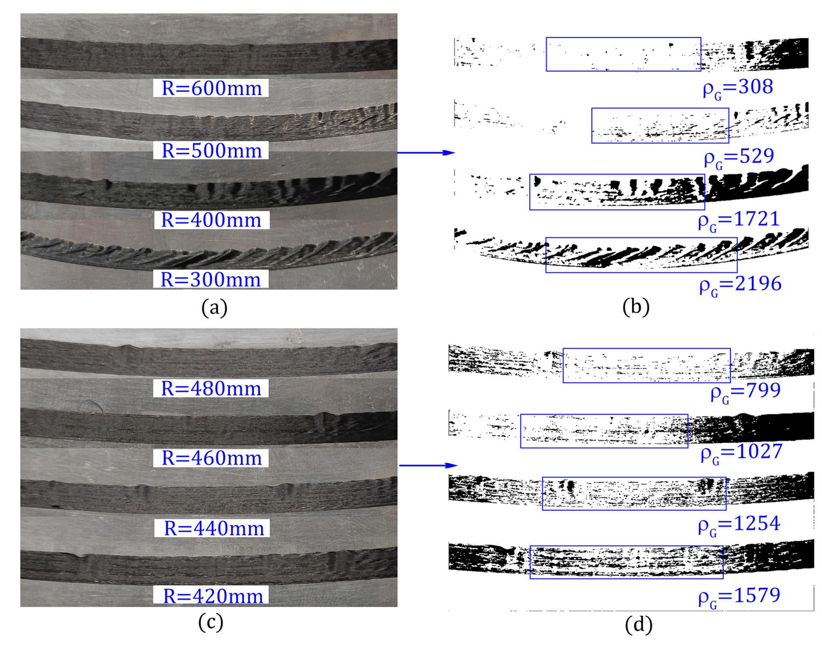
Numerical optimization process



Process chart of calculation and iteration of the optimization

Turning radius test of prepregs

$$\cos\theta = \cos T_0 - \kappa|x|$$

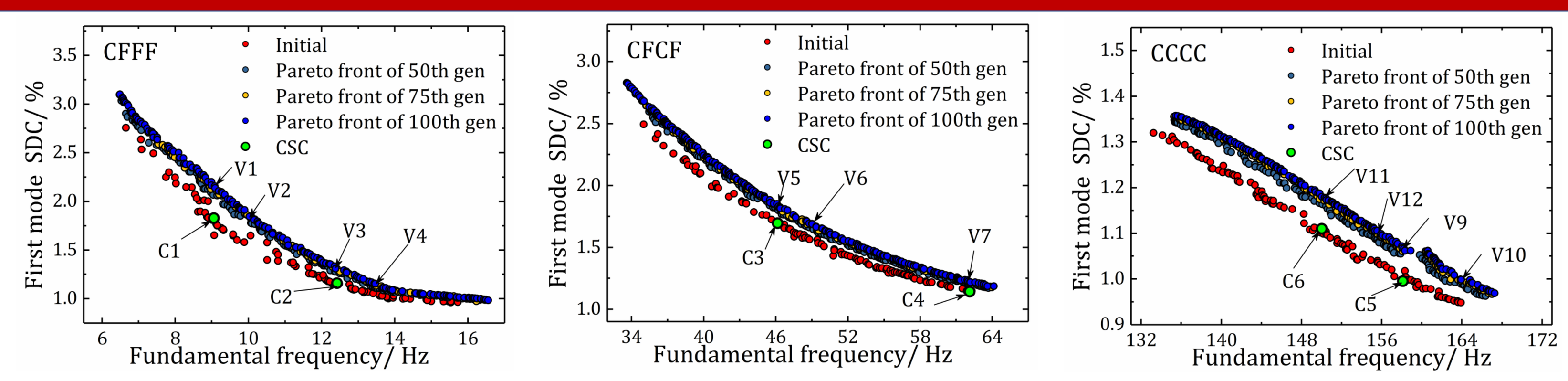


Placement quality of prepregs under different turning radii.

