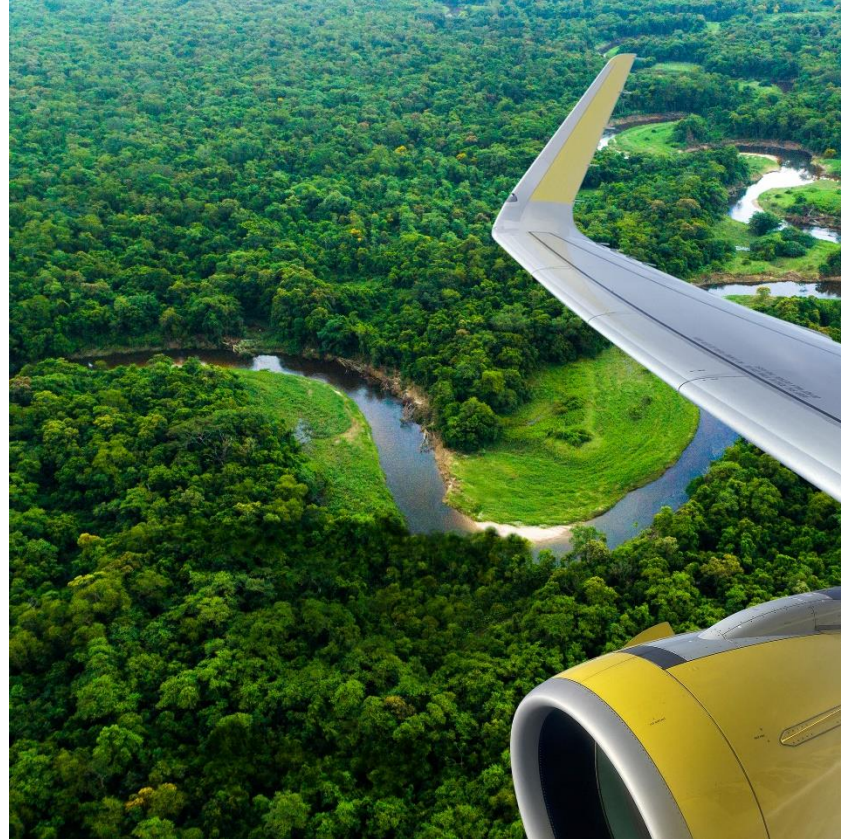




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An efficient multiparametric methodology for damage prognostics and SHM of ice protection composite laminates

Sindhu Bushpalli; Saheed O. Ojo; Vassilios Tsachouridis; Majid A. Bhinder; Stylianos Basagiannis; El Hassan Ridouane



Outline

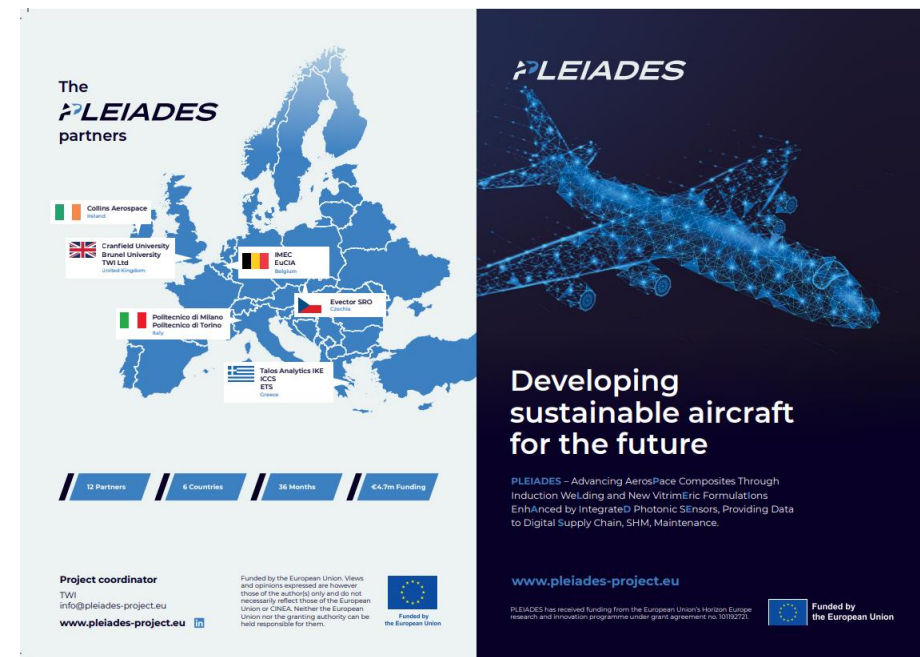
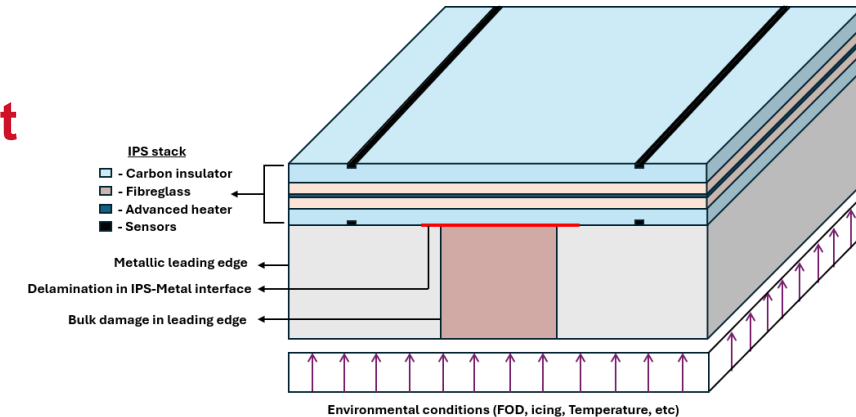
- Introduction
- 1D models
- Optimization algorithm
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- Summary



