Reliability Design of Naval Multilayer Fiber Composites Panels Using Evolutionary Algorithms and Stochastic Structural Mechanics

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Abstract

• A methodology based on evolutionary algorithms and stochastic structural mechanics for the design of high-reliability naval multilayer composite structural panels, is presented.

•Mechanical response of structural panels was modeled using the Multilayer Classical Plate Theory and Finite Element Method.

•Sea wave loads were modeled as stochastic dynamic loads using the Simulation Based Reliability Analysis approach.

•The structural reliability of the panel, as function of the composite ply's fiber direction, was considered as a design variable.

•In order to maximize the structural reliability, an optimization methodology based on stochastic algorithms, was proposed.

Outline

- Motivation
- Composite materials
- Computational FEM model
- Stochastic structural mechanics
- Particle swarm optimization methodology - PSOM
- Sea wave load modeling
- Proposed SBRA/PSOM design metodology
- Computational implementation
- Conclusions

Motivation

- The use of composite materials on structural naval applications has been growing in the last decades → **great effort on analysis and design techniques**.

- Large number of design variables and the complexity of the mechanical behavior appears in composite structural design → **projects much more difficult and laborious**.

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www.gizmodo.com.au

Motivation

Botes Orca (Cotecmar): Proyecto de investigación en diseño de estructuras navales con materiales compuestos (2009-2010)

INDUMIL COLOMBIA

COTECMAR

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Composite materials

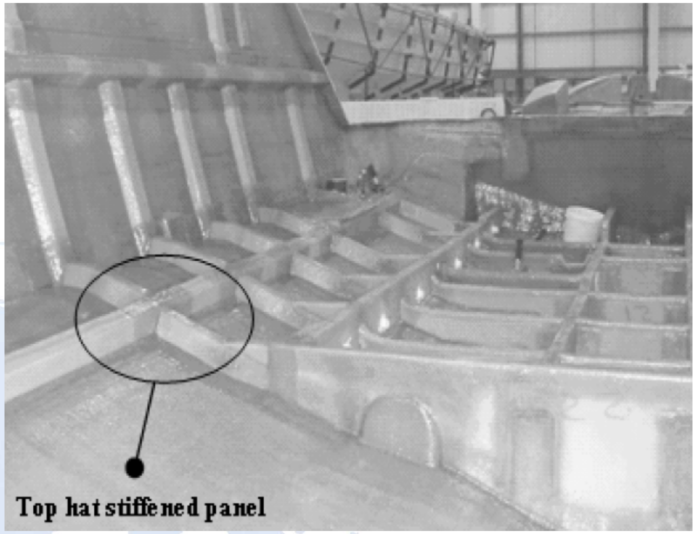
•Composite laminate plates are constituted by bonded layers (in general: orthotropic layers)

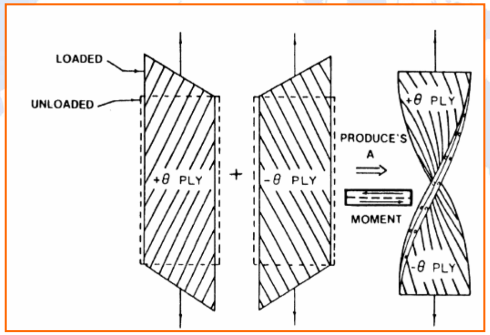
•Coupled extensional-bending effects appears.

•Mechanical behavior of composite materials is rather than straightforward.

•Naval structures are built using reinforced panels, showing complex structural response.

•In general is not possible to model the entire structure as a plate assembled system. In general plate formulations and continuum mechanics models must be used.

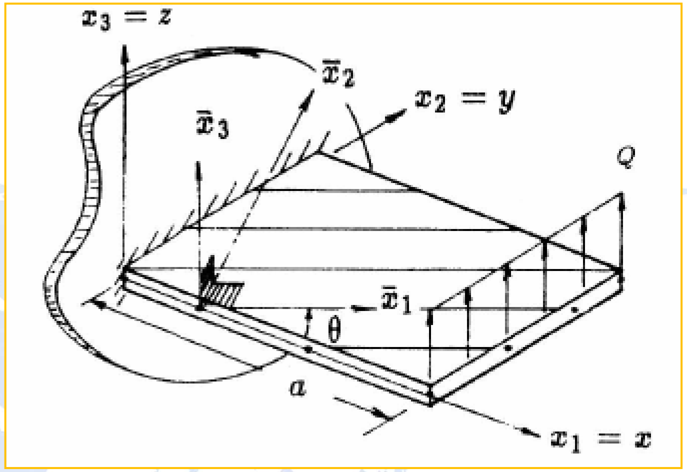




Composite materials

- **The orthotropic plate.** The in-plane stress-strain relation in material coordinates in a single orthotropic lamina are:

$$\begin{Bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_6 \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 \\ 0 & 0 & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \bar{\varepsilon}_1 \\ \bar{\varepsilon}_2 \\ \bar{\varepsilon}_6 \end{Bmatrix}$$



$$\bar{Q}_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}}, \quad \bar{Q}_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}}$$

$$\bar{Q}_{12} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}}, \quad \bar{Q}_{66} = G_{12}$$

$$\begin{Bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_6 \end{Bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\cos\theta\sin\theta \\ \sin^2\theta & \cos^2\theta & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix}$$

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Composite materials

- Fiber-reinforced composites are manufactured in form of thin sheets (laminae or layers).

- The classical laminated plate theory (CLPT) is based on Kirchhoff-Love plate theory (thin plate theory):

Straight lines perpendicular to the midplane before deformation remains (1) straight, (2) inextensible and (3) normal to the midsurface after deformation:

$$\boxed{\gamma_{xz} \rightarrow \sigma_{xz} \equiv 0 \quad \text{and} \quad \gamma_{yz} \rightarrow \sigma_{yz} \equiv 0}$$

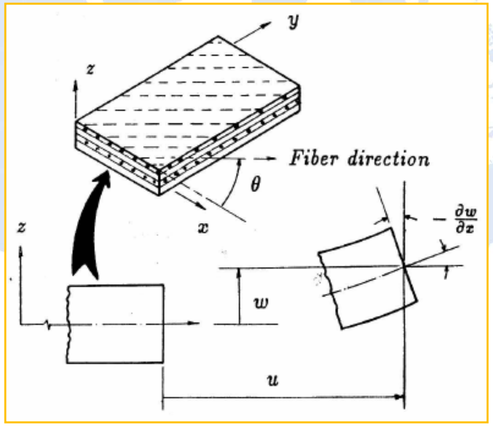
i.e. classical plate theory does **not account for transverse deformation and stress state**.