The smaller prepreg turning radius the larger the placement defects

Optimization results

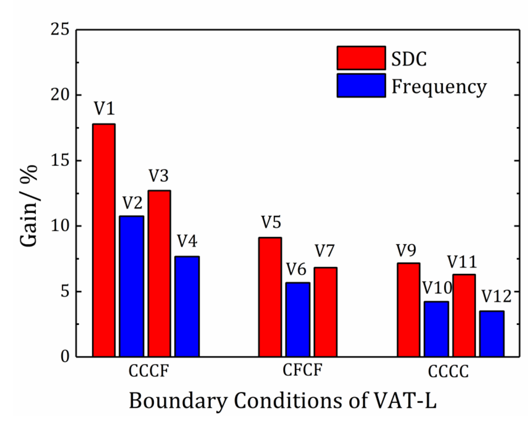
Corresponding to any point of the reference points C1 to C6 in Figure on the right, select any two points (optimization points) on the Pareto Frontier of VAT-L for comparison; any of the two parameters (fundamental frequency or modal One of SDC) of both the reference point and the two corresponding optimization points is kept the same, and the other parameter is compared.



Pareto Fronts of different boundary conditions, obtained from multi-objective optimizations to maximize fundamental frequency and SDC of the first vibration mode

Layup and vibration properties of VSC and VAT laminates of Pareto Fronts

Laminate	Boundary condition	Ply	Frequency (Hz)	SDC (%)	Gain (%)
C1	CFFF	$[\pm45°]_{2s}$	9.05	1.83	
V1		$[\pm\langle55.39°, 38.61°\rangle, \pm\langle52.18°, 42.60°\rangle]_s$	9.05	2.16	17.80
V2		$[\pm\langle50.36°, 34.69°\rangle, \pm\langle52.67°, 43.12°\rangle]_s$	10.02	1.84	10.76
C2		$[\pm30°]_{2s}$	12.41	1.16	
V3		$[\pm\langle39.39°, 26.65°\rangle, \pm\langle32.87°, 32.74°\rangle]_s$	12.42	1.31	12.70
V4		$[\pm\langle35.14°, 22.39°\rangle, \pm\langle32.18°, 21.33°\rangle]_s$	13.37	1.17	7.66
C3	CFCF	$[\pm45°]_{2s}$	46.15	1.70	
V5		$[\pm\langle35.55°, 52.84°\rangle, \pm\langle42.06°, 46.92°\rangle]_s$	46.17	1.85	9.12
V6		$[\pm\langle34.83°, 48.50°\rangle, \pm\langle42.43°, 52.33°\rangle]_s$	48.77	1.70	5.66
C4		$[\pm30°]_{2s}$	62.13	1.14	
V7		$[\pm\langle26.41°, 36.41°\rangle, \pm\langle25.34°, 25.17°\rangle]_s$	62.13	1.22	6.82
C5	CCCC	$[\pm45°]_{2s}$	158.11	1.00	
V9		$[\pm\langle38.00°, 27.84°\rangle, \pm\langle38.79°, 27.65°\rangle]_s$	158.20	1.07	7.17
V10		$[\pm\langle59.97°, 47.19°\rangle, \pm\langle54.21°, 54.82°\rangle]_s$	164.80	1.00	4.23
C6		$[\pm30°]_{2s}$	150.01	1.11	
V11		$[\pm\langle29.10°, 19.47°\rangle, \pm\langle22.65°, 14.56°\rangle]_s$	150.02	1.18	6.29
V12		$[\pm\langle35.66°, 22.46°\rangle, \pm\langle29.19°, 19.24°\rangle]_s$	155.26	1.11	3.51



