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Different approaches to deal with Bounded-But-Unknown Uncertainties: Application to MEMS

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Random characteristics of cross sections catalogue for space trusses.

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On membrane elements with drilling degrees of freedom in topology optimization

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On Eigenfrequency Optimization of Plates with a Hole

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Multidisciplinary Optimization of Machine Elements

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A Cross-sectional Shape Initial Design Method for Automotive Frame Structures Using Genetic Algorithms

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Optimum Design of the Tooth Surface in the Helical Gears for the Noise Reduction Using a Response Surface Method

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Contribution to the optimization of closed-loop multibody systems : application to parallel manipulators

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Stress-constrained truss-type topology optimization problems that can be formulated and solved as linear or convex optimization problems

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Discrete Fiber Angle Optimization of General Shell Structures using a Multi-Phase Material Analogy

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Robust Optimal Design Formulation Using Gradient Index and Its Application to MEMS Structures

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Long-Distance, Gradient Based Identification of Corrosion Through Analysis of Piezo-Generated Impulse Transmission

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Identification of Leakages in Water Networks-Virtual Distortion Method Approach

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Design optimization in rotordynamics with eigenvalue constraints

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A branch-and-cut method for global optimization of minimum weight truss topology problems with stress, displacement, and local buckling constraints

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Reliability and Robustness of Optimized Continuous Caster Submerged Entry Nozzle

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Optimal design of shells against buckling under overall bending with shearing force taken into account

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Optimal design of annular plates against buckling under loadings controlled by displacements

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Structural Topology Optimization of Vibrating Structures with Specified Eigen-frequencies and Eigen-modes

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Finite element-based optimum reinforcament dimensioning of concrete plates and shells

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Optimum Design of the Bracket for Satellite Antenna

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Articulated Mechanism Design–Introduction of DOF Constraint

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Property Optimization of Vehicle Body Structure Elements using Simplified Models

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COMPARISON OF SUPPORT AND LAYOUT OPTIMIZATION METHODS

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Shape optimization of a truck aluminum wheel in integrated CAD/FEM environment

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On Application of Stochastic Optimization to Reconstruction of Spatial Random Microstructures

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Optimization of plastic strain-hardening plates of piece-wise constant thickness

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Chromosome Repairing in Genetic Methods for Multi-Objective Topology Optimization of Structures with Equality Constraint on Volume

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A Multi-Phase Level Set Model for Multi-Material Structural Optimization

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Range Zooming for Genetic Range Genetic Algorithms

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Design of ‘dynamic materials’ as an optimisation problem

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An Optimum Safety Factor Approach for Reliability-Based Optimal Design

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Topology and Sensitivity – Based Optimization of Stiffened Plates and Shells

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Optimal Design of Smart Structures using Adjoint Method

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On Optimal Geometrically Non-Linear Trusses

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SHAPE OPTIMIZATION of THERMOVISCOELASTIC CONTAC PROBLEMS by LEVEL SET METHOD

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Optimized Approach for the Design of Microfabricated Compliant Mechanisms

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Optimum design of spatial trusses using hybrid formulation of the problem

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Second-Order Cone Programming for Contact Analysis of Cable Networks

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Robust Design Optimization of Extrusion Slit Die Design Using Several Multi-Objective Optimization Methods

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Topological design optimization of 2D and 3D continuum structures with design-dependent surface loading

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Structural Optimization in Assistance to Materials Selection

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Optimum Design of Lateral Braces of Columns under Buckling Constraints Considering Critical Imperfection

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TOPOLOGICAL DESIGN OF WATER RETAINING STRUCTURES

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Use of Response Surface Methods to Aid Understanding and Visualization in Aircraft Design

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Design of Piezoelectric Plate and Shell Actuators Using Topology Optimization

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AnyBody - a software system for ergonomic optimization

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Efficient Reliability-Based Design Optimization for Dynamic Structures

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Evolutionary computation in optimisation of 2-D structures

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Optimization of Vibrating Column with Periodic Cross-section and on Various Foundation

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Sensitivity Analysis of Optimized Structures with Hill-Top Branching

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Minimization of Probabilistic Analysis Confidence Interval through a Novel Experimental Design Process

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Optimum Kinematic Dimensional Synthesis of Generic Mechanisms Using G. A

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On the Application of Tabu Search to Optimisation of Hydrostatically Loaded Barrels