Introduction: Overall presentation idea

Damage propagation model development for system assessment

- ❖ Structural analyses and 3D FE validation of IPS system
- ❖ SHM analysis of IPS system
 - Development of simplified 1D damage formulations
 - Implementation of –electro-thermo-mechanical beam model for damage propagation analysis of IPS laminates with embedded photonic sensors
 - Thermostatic analysis and 3D FE validation of a single-zone CNT IPS with uniform temperature distribution
 - Thermostatic analysis and 3D FE validation of multi-zone CNT IPS with layer wise temperature distribution
 - Damage propagation analysis and 3D FE validation of IPS





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1D models: Basic methodology

Equilibrium equations

$$\underbrace{\begin{bmatrix} m_{uu} & m_{uw} & m_{u\varphi} \\ m_{wu} & m_{ww} & m_{w\varphi} \\ m_{\varphi u} & m_{\varphi w} & m_{\varphi\varphi} \end{bmatrix}}_{\text{Mass matrix}} \begin{Bmatrix} \ddot{u}_0 \\ \ddot{w}_0 \\ \ddot{\varphi}_0 \end{Bmatrix} + \underbrace{\begin{bmatrix} k_{uu} & k_{uw} & k_{u\varphi} \\ k_{wu} & k_{ww} & k_{w\varphi} \\ k_{\varphi u} & k_{\varphi w} & k_{\varphi\varphi} \end{bmatrix}}_{\text{Stiffness matrix}} \begin{Bmatrix} u_0 \\ w_0 \\ \varphi_0 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}$$

The governing equations comprise of:

- Semi-layer wise mechanics indicating that some variables are approximated according to ESL mechanics while other variables are captured according to LW mechanics.
- Delamination captured using penalty parameters (i.e., normal and tangential tractions are enforced at the delamination interfaces)
- Bulk damage is approximated according to continuum damage mechanics based on which stiffness can be degraded at predetermined location. So, the stiffness matrix is damage dependent.
- Boundary conditions is clamped-free
- Compatibility equations between beam subdomains are enforced to capture damage-induced discontinuity skipped for convenience

Differential quadrature method

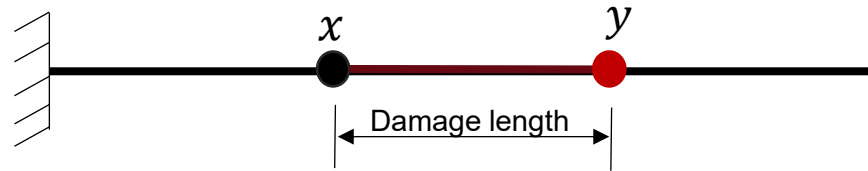
Numerical Implementation

$$\mathbf{u}(x) = \sum_{i=1}^N l_i(x) \tilde{\mathbf{u}}_i$$

$l_i(x)$ is high-order Lagrange polynomials

1D models: Basic methodology

Damaged beam representation



Mixed damage parameters

$x = ?$	x damage tip (localisation)
$y = ?$	y damage tip (localisation)
$\Gamma = ?$	Bulk damage intensity (quantification)
$\lambda = x - y = ?$	Damage length (quantification)

Delamination parameters

$x = ?$	x damage tip (localisation)
$y = ?$	y damage tip (localisation)
$\Gamma = 0$	Damage intensity (quantification)
$\lambda = x - y = ?$	Damage length (quantification)



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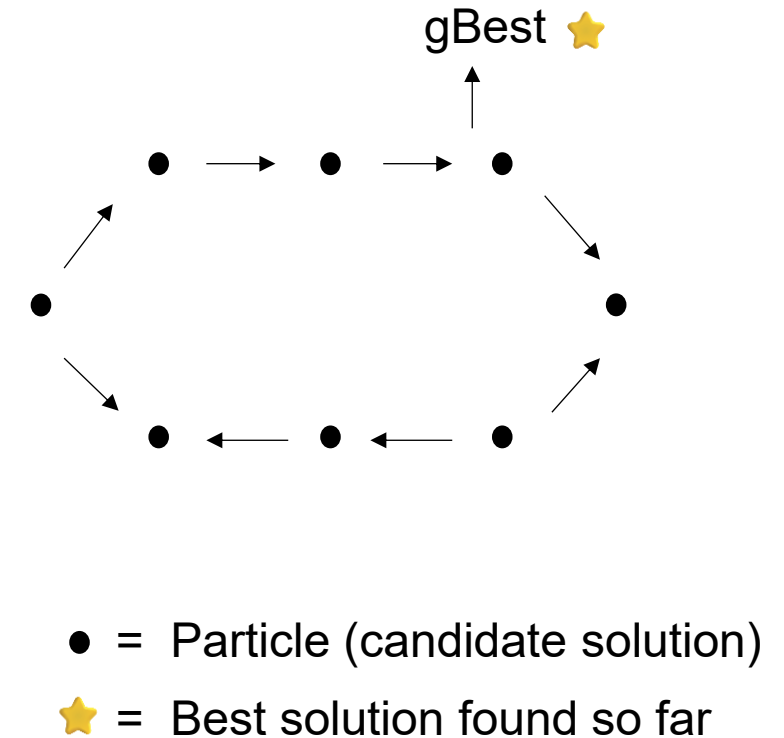


Optimisation algorithm: Basic concept

❑ Swarm optimization methodology

❑ Inspired by bird flocking and fish schooling behaviour

- Particles = candidate solutions
- Each particle remembers its Personal Best (pBest)
- The swarm shares the Global Best (gBest)
- Particles move based on pBest and gBest
- Over time, the swarm converges to an optimal solution