Gains achieved by different Pareto Fronts

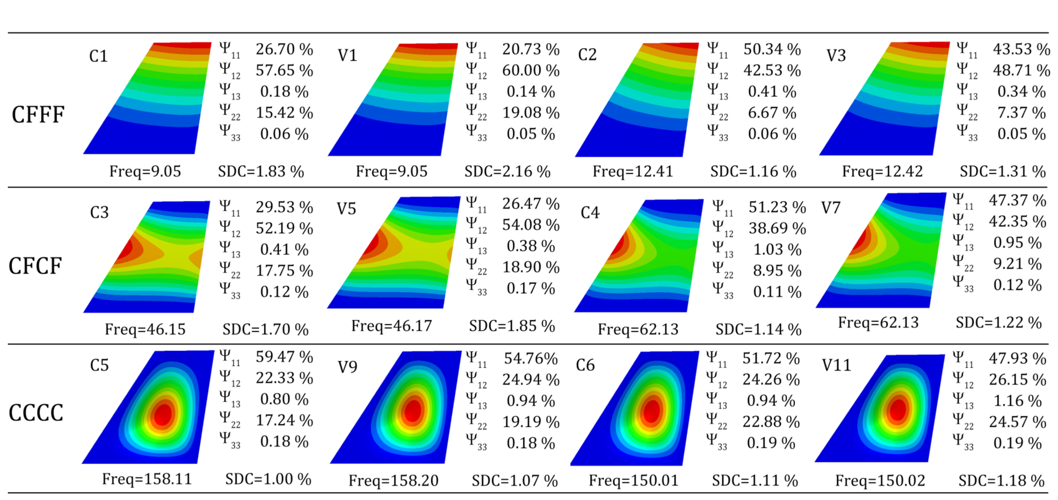
The modal SDC and fundamental frequency can be greatly improved by optimizing the fiber trajectory

Improvement degree：modal SDC > fundamental frequency

improvement degree：CFFF>CFCF>CCCC

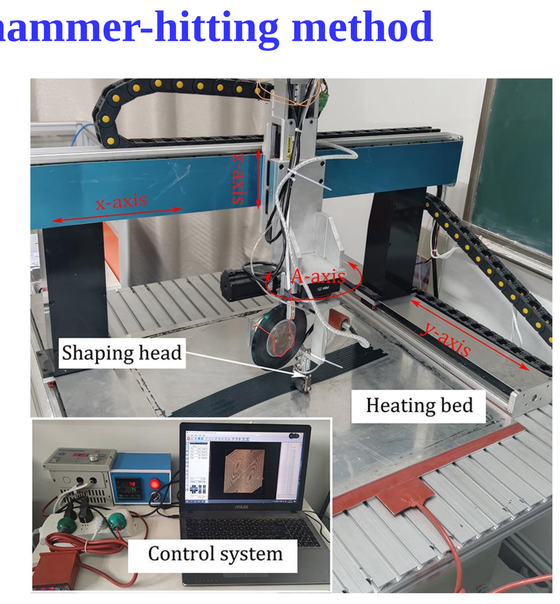
The damping in the direction 12, ψ12, is generally the main one to be improved when regarding improving the damping of a structure by optimizing the fiber trajectory.

Experimental validation

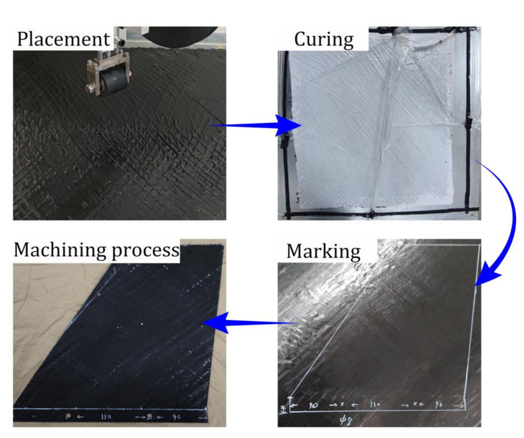


Vibration properties of 6 conventional constant stiffness laminates and their 6 optimally damped Pareto Fronts under three kinds boundary conditions

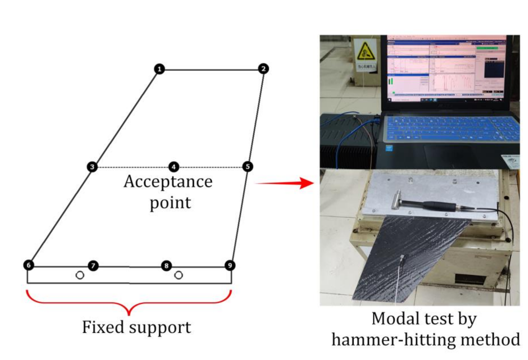
hammer-hitting method



Prepreg curve-steered AFP machine



Production process of test laminates.



Hammer-hitting method for modal test and their test points

Comparison of test and calculation results

Laminate	Fundamental frequency			Damping (%)		
	Calculation (Hz)	Test (Hz)	Error (%)	Calculation	Test	Error
C1	9.05	9.64	6.52	1.83	1.63	10.93
V2	10.02	10.89	8.69	1.84	1.68	8.69