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Minimum Cost Design of Ring-stiffened Cylindrical Shells Subject to Axial Compression and External Pressure

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An Effective Procedure for Topology Optimization of Continuum Structures Subjected to Self – Weight Loading

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Comparison and Application of Ant Algorithm and Other Biological Algorithm in Structural Optimization

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Adaptive Shape Optimization of Structure using Genetic Algorithms

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OPTIMAL AUTOMATIC DESIGN OF CRANKSHAFTS

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Two-phase Topology Optimization of Plates and Three-Dimensional Bodies

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Topology Optimization of Shells and Surface Michell Structures

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Using LDL^T decomposition for eigenvalue constraint

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An Elementary Proof of the Michell Sphere Being the Lightest Among All the Uniformly Stressed Shells Loaded by Two Opposite Torques

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Extended functions for the consideration of uncertainties in the definition of structural optimization problems

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Minimum Cost of Reinforced Concrete Building Grillages by Simulated Annealing

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OPTIMAL DESIGN OF REINFORCED CONCRETE PLATES BY SIMULATED ANNEALING

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Efficient Evaluation Approaches for Probabilistic Constraints in Reliability-Based Design Optimization

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Design of composite laminates as an optimization problem: a new genetic algorithm approach based upon tensor polar invariants

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Limitations of the gradient projection method in Pareto optimum sensitivity analysis

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A Nash game approach for Multidisciplinary topology design

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Optimal Shape and Configuration Optimization of Multi-Loaded Structures with Manufacturing Tolerances

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Application of Thermographic Methods in Identification of Structure Properties

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Optimization of L-shaped laminated plates via mortar spectral method

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Sail Optimization for Maximal Speed Design

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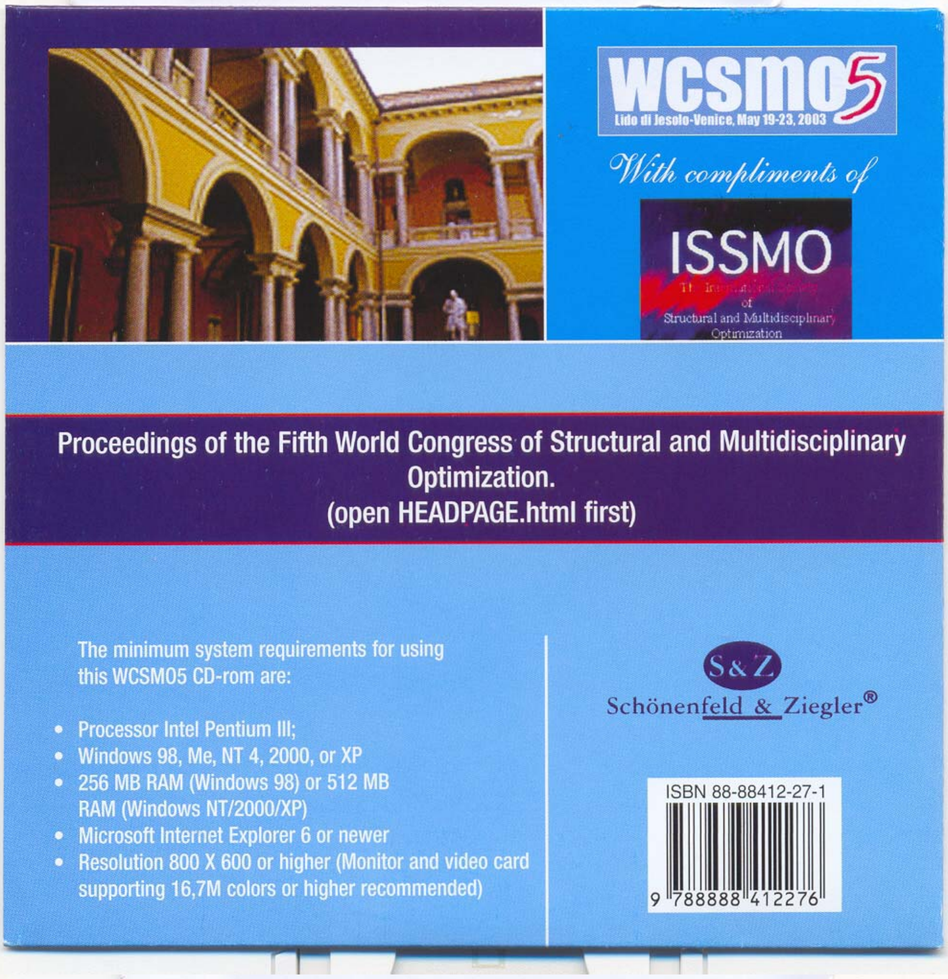