Unified Butterfly Optimization Algorithm

Search criteria

$$x_i^{t+1} = \mu[x_i^t + (r^2 \times x_j^t - x_k^t) \times f_i] + (1 - \mu)[x_i^t + (r^2 \times g_{best} - x_i^t) \times f_i]$$

$$\mu(t) = \exp\left(\frac{t \log 2}{t_{max}}\right) - 1$$

Objective function with noise

$$F(x, y, \Gamma, \lambda) = \sqrt{\frac{1}{n} \sum_{i=1}^n [\omega_i^m - \omega_i^c]^2}$$

$$\omega_{noise} = \omega_{noisefree} \left(1 + \frac{\beta \gamma}{100}\right)$$

where β is a random number with zero mean with unit standard deviation
 γ (3%) is noise level in percentage

Position update

- Each particle/butterfly updates position using
- Velocity-based mechanism for exploitation
- Fragrance-based mechanism for exploration

Switching mechanism

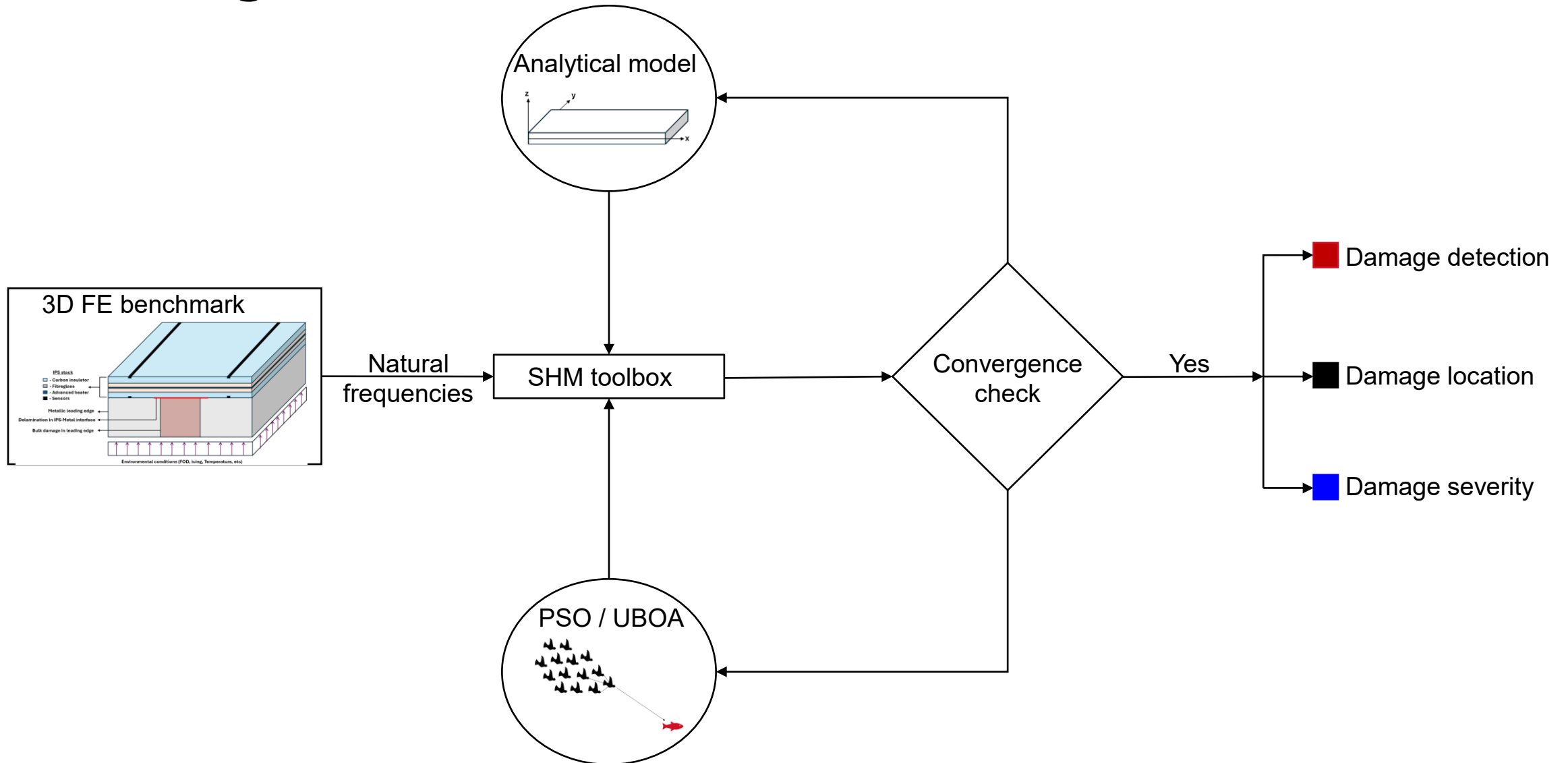
- Algorithm alternates b/w UPSO & BOA position updates depending on fitness of the current population

Fitness evaluation

- Fitness is based on the objective function, and updates solution to move closer to g_{best}

Ojo, S., Bushpalli, S., Tsachouridis, V., & Ridouane, E. H. (2025). An Analytical-Based Structural Health Monitoring Procedure for Damage Detection and Monitoring in Composite Beams. Available at SSRN 5399096.