Composite materials

- **Displacements and strains hypothesis of CLPT:**
  - The layers are bonded perfectly bonded together
  - Material of each layer is linear elastic and orthotropic
  - Each layer is of uniform thickness
  - The strain are small

- First two assumptions of Kirchhoff hypothesis require that displacement to be such that:

$$\boxed{\begin{aligned} u_1(x,y,z,t) &= u(x,y,t) + z\phi_1(x,y,t) \\ u_2(x,y,z,t) &= v(x,y,t) + z\phi_2(x,y,t) \\ u_3(x,y,z,t) &= w(x,y,t) \end{aligned}}$$



Composite materials

- Equations of motion (govern equations) can be expressed in terms of displacement as:

- ***x-direction:***

$$\frac{\partial}{\partial x}\left[A_{11}\frac{\partial u}{\partial x}+A_{12}\frac{\partial u}{\partial y}+A_{16}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+B_{11}\left(-\frac{\partial^2 w}{\partial x^2}\right)+B_{12}\left(-\frac{\partial^2 w}{\partial y^2}\right)\right.$$
$$\left.+B_{16}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]+\frac{\partial}{\partial y}\left[A_{16}\frac{\partial u}{\partial x}+A_{26}\frac{\partial u}{\partial y}+A_{66}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right.$$
$$\left.+B_{16}\left(-\frac{\partial^2 w}{\partial x^2}\right)+B_{26}\left(-\frac{\partial^2 w}{\partial y^2}\right)+B_{66}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]=I_0\frac{\partial^2 u}{\partial t^2}+I_1\frac{\partial^3 w}{\partial x\partial t^2}$$

Composite materials

- ***y-direction:***

$$\frac{\partial}{\partial x}\left[A_{16}\frac{\partial u}{\partial x}+A_{26}\frac{\partial v}{\partial y}+A_{66}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+B_{16}\left(-\frac{\partial^2 w}{\partial x^2}\right)+B_{26}\left(-\frac{\partial^2 w}{\partial y^2}\right)\right.$$

$$\left.+B_{66}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]+\frac{\partial}{\partial y}\left[A_{12}\frac{\partial u}{\partial x}+A_{22}\frac{\partial v}{\partial y}+A_{26}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right.$$

$$\left.+B_{12}\left(-\frac{\partial^2 w}{\partial x^2}\right)+B_{22}\left(-\frac{\partial^2 w}{\partial y^2}\right)+B_{26}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]=I_0\frac{\partial^2 v}{\partial t^2}+I_1\frac{\partial^3 w}{\partial y\partial t^2}$$

Composite materials

- ***z-direction:***

$$\frac{\partial^2}{\partial x^2}\left[B_{11}\frac{\partial u}{\partial x}+B_{12}\frac{\partial v}{\partial y}+B_{16}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+D_{11}\left(-\frac{\partial^2 w}{\partial x^2}\right)+D_{12}\left(-\frac{\partial^2 w}{\partial y^2}\right)\right.$$

$$\left.+D_{16}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]+2\frac{\partial^2}{\partial x\partial y}\left[B_{16}\frac{\partial u}{\partial x}+B_{26}\frac{\partial v}{\partial y}+B_{66}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right.$$

$$\left.+D_{16}\left(-\frac{\partial^2 w}{\partial x^2}\right)+D_{26}\left(-\frac{\partial^2 w}{\partial y^2}\right)+D_{66}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]$$

$$+\frac{\partial^2}{\partial y^2}\left[B_{12}\frac{\partial u}{\partial x}+B_{22}\frac{\partial v}{\partial y}+B_{26}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right.$$

$$\left.+D_{12}\left(-\frac{\partial^2 w}{\partial x^2}\right)+D_{22}\left(-\frac{\partial^2 w}{\partial y^2}\right)+D_{26}\left(-2\frac{\partial^2 w}{\partial x\partial y}\right)\right]+q=I_0\frac{\partial^2 w}{\partial t^2}+I_1\left(\frac{\partial^3 u}{\partial x\partial t^2}+\frac{\partial^3 v}{\partial y\partial t^2}\right)$$

Composite materials

- For the **uncoupled case**, the transverse deflection *w* under applied transverse force *q* is governed by:

$$-D_{11}\left(-\frac{\partial^4 w}{\partial x^4}\right)+2\left(D_{12}+2D_{66}\right)\frac{\partial^4 w}{\partial x^2 \partial y^2}+D_{22}\frac{\partial^4 w}{\partial y^4}-4\left(D_{16}\frac{\partial^4 w}{\partial x^3 \partial y}+D_{26}\frac{\partial^4 w}{\partial x \partial y^3}\right)+q=I_0\frac{\partial^2 w}{\partial t^2}$$

- **These equations are so complex! →** In general, closed solutions does not exist. But, numerical (approximates) solutions can be found:

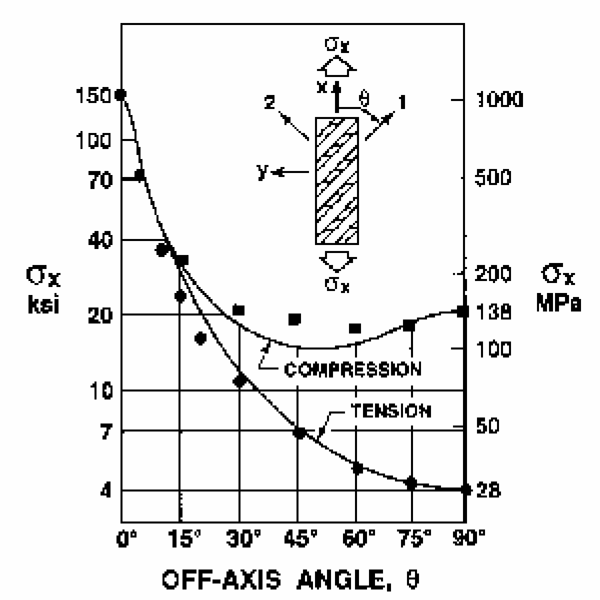
  – Finite difference method
  – **Finite element method**
  – Boundary element method

Composite materials

- Tsai-Hill failure criteria is based on Hill's failure criteria for anisotropic materials, adapted to failure analysis on composite materials. Mathematically:

$$f = \frac{\sigma_{11}^2}{X^2} - \frac{\sigma_{11}\sigma_{22}}{XY} + \frac{\sigma_{22}^2}{Y^2} + \frac{\tau_{12}^2}{S^2} > 1$$

  - ***f*** : failure index
  - σ_{11}, σ_{22} y τ_{12} : plane stress tensor components.
  - ***X***, ***Y*** y ***S*** : Longitudinal strength, transversal strength and shear strength, respectively.



Computational FEM model

- The finite element formulation for CPLT is obtaind from weak form of govern equations (virtual work principle) given by:

$$\boxed{\int_{\Omega} \boldsymbol{\sigma}^T \delta \boldsymbol{\varepsilon} d\Omega + \int_{\Omega} \mathbf{b} \delta \mathbf{u} d\Omega + \int_{\Gamma} \mathbf{t}_{\Gamma} \delta \mathbf{u}_{\Gamma} d\Gamma = 0}$$

- In this way, we obtain:

$$\boxed{\sum_{e=1}^{nel} \left[\int_{\Omega_e} \mathbf{Q}^e \mathbf{B}^e d\Omega_e \right] \mathbf{u}_e = \sum_{e=1}^{nel} \left[\int_{\Omega_e} \mathbf{b}^e \cdot \mathbf{B}^e d\Omega \right] + \sum_{e=1}^{nel} \left[\int_{\Gamma_e} \mathbf{t}_{\Gamma} \cdot \mathbf{B}^e{}_{\Gamma} d\Gamma \right]}$$

Computational FEM model

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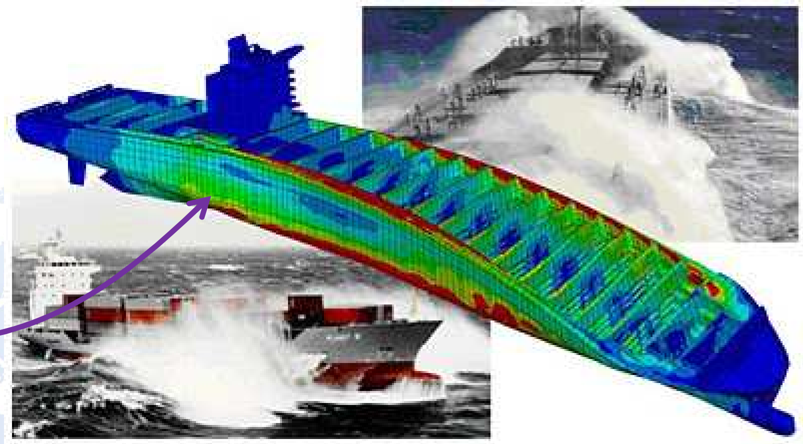