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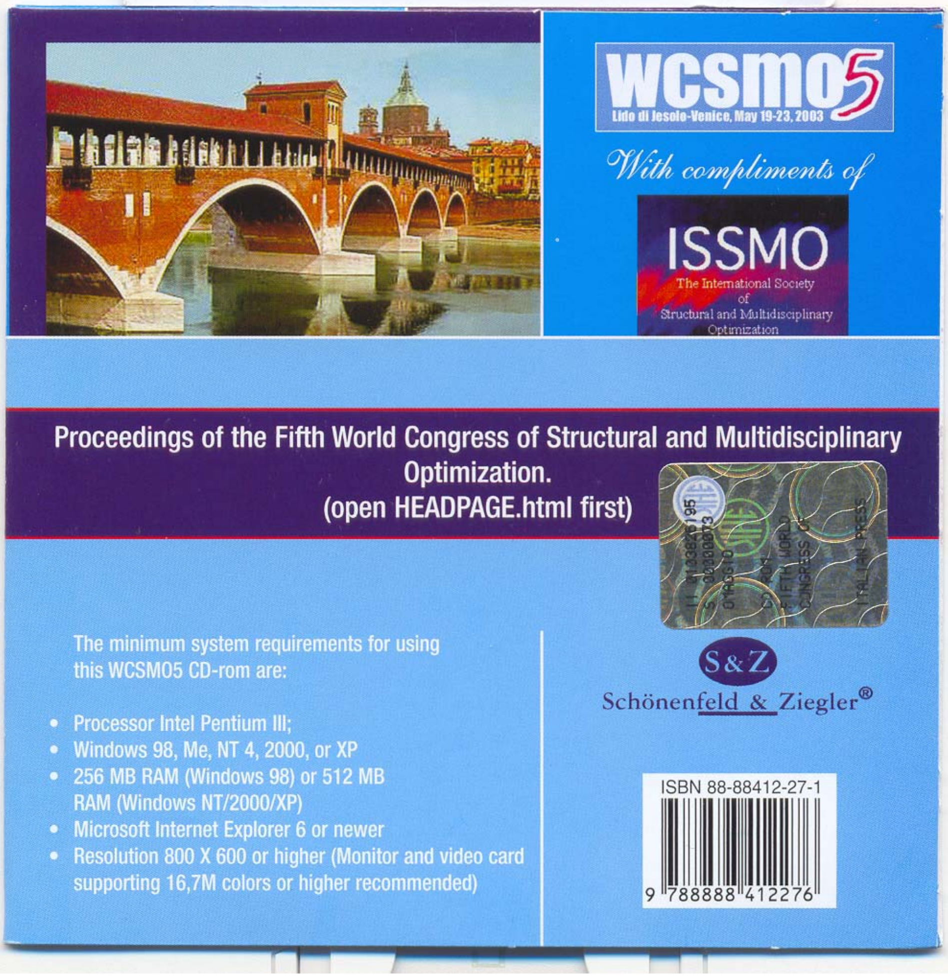

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Shape and Tailoring Optimization of an Aircraft Air Intake Ramp by Genetic Algorithm

Gianni Caligiana, Francesco Cesari, Alfredo Liverani.

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1. Abstract

Optimization of an hypersonic aeroplane air intake ramp, made by a metal matrix long fibre reinforced composite material (Ti6Al4V/SCS-6), has been performed. Low weight and low deflection (high stiffness) have been considered as search objectives. Ply number and optimal fibre orientation, about the reference longitudinal direction of the main ramp laminate (tailoring), have been determined. Fatigue strength of plies inside the laminate has been introduced as constraint. Thermal and pressure loads during flight operation, accounting for some peculiar situations, like hammershock overpressures, have been considered during design. Finite Element Method (FEM) analysis has been performed through an "ad hoc" numerical program developed by one of the authors. A search module based on Genetic Algorithms (GAs), developed inside DIEM Department, has been interfaced with FEM numerical program. Optimization results are recorded and discussed.