SHM algorithm





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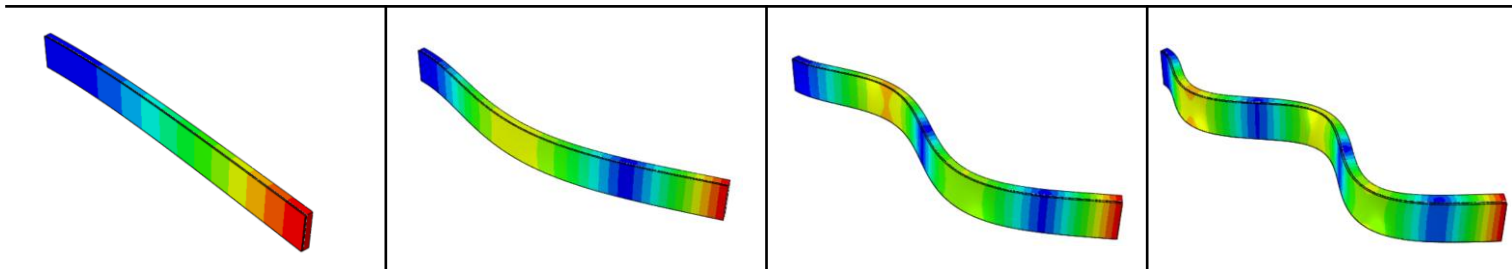


SHM tests 2 Frequencies

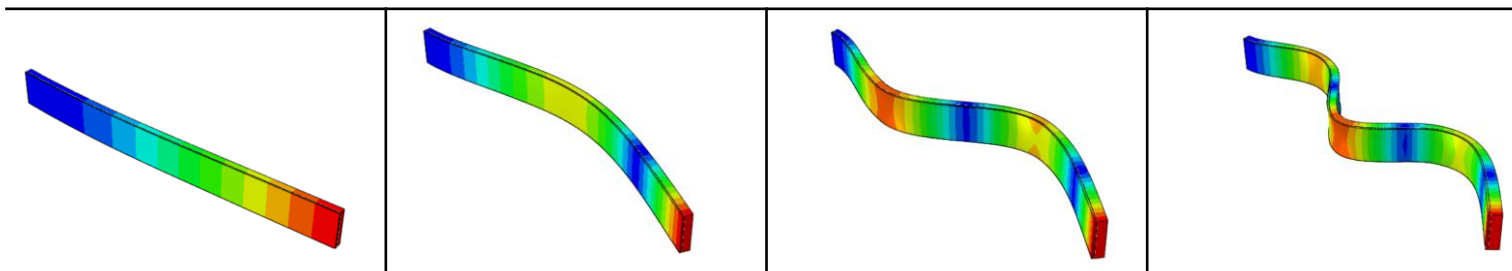
Delamination damage

	No damage			
	ω_1	ω_2	ω_3	ω_4
1D_3	44.36	277.27	773.92	1504.80
1D_5P	44.36	277.34	773.33	1506.26
3D_FE	43.76	273.19	761.78	1485.10
	40% delamination damage			
	ω_1	ω_2	ω_3	ω_4
1D	43.69	272.06	643.30	1358.18
1D_5P	43.69	272.09	643.03	1351.81
3D_FE	43.81	275.33	645.95	1354.90
	60% delamination damage			
	ω_1	ω_2	ω_3	ω_4
1D	42.25	283.96	539.31	1094.94
1D_5P	42.25	283.61	537.98	1091.69
3D_FE	42.34	263.09	587.28	1180.5