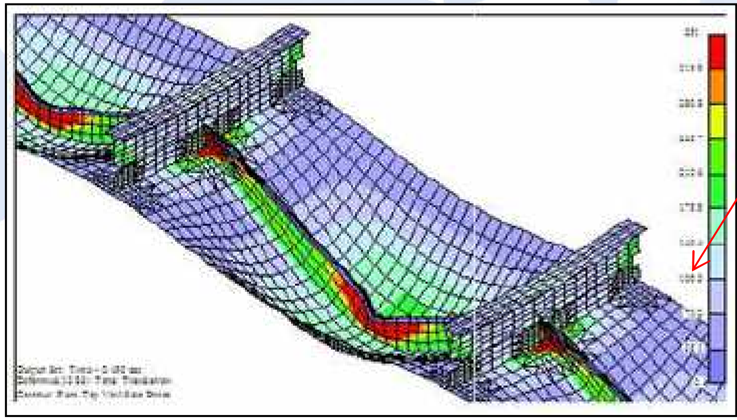
$$\int_{\Omega} \boldsymbol{\sigma}^{T} \delta\boldsymbol{\varepsilon}\, d\Omega + \int_{\Omega} \mathbf{b}\, \delta\mathbf{u}\, d\Omega + \int_{\Gamma} \mathbf{t}_{\Gamma} \delta\mathbf{u}_{\Gamma}\, d\Gamma = 0$$

Domain's discretization

$$\sum_{e=1}^{nel}\left[\int_{\Omega_e} \mathbf{Q}^{e}\mathbf{B}^{e}\, d\Omega_e\right]\mathbf{u}_e = \sum_{e=1}^{nel}\left[\int_{\Omega_e} \mathbf{b}^{e}\cdot\mathbf{B}^{e}\, d\Omega\right] + \sum_{e=1}^{nel}\left[\int_{\Gamma_e} \mathbf{t}_{\Gamma}\cdot\mathbf{B}^{e}{}_{\Gamma}\, d\Gamma\right]$$

Computational FEM model

- Generic discretization of continuum problems.
- Treatments of complex geometries, loads and boundary conditions.
- Flexibility for implementation of material models



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Computational FEM model

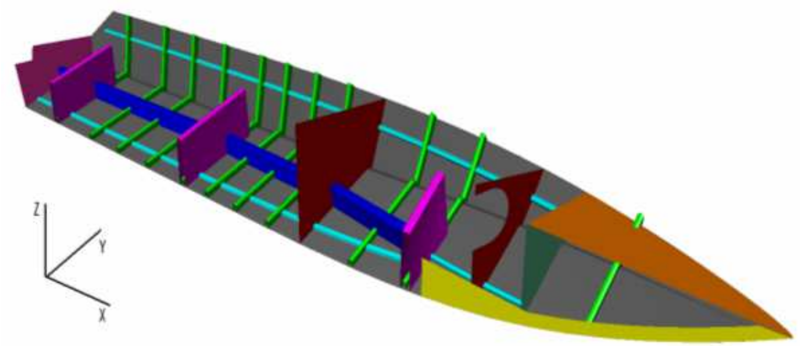
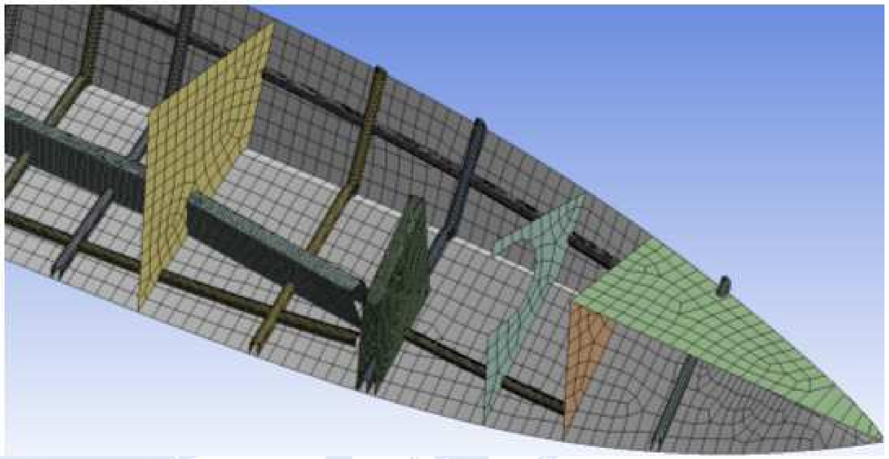
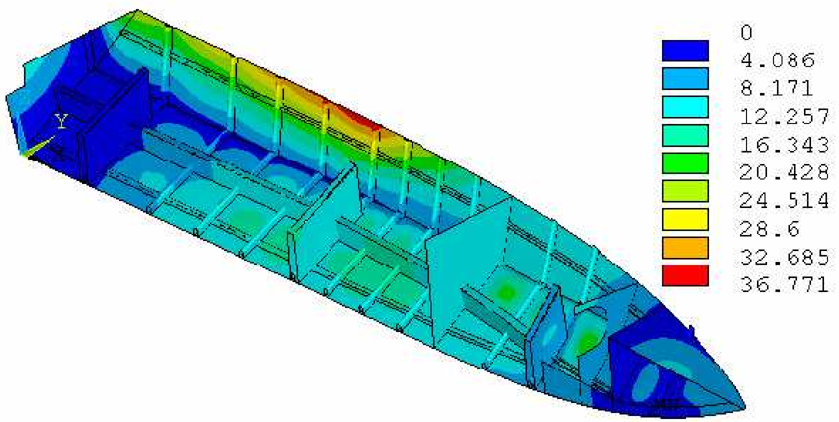


Ilustración 3 Sección simétrica del casco





Optimization in engineering design

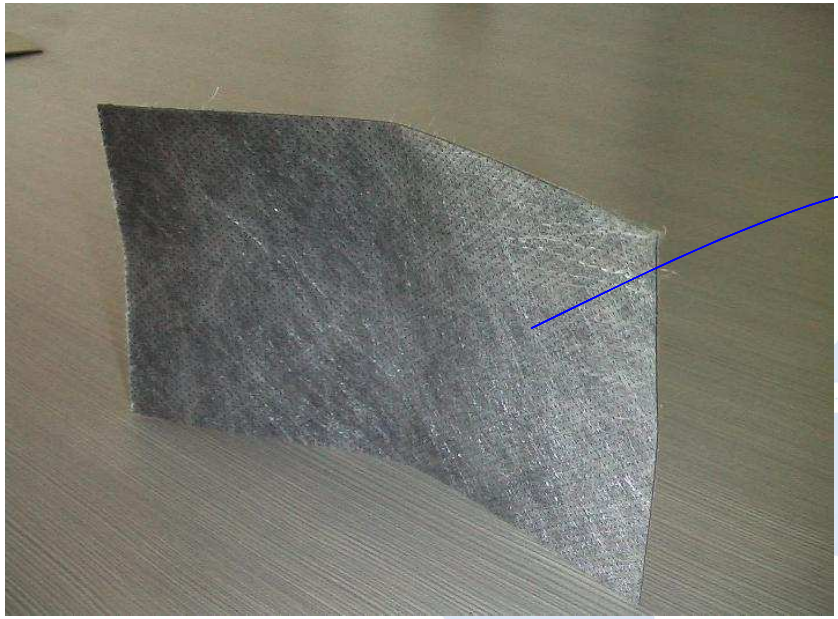
"The development of an accurate model of the system, in order to analyze its response (internal and external) to its environment, and the use of an optimization method to determine the characteristics of the system that best achieve a specific objective, also fulfilling certain restrictions prescribed in the features and response of system"