2. Keywords: genetic algorithms, optimization, composite materials, tailoring, finite element.

3. Introduction

Optimization [1-4] is an increasingly important tool to be utilized while structurally designing components. This is particularly true in aerospace, automotive and naval fields, in which recent exploit of composite materials [5-7] forces to improve both material itself and component shape. The stringent needs for high stiffness and low weight, while meeting strength requirements, compel designer to suitably reduce the number of plies to be utilized and to improve reinforcement orientation inside each ply.

Aims of the work are study, analysis and structural optimization of the air intake ramp for an hypersonic aeroplane prototype (Fig. 1). Ramp (Fig. 5a) consists of a plate composed by several layers (Fig. 5b) of a metal matrix long fibre composite material reinforced by some T-beams (Fig. 1 and Fig. 5a) produced with the same composite material (§ 4 and § 5). A Ti-6Al-4V alloy [8] is utilized for the matrix, while internal reinforcement is made by means of continuous SiC fibres of 142 micron diameter [9] (see § 5.2).

Optimization (§ 5.3) is limited to the main panel of the ramp, while assuming fixed configurations for the T-ribs (Fig. 5c). Design variables are thickness of ramp laminate (or, in other words, total number of plies) and reinforcement orientation angles of each ply about the reference longitudinal axis of the main panel (Fig. 5b). Search objectives are laminate minimum weight (§ 5.5) and maximum stiffness (§ 5.6).

Numerical tool utilized to perform analysis and search is briefly described in § 5.1.

4. Air intake ramp

The proposed configuration for the air intake ramp is shown in Fig. 1. A preliminary analysis is performed to identify suitable constraints for the ramp [10]. Slight curvature of the main panel is disregarded in this scheme.

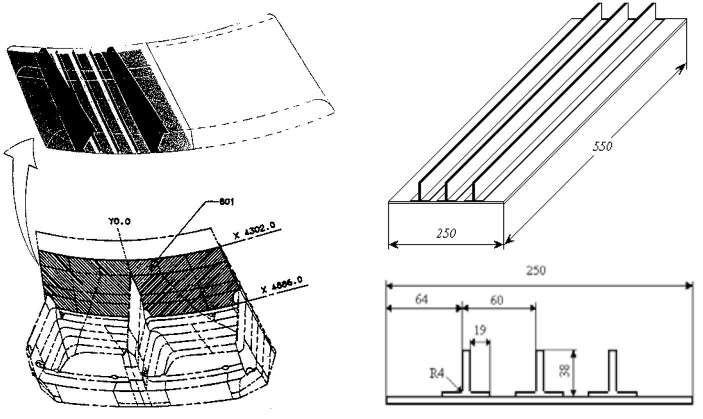


Figure 1. Air intake configuration and corresponding sketch.

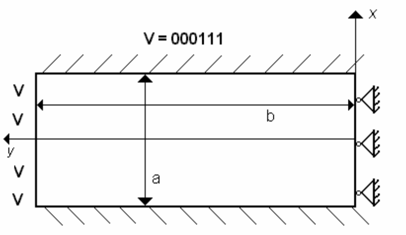


Figure 2. Scheme assumed for the constraint.

4.1. Constraint assumption

The plate is joined to fuselage through two "I" beams (Fig. 1) so stiff to be considered as a full restraint along longitudinal edges. The internal edge of the plate (towards air intake) is assumed as simply supported (pinned). The assumption is justified by the relative high compliance of the composite ramp, as compared to the stiffness of the joined air intake structure. This results in approximately restraining all displacements, while allowing, almost completely, rotations. On the other side (the external transversal edge), the ramp is connected to a deflector of stiffness very similar to that of the panel itself. Conversely, displacements can now be allowed, while rotations would probably not. Constraint assumption is shown in Fig. 2, where "V" sign stays for completely restrained rotations.