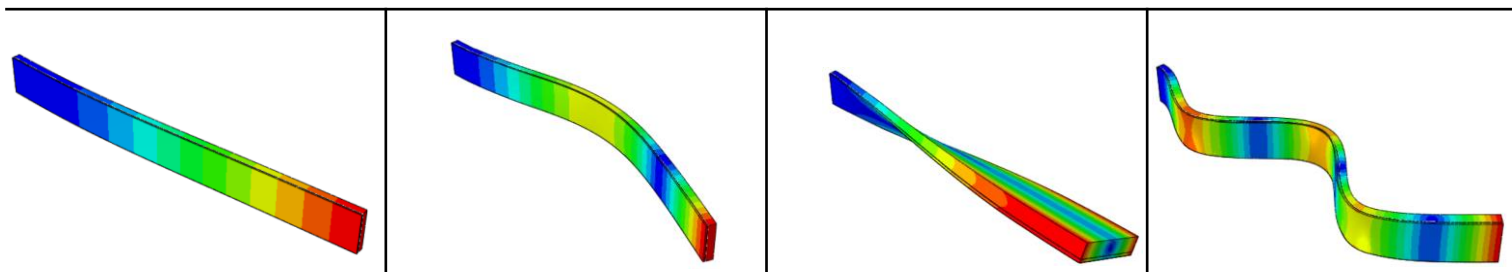
No damage



40% Delamination



60% delamination

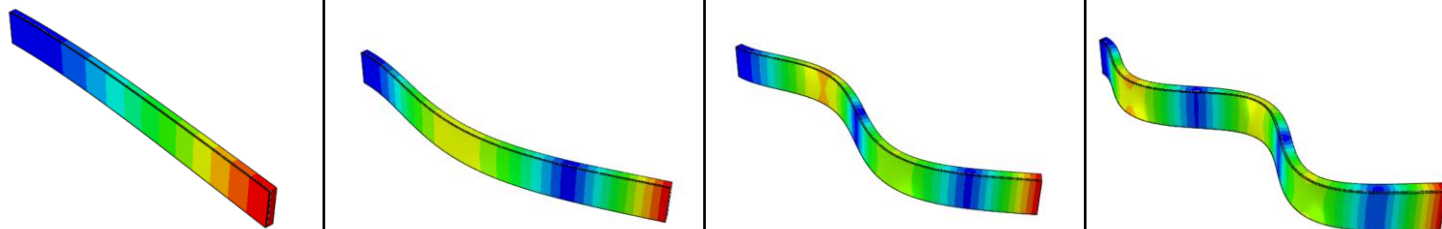


SHM tests 2 Frequencies

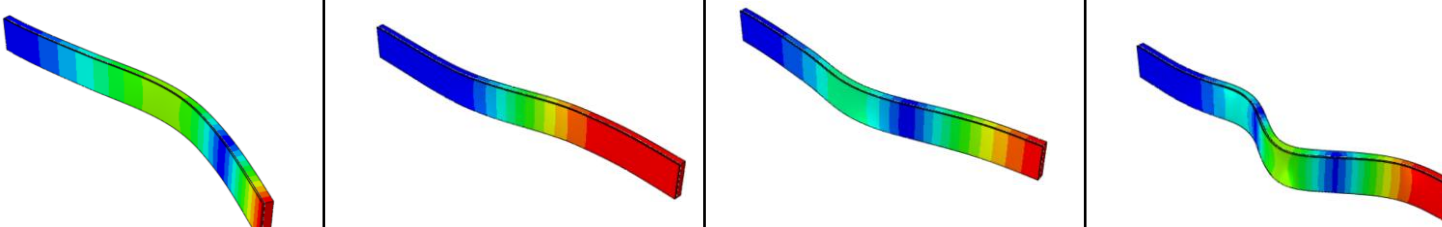
Mixed damage

	No damage			
	ω_1	ω_2	ω_3	ω_4
1D	44.36	277.27	773.92	1504.80
1D_5P	44.36	277.34	773.33	1506.26
3D_FE	43.76	273.19	761.78	1485.10
	40% mixed damage			
	ω_1	ω_2	ω_3	ω_4
1D	41.01	240.26	533.3	1175.13
1D_5P	41.01	240.03	533.18	1175.69
3D_FE	41.19	242.31	538.21	1172.4
	60% mixed damage			
	ω_1	ω_2	ω_3	ω_4
1D	37.39	201.30	460.81	924.63
1D_5P	37.39	200.94	460.51	924.23
3D_FE	37.57	220.51	455.13	947.03

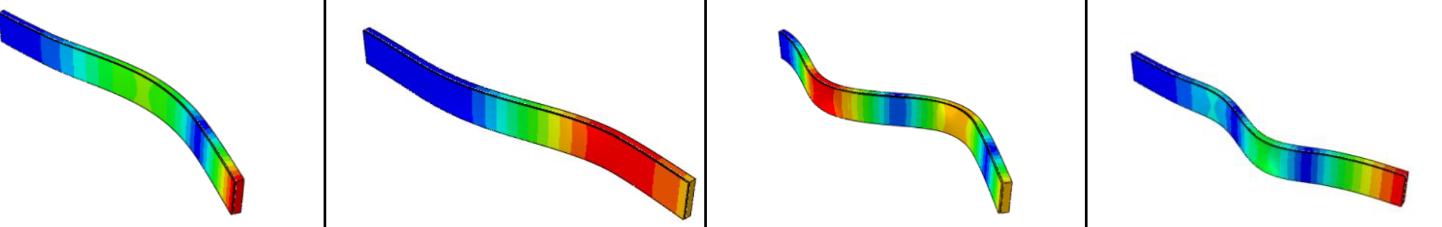
No damage



40% Damage

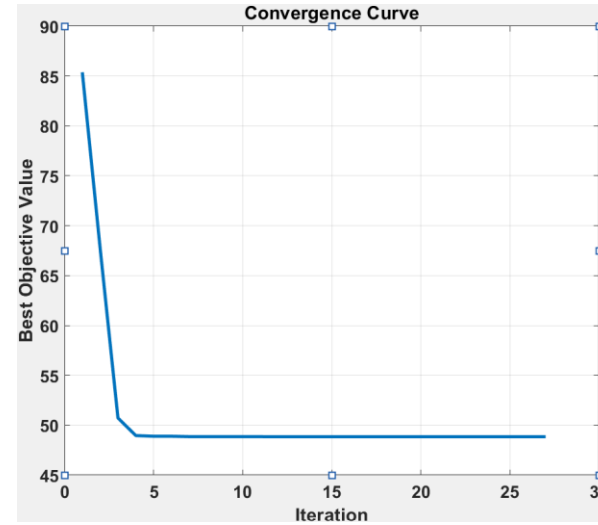
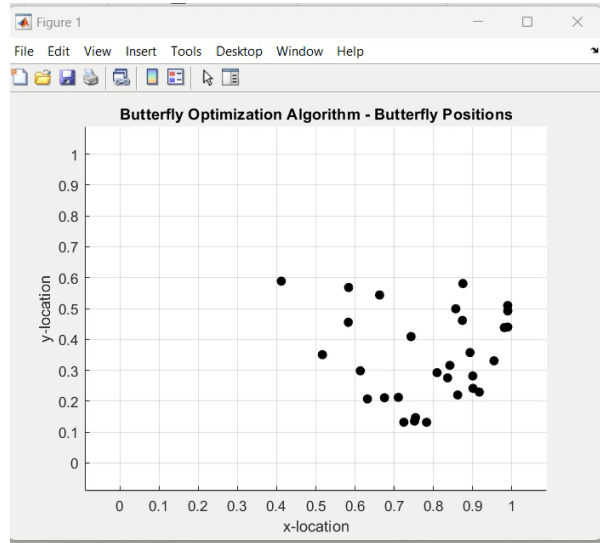