-O. Hughes

Stochastic structural mechanics

- The **presence of uncertainty** in the analysis and design of naval composite structures has always been recognized.
- Traditional approaches **simplified the problem** by considering the uncertain parameters to be deterministic, and accounted for the uncertainties through the use of empirical safety factors.
- An alternative way to look at the problem is consider **stochastic nature** of the variables involved in the problem, such as, strength, geometrical dimensions, etc.
- In this case, on might measure the **probability of failure** to satisfy some performance criterion and the corresponding term would be risk and/or failure probability.

Stochastic structural mechanics



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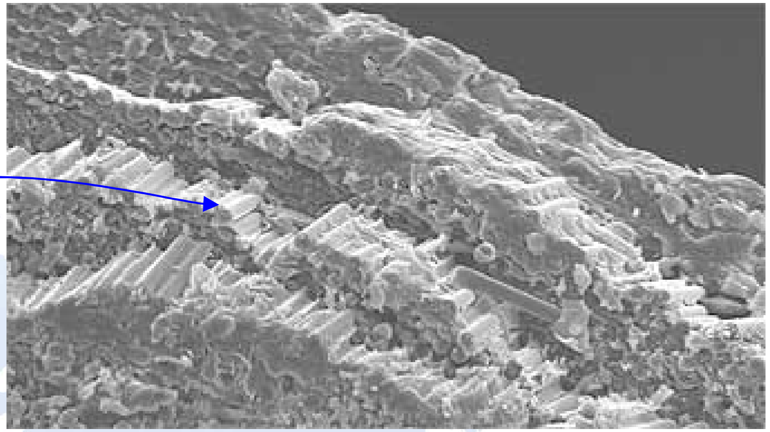
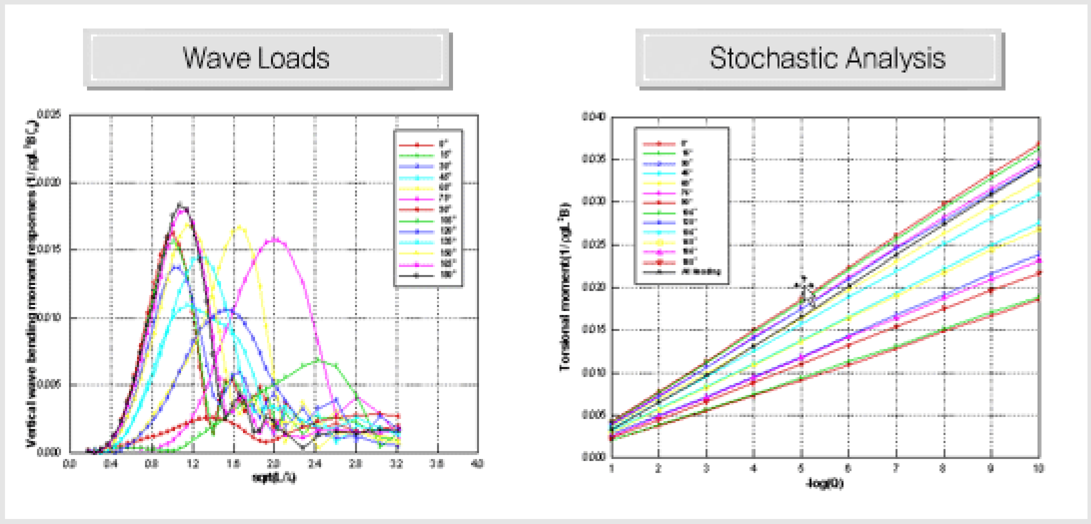