4.2 Loading conditions

Air intake ramps are subjected to thermal loading cycles and to dynamic loadings, like hammershock in transonic or supersonic ranges. Both effects are considered even if thermal effects seem to be negligible compared with hammershock ones. Load experimental measurements have been performed in flight conditions [9]. During analysis, an equivalent static uniform pressure, able to produce the same effects as actual thermal loadings, has been predicted and applied perpendicular to the neutral plane of the composite panel. In the investigation of hammershock phenomenon (Fig. 3), static pressure loads, corresponding to the maximum pressure peaks identified in the dynamic history, are considered. This choice can be justified by the theoretical calculus, Eq. (1), of the displacement amplification factor "D" (the rate between structure deflection under impulsive loading and static deflection under a load equal to the maximum load identified during hammershock).

$$\begin{cases} D = \dfrac{\omega_o t_o}{\omega_o^2 t_o^2 - \pi^2}\left(\omega_o t_o \sin\dfrac{\pi t}{t_o} - \pi \sin \omega_o t\right) & \text{for} \quad 0 \le t \le t_o \\ D = -\dfrac{\pi \omega_o t_o}{\omega_o^2 t_o^2 - \pi^2}\left[\sin(\omega_o (t - t_o)) + \sin \omega_o t\right] & \text{for} \quad t > t_o \end{cases} \tag{1}$$

During analysis, typical hammershock loadings have been assimilated to sinusoidal loadings. Characteristic peak duration has been estimated and compared to half period free vibration for the structure. As a result of calculation, maximum structure deflection seems to appear during loading application and "D" factor results almost equal to one (Fig. 3). Consequently, pressure loadings equal to maximum pressure values detected during hammershock are statically imposed to the structure. Details about loading modelling and resulting numerical evaluations can be found in [10, 11].

- $t_o \approx 0,05$ s >> $\pi/\omega_o \approx 0,0042$ s (half-period of free vibration);
- maximum value of D ≈ 1; D = Displacement amplification factor.

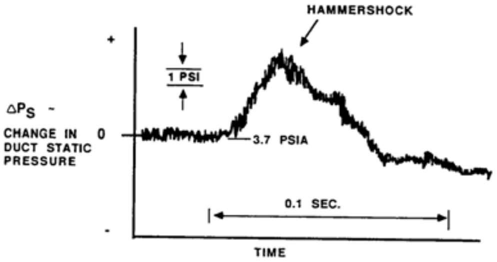


Figure 3. Hammershock loading.

5. Ramp analysis

Analysis of the air intake ramp is performed through a numerical tool developed at DIEM [12]. This program is composed of a Finite Element Method (FEM) nucleus [13], for the structural analysis of symmetrical laminates in composite material, interlaced with a Genetic Algorithm (GA) [14].

5.1 Numerical Tool

a) The FEM kernel (named UGUSCOMP), developed by one of the authors for composite material structural analysis, is based on Hughes finite element. It has been derived by Mindlin's theory of plates and its main features include potential independence from a specific shell theory and absence of "locking" phenomena or spurious strain modes. It does not need any numerical artifice in the formulation, it is easy and economical to implement (owing to low degree of interpolating polynomials employed), it provides reliable results and it shows almost complete insensitivity to distortion in meshing. The use of Mindlin's theory of plates allows to include the effects of shear strains. Tsai-Hill and Tsai-Wu failure criteria for long fibre composite materials have been considered [5].
b) GA numerical module has been developed in Department too [14]. It utilizes a binary coded population of a fixed number of individuals (corresponding to an identical number of candidate solution strings). Standard operators are provided like selection, crossover and mutation. Robustness and reliability of genetic algorithms [15-16] have suggested their employment for this application, in which several design criteria and constraints must be considered.

5.2 Material Modelling

Ti-6Al-4V/SCS-6 composite material for the air intake is obtained through a diffusion bonding process [7]. Matrix is originally in the form of Titanium, Aluminum and Vanadium alloy (Ti-6Al-4V) matrix foils of 150 µm thickness. Reinforcement is obtained by a woven fabric of Silicon Carbide (SCS-6) parallel monofilaments (140 fpi) of about 142 µm of diameter. Material before and after diffusion bonding process is shown schematically in Fig. 4 (dimensions in figure are expressed in microns). Modelling of each ply of Ti-6Al-4V/SCS-6 composite material, after diffusion bonding process, results in a well defined theoretical geometric arrangement (Fig. 4), corresponding to a constant pitch among fibres (about 181 µm) and a prefixed fibre volume fraction (about 0,33). Main mechanical characteristics of fibre, matrix and of the whole composite material (along different directions) are reported in Table 1 and Table 2 at room temperature (RT) or at 400 and 900 Kelvin degrees. Details on