60% Damage



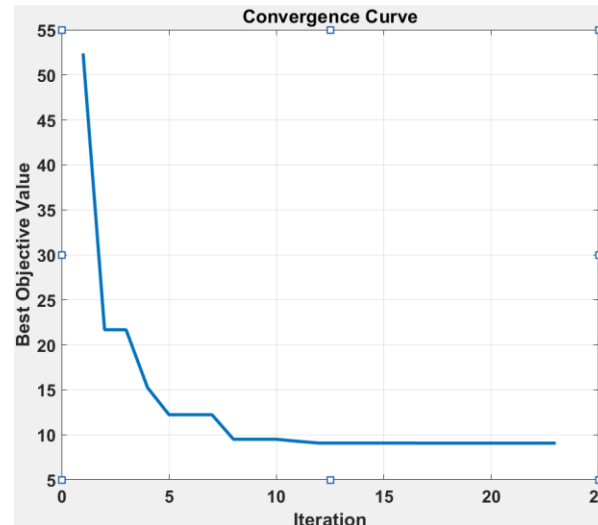
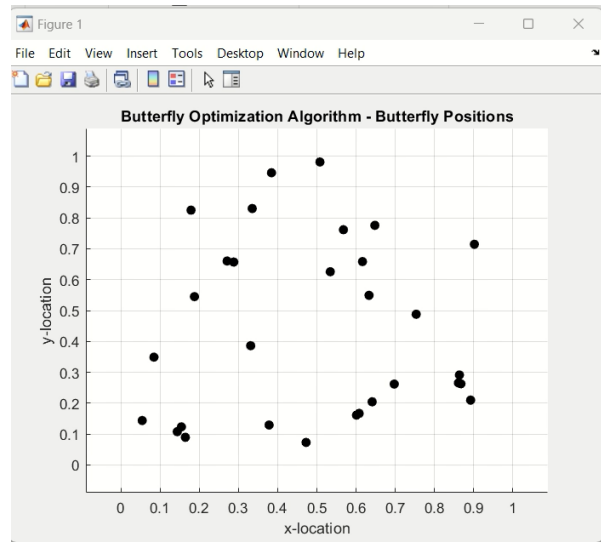
SHM analysis: 2-parameter delamination damage

60%



UBOA			
Model	x	y	Damage length
40% delamination			
3D_FE	0.3	0.7	0.4
1D_3P	0.3	0.7	0.4
1D_5P	0.3	0.7	0.4
60% delamination			
3D_FE	0.2	0.8	0.6
1D_3P	0.15	0.74	0.59
1D_5P	0.26	0.88	0.62

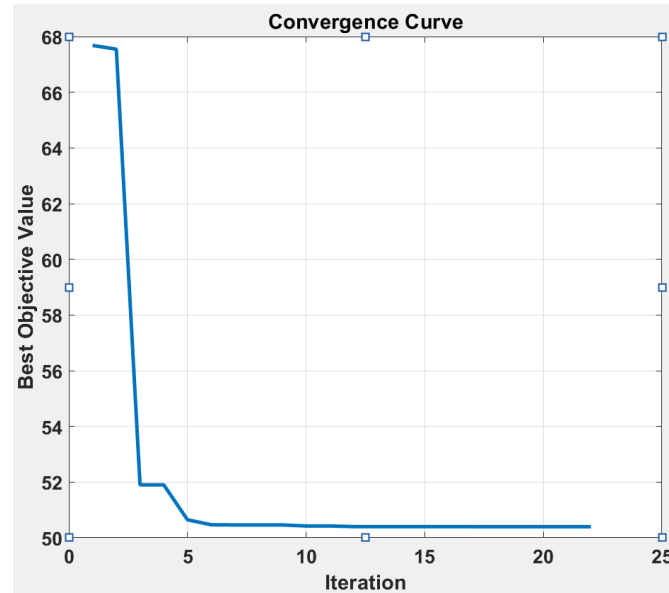
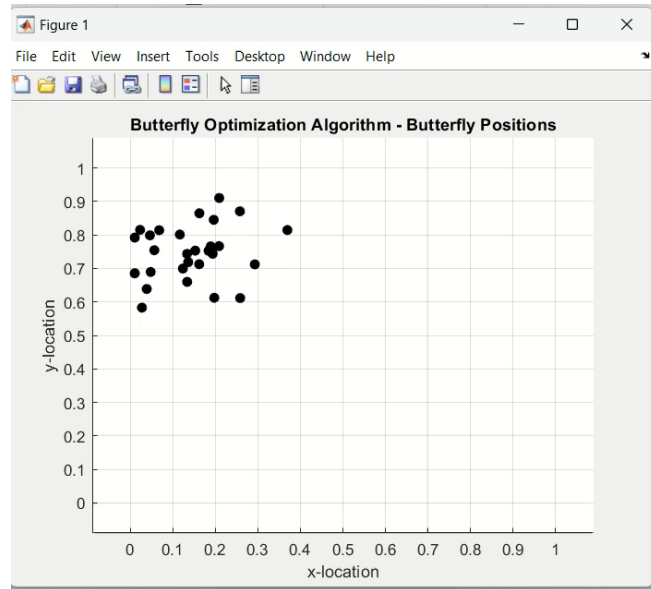
40%



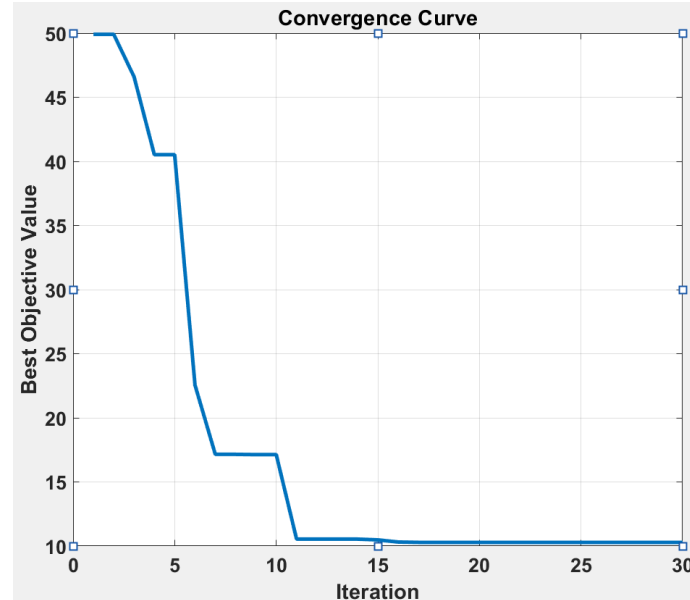
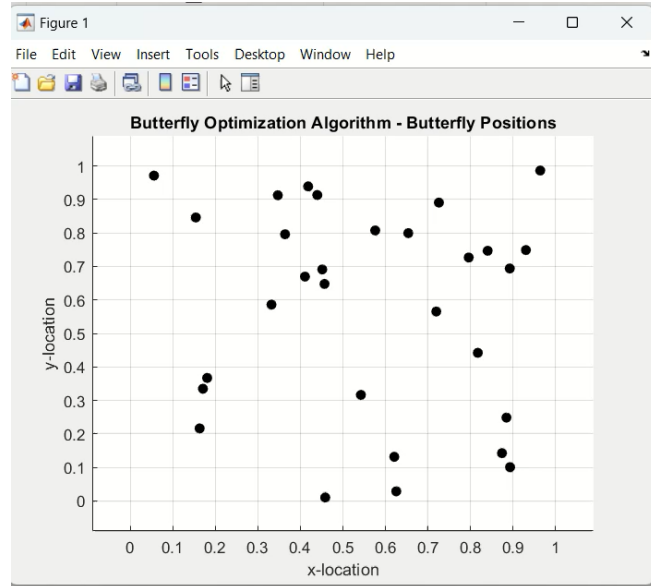
PSO			
Model	x	y	Damage length
40% delamination			
3D_FE	0.3	0.7	0.4
1D_3P	0.3	0.7	0.4
1D_5P	0.3	0.7	0.4
60% delamination			
3D_FE	0.2	0.8	0.6
1D_3P	0.15	0.74	0.59
1D_5P	0.14	0.74	0.6