solutions.3m.com

Stochastic properties in composites

Stochastic structural mechanics

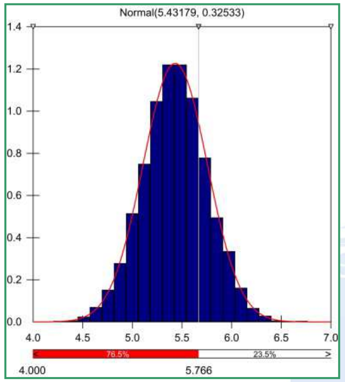
www.ivt.ntnu.no

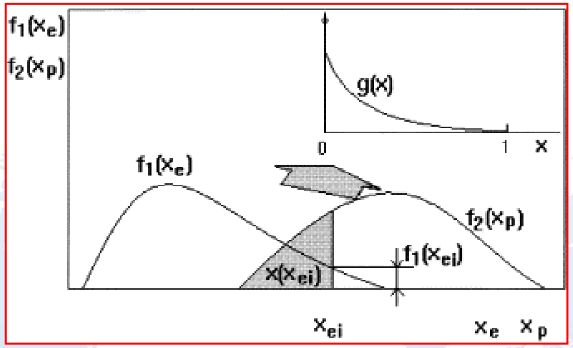


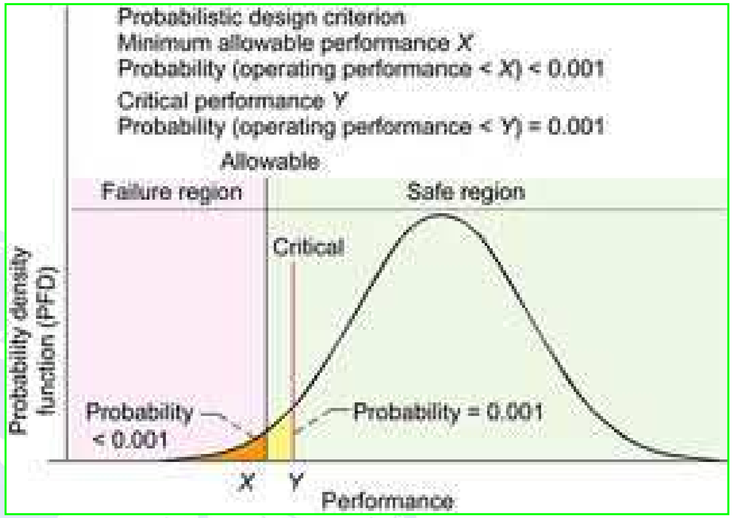
www.krs.co.kr

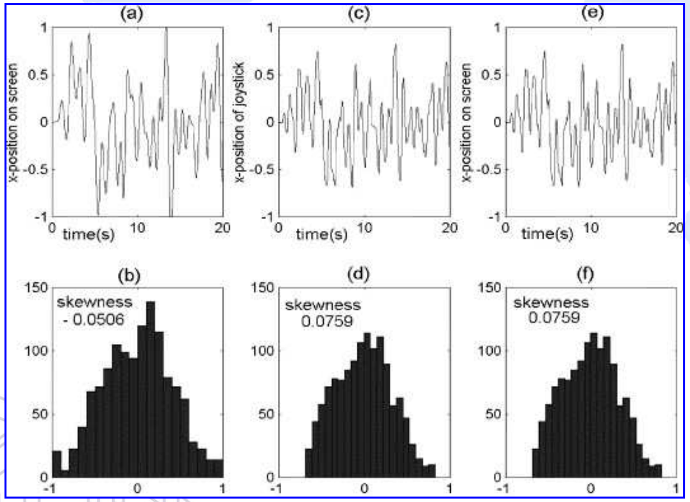
Stochastic sea waves

Stochastic structural mechanics









www.grc.nasa.gov

www.sciencedirect.com

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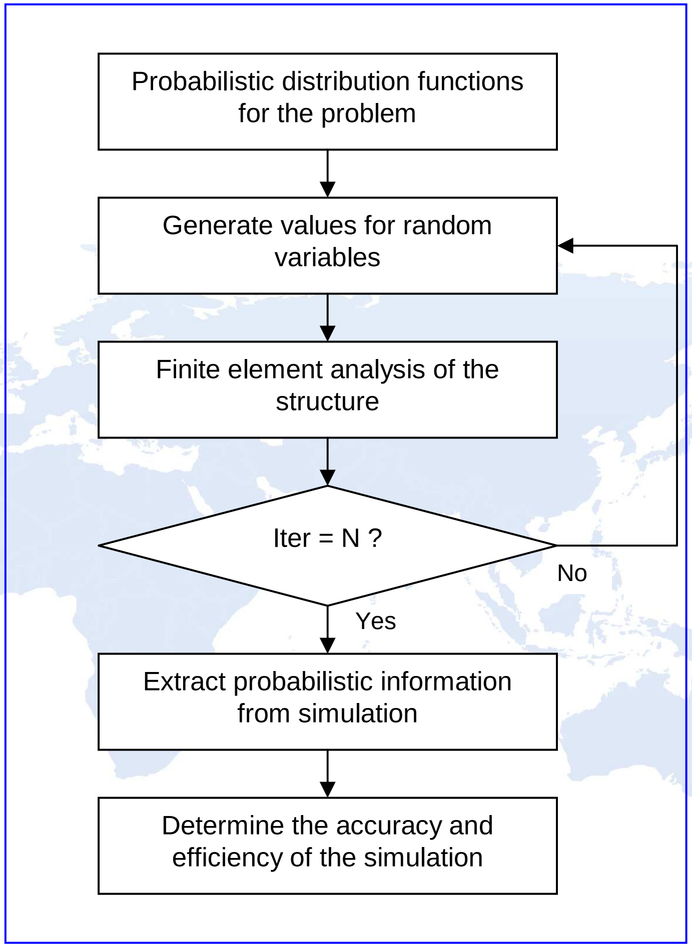
Stochastic structural mechanics

- Several methods with various degrees of complexity have been proposed to estimate the probability of failure.

- In any case, estimating the probability of failure using these techniques requires a background in probability and statistics.

- The method commonly used for this purpose is called the **Monte Carlo Simulation Technique**.



Optimization methods

- **Derivatives based methods:**
  - Conjugated gradient methods
  - Linear and non-linear programming
- **Stochastics (metahuristics) methods:**
  - Genetic algorithms
  - Differential evolution
  - Particle swarm optimization

Particle swarm optimization

- The formulation of the optimal structural design problem is built in terms of numerical optimization. In these terms, the minimization problem can be stated as follow:

Given a set of parameters $\mathbf{x}$ minimize a function $f(\mathbf{x})$
subjected to the restrictions $g_j(\mathbf{x}) \leq 0$

- In this work objective function $f(\mathbf{x})$ is given by *P(F>Fperm) .i.e. minimum probability of failure or maximum structural relibility.*

- Only ply angles in laminate are considered as parameters design.

Particle swarm optimization

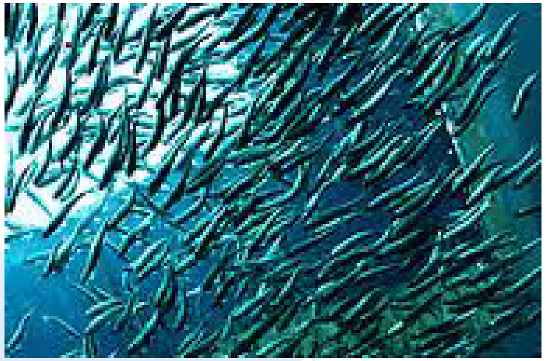
- As presented by Parsopoulos and Vrahatis the objective function is augmented with a “penalty” factor H(**x**), which contains the information from the restriction:

$$F(\mathbf{x}) = f(\mathbf{x}) + H(\mathbf{x})$$
$$H(\mathbf{x}) = \sum \theta(q_i(\mathbf{x}))q_i(\mathbf{x})^{\gamma(q_i(\mathbf{x}))}$$
$$q_i(\mathbf{x}) = \max\{g_i(\mathbf{x}),0\}$$

- The term $q_i(\boldsymbol{x})$ is known as the relative violation of the restriction. The task of the functions $\Theta(q_i)$ and $\gamma(q_i)$ is to control the input from the violation to the penalty factor.

Particle swarm optimization

- The particle swarm optimization method, introduced by Kennedy and Eberhart (1995)
- The technique was originally conceived to simulate the behavior of bird flocks or fish shoals in their search for food.
- As the distance between each individual and the food position is modeled through a function, it was quickly noticed that any function could be minimized by the use of the technique.



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Particle swarm optimization

- The idea behind the method is the fact the individuals from the population share certain information, which is, the best position that has been found so far (in general terms, the best merit).
- Each individual uses this information beside the knowledge of its own best found position to direct its search.
- If the position of an individual ***i*** in the search space is $\boldsymbol{x}_i$, the best position found so far by the entire population is $\boldsymbol{x}^g$ and the best position found by the individual is $\boldsymbol{x}^p$, the search rule is:

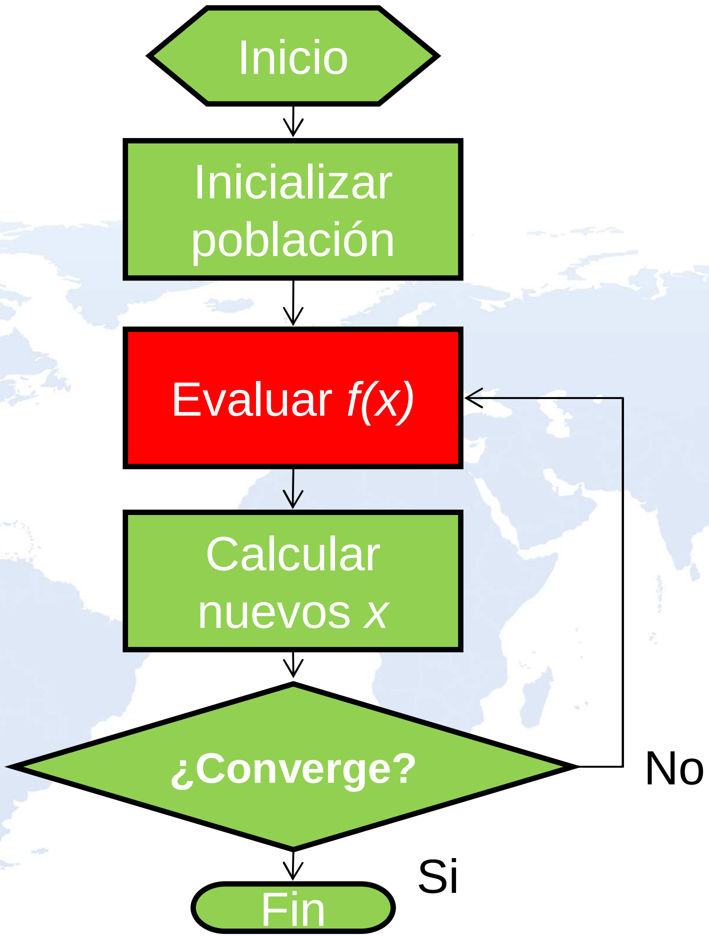
$$v_{ij}^{k+1} = \chi\left(\omega v_{ij}^{k} + c_1 r_1\left(x_j^k - x_{ij}^k\right) + c_2 r_2\left(x_{ij}^p - x_{ij}^k\right)\right)$$

$$x_{ij}^{k+1} = x_{ij}^{k} + v_{ij}^{k+1}$$

Particle swarm optimization

- The parameters $\boldsymbol{\omega}$, $\mathbf{c_1}$ and $\mathbf{c_2}$ are known as the inertia, cognition and confidence.
- The factor $\boldsymbol{\chi}$ is known as the constriction and its job is to prevent the swarm from exploding by the unbound increment of the velocity.
- The numbers r_1 and r_2 are randomly chosen from the interval.
- The search rule is applied iteratively until a convergence criterion is met, the desired optimum is found or we run out of time.

Optimization : Swam particle method: computational implementation



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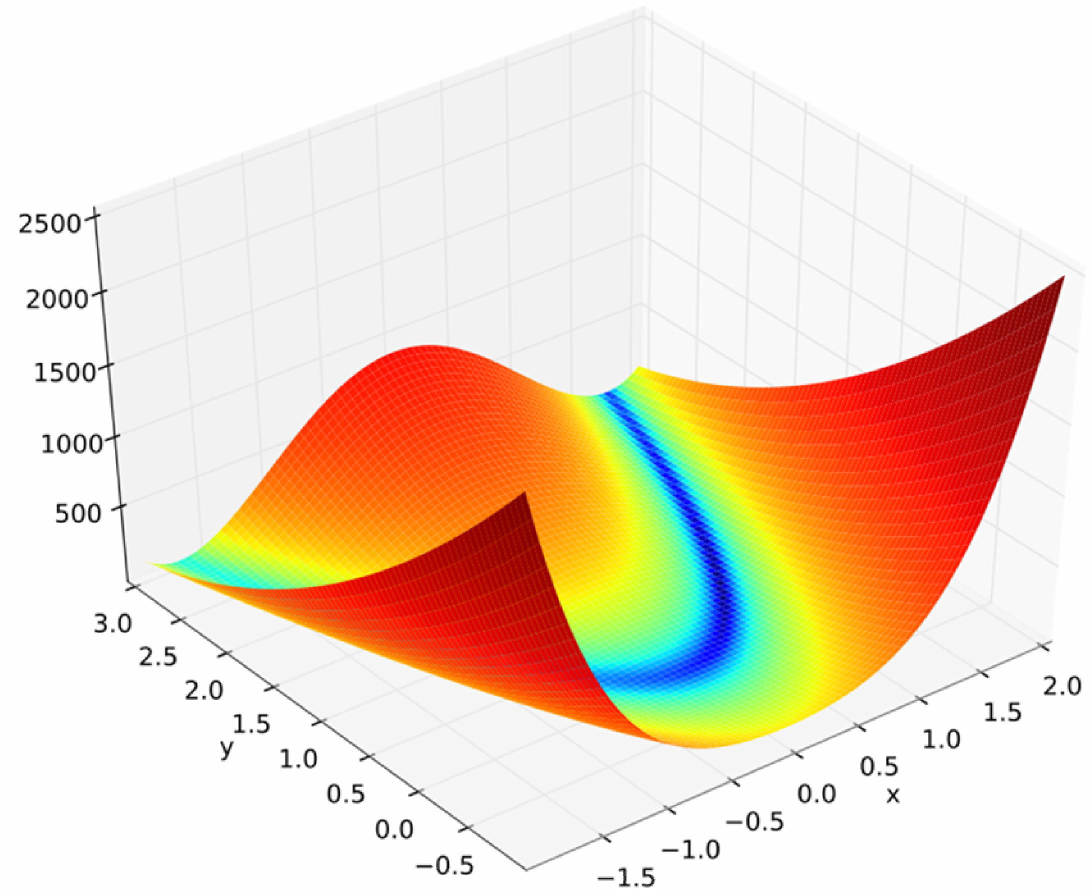
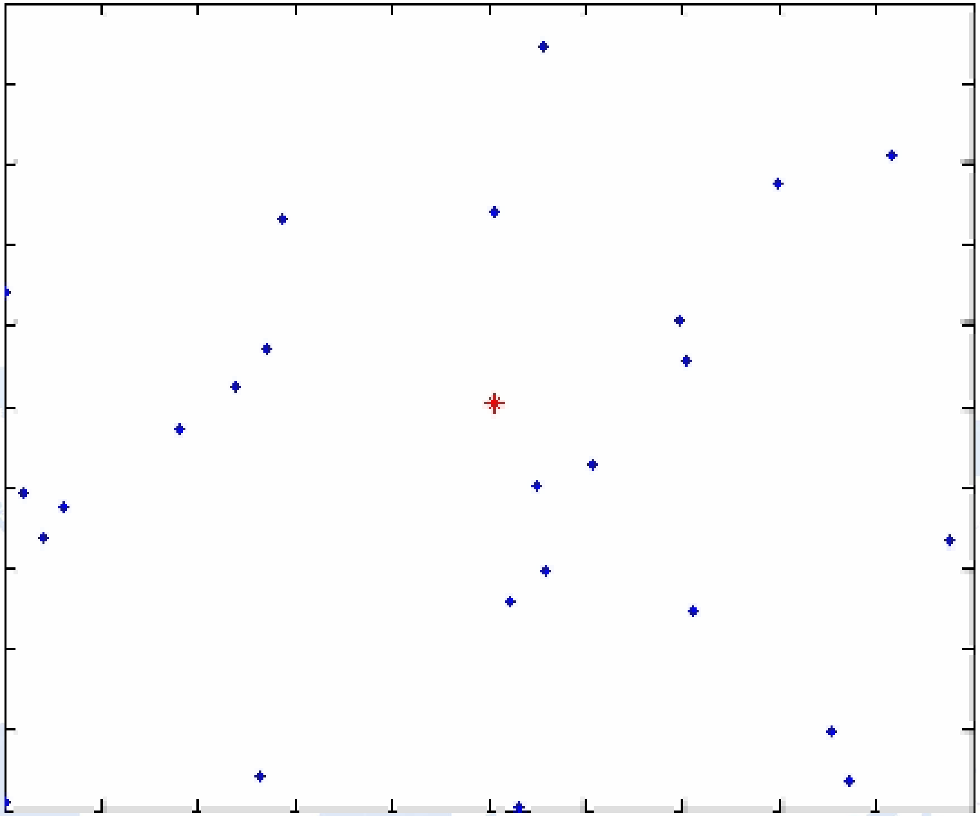
Optimization : Swarm particle method, an example





runOptimization.py
-Rutina de control principal

initStudy.py
-Crear carpetas y copiar archivos de análisis (export y comm)

optimizer.py
-Implementa algoritmos de búsqueda (Enjambre de Partículas, Evolución Diferencial)

problem.py
-Definición de función objetivo, función de restricciones y función de penalidad

Config.xml
-Almacena parámetros de algoritmos de búsqueda y de funcionamiento del programa (numero de procesos, etc)