SHM analysis: 2 parameter mixed damage

60%



40%

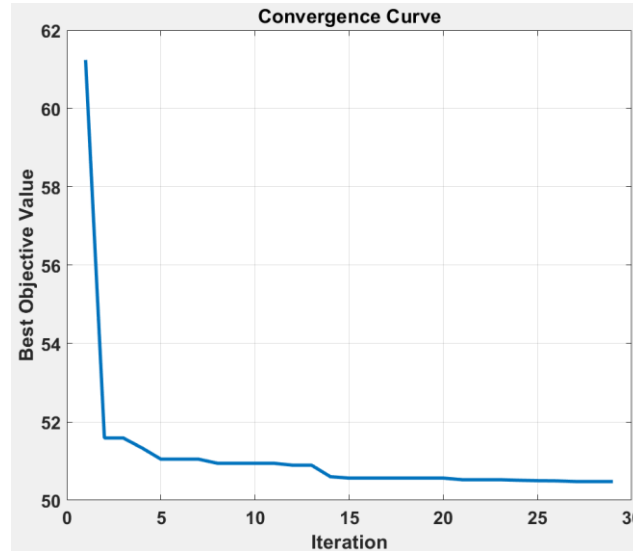
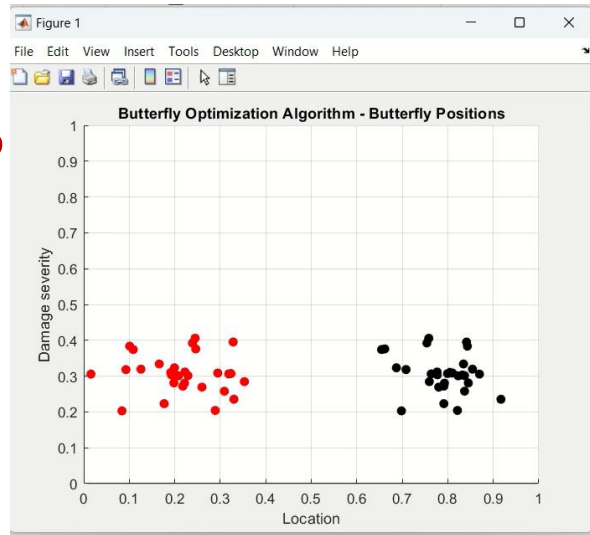


UBOA			
Model	x	y	Damage length
40% mixed damage			
3D_FE	0.3	0.7	0.4
1D_3P	0.28	0.69	0.41
1D_5P	0.28	0.69	0.41
60% mixed damage			
3D_FE	0.2	0.8	0.6
1D_3P	0.15	0.77	0.62
1D_5P	0.24	0.85	0.61

PSO			
Model	x	y	Damage length
40% mixed damage			
3D_FE	0.3	0.7	0.4
1D_3P	0.28	0.69	0.41
1D_5P	0.28	0.69	0.41
60% mixed damage			
3D_FE	0.2	0.8	0.6
1D_3P	0.19	0.79	0.59
1D_5P	0.19	0.79	0.59

SHM analysis: 3 parameter mixed damage

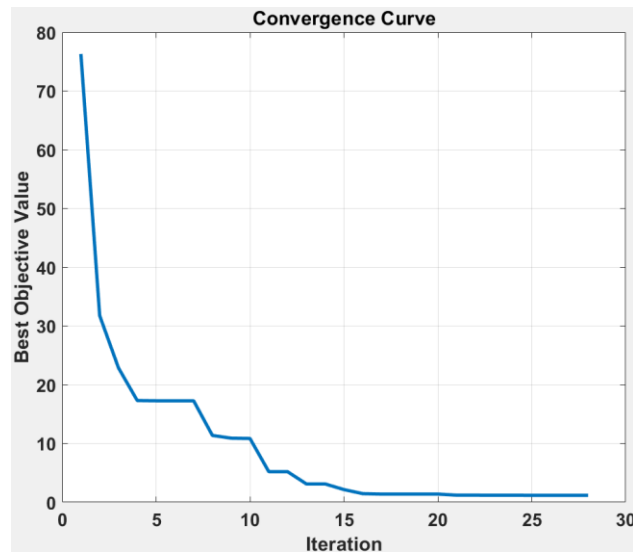
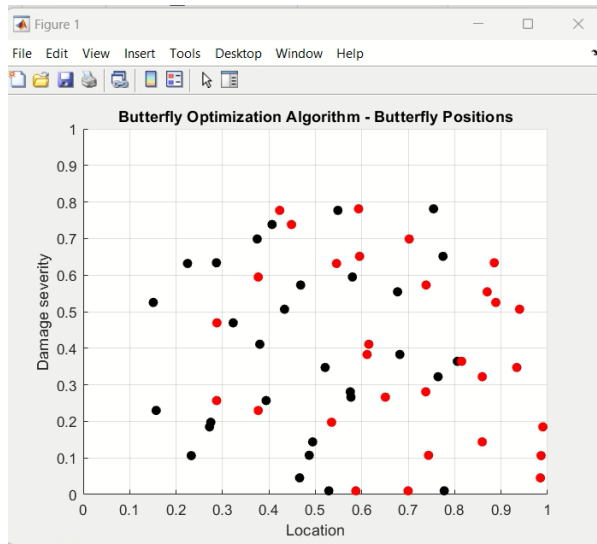
60%