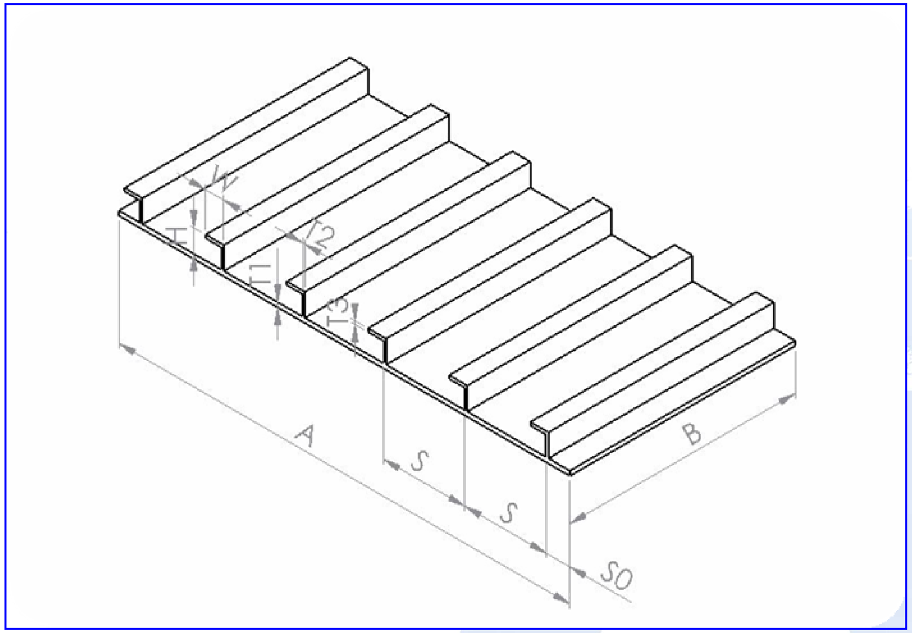
meshCreator.py
-Creación de la geometría paramétricamente y mallado

postProcess.py
-Extracción de los resultados de interés (DZ y Von Misses máximos)

SALOME

Code_Aster

Swarm optimization: an application example: Reinforced steel naval panel



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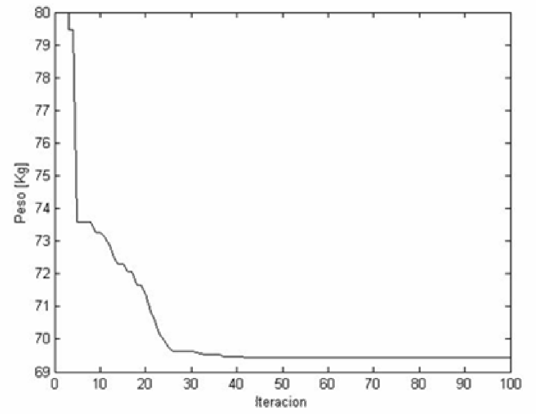
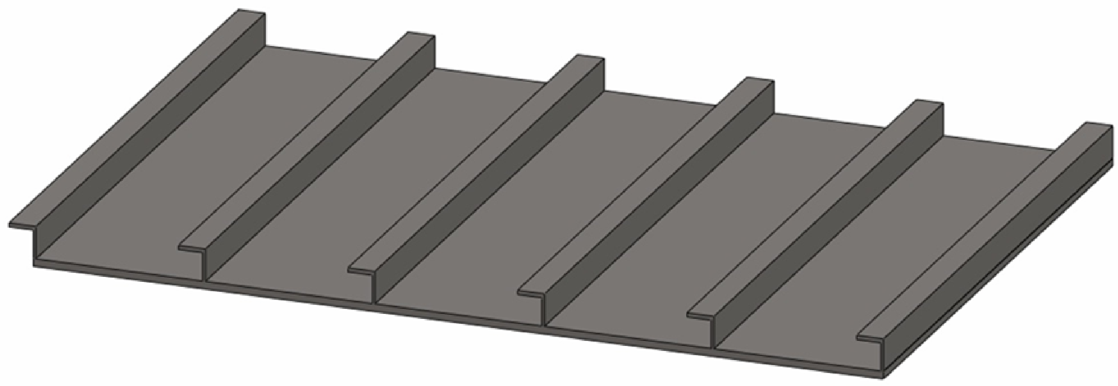
Swarm optimization: an application example: Naval panel optimization

F(S,Ti,W,H) = Weight			
$S > 0$	$T3 > 0$	$T3 < H$	$Ixx > Imin$
$T1 > 0$	$W > 0$	$W > T2$	$\delta max < \delta per$
$T2 > 0$	$H > 0$	$Smax > S > W$	$\sigma max < Sy$

Swarm optimization: an application example: Naval panel optimization





Swarm optimization: Computational Cost

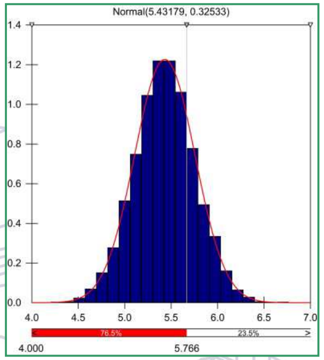
		Inicio	Fin	Duración
Caso 1	PSO	04/29/11 11:45:00	04/30/11 05:09:22	17:24
	DE	05/02/11 10:14:55	05/03/11 10:31:32	24:17
Caso 2	PSO	05/25/11 11:42:15	05/28/11 15:27:43	75:46
	DE	05/23/11 15:25:58	05/24/11 16:37:22	25:12
Caso 3	PSO	07/04/11 12:10:22	07/07/11 18:35:30	78:25
	DE	07/01/11 22:19:08	07/04/11 12:05:30	61:46

Sea wave load modeling

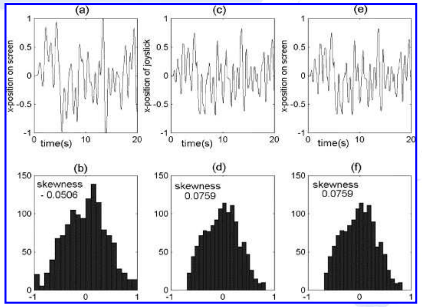
- This pressure distribution can be obtained directly from experimental data. In general, pressure distribution on the panel can be expressed mathematically through a function of the type:

$$\boxed{p(x,y,t) = P(t)X(x,y)}$$

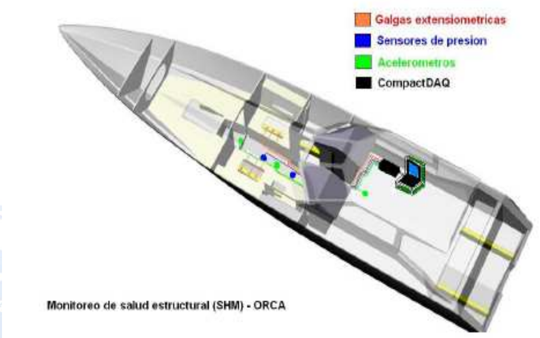
- In this work, function *P(t)* is taken as:

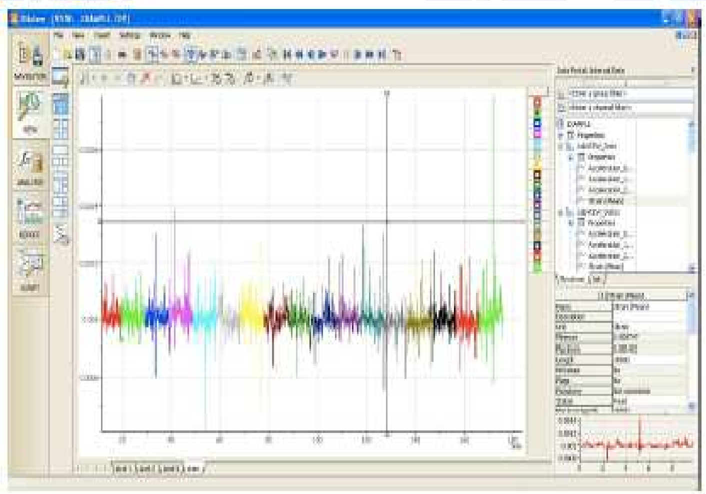


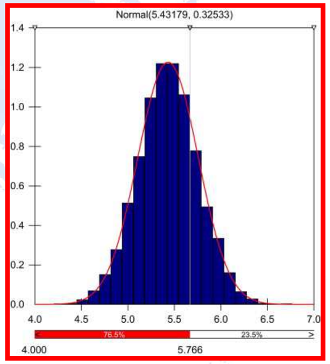
$$\boxed{P(t) = P_{\max}\left(\frac{t}{\alpha}\right)^{n} e^{-t/\theta}}$$



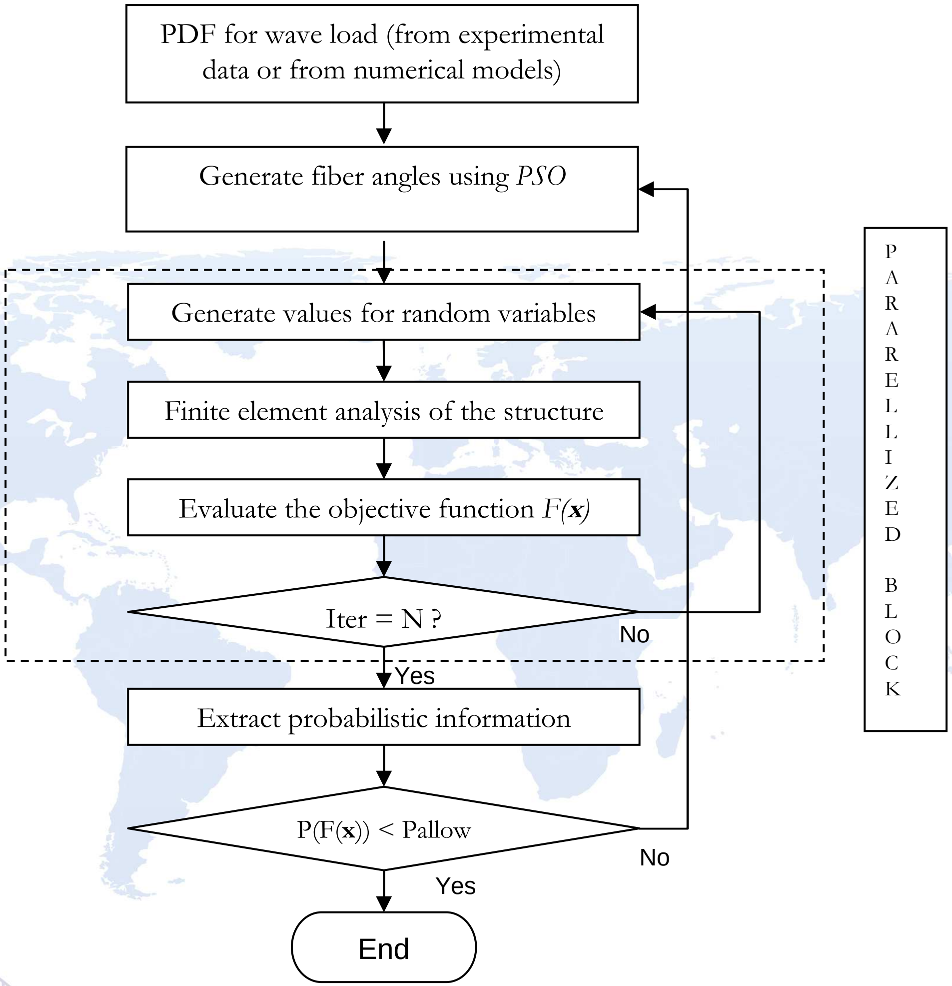
Sea wave load modeling







Proposed SBRA/SPOM design metodology



Computational implementation

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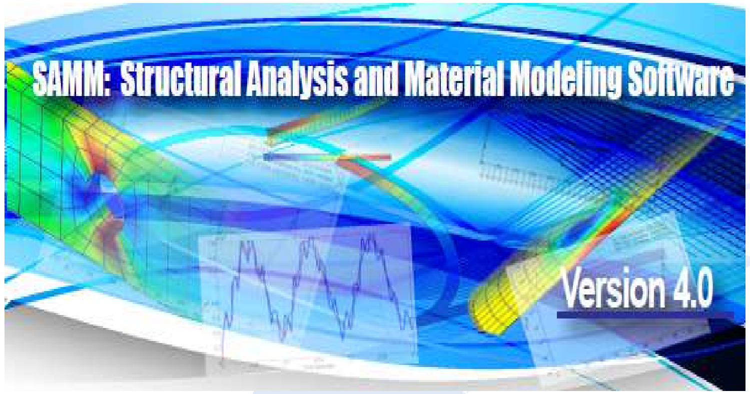
COTECMAR

- HP Proliant DL785G5, 32 processors, 256 GB RAM, 2 TB HD.
- +100 processors SPIDER (UTB)
- GRID COLOMBIA (RENATA)

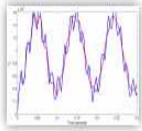
Computación de Alto Desempeño: HPCLAB



LINEAR DYNAMIC ANALYSIS

EIGENVALUE ANALYSIS

- Natural frequencies shaped
- Eigenvalue extraction algorithms
  - Conventional subspace iteration
  - Accelerated subspace iteration
  - Lanczos Method
  - Inverse iteration
  - Guyan reduction
- Extraction of zero frequencies(rigid body modes)
- Cyclic symmetric structure, given the mode shaped of one sector

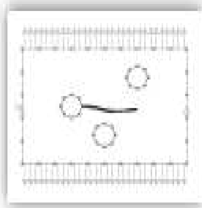


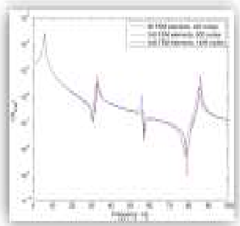
MATERIAL PROPERTIES

- Isotropic or orthotropic, temperature dependent
- Directional tensile, compressive, and shear failure stress for composite elements
- Laminated composites:
  - Classic composite plate theory
  - Sandwich plates
  - First order shear deformation theory
  - Tsai-Hill Failure Criteria
  - Tsai-Wu Failure Criteria

DIRECT TRANSIENT DYNAMIC ANALYSIS

- Newmark -Beta method for implicit time integration
- Lumped and consistent mass formulation
- Discrete damper elements and proportional (Raleigh)
- Nonzero initial conditions
- Time dependent boundary conditions
- Force due to moving frames of references
  - Linear and angular force





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ADVANCED ENGINEERING SOLUTIONS

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Conclusions

A methodology for optimizing naval panels made of laminated composites using genetic algorithms, stochastic mechanics and the finite element method, was presented. Through minimizing the probabilistic failure criteria of the panel in function of the direction of the fibers in the laminate, it is possible to find designs with high resistance sea loads for a given system.

Questions

Thank you!