UBOA				
Model	x	y	γ	Damage length
40% mixed damage				
3D_FE	0.3	0.7	0.27	0.4
1D_3P	0.29	0.71	0.24	0.42
1D_5P	0.33	0.74	0.27	0.41
60% mixed damage				
3D_FE	0.2	0.8	0.27	0.6
1D_3P	0.19	0.78	0.29	0.59
1D_5P	0.18	0.77	0.28	0.59

PSO				
Model	x	y	γ	Damage length
40% mixed damage				
3D_FE	0.3	0.7	0.27	0.4
1D_3P	0.29	0.71	0.24	0.42
1D_5P	0.29	0.70	0.24	0.41
60% mixed damage				
3D_FE	0.2	0.8	0.27	0.6
1D_3P	0.17	0.76	0.3	0.59
1D_5P	0.17	0.76	0.3	0.59

40%





Outline

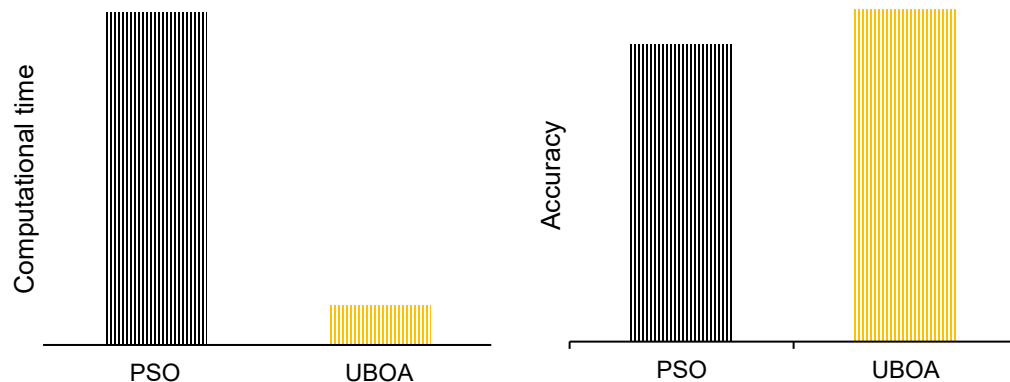
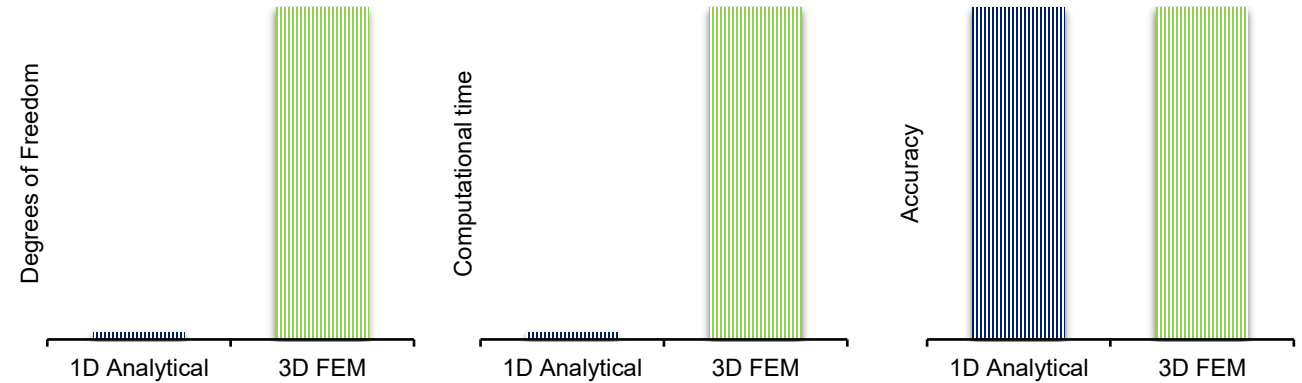
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Summary

1D analytical tool

- Simple computational tool for structural design as well as for SHM
- Simplicity and speed of the tool
- Performance and efficiency of 1D model compared to 3D FEM



UBOA algorithm

- Superior convergence rates in terms of number of iterations and time
- UBOA: 75-80% increase in speed, 80-88% lower number of iterations
- Random switch b/w local and global search is suppressed, minimising the randomisation of local search on global convergence, leading to better efficiency.

Acknowledgement

This research is supported by project PLEIADES (Advancing Aerospace Composites through Induction Welding & New Vitrimeric Formulations Enhanced by Integrated Photonic Sensors, Providing Data to Digital Supply Chain, SHM, Maintenance) - European Union's Horizon Europe research and innovation program under grant agreement no. 101192721.

<https://pleiades-project.eu/>

The authors acknowledge RTX Collins Aerospace - Ice Protection Businesses and teams for providing CNT Heater Ice Protection Systems for analysis and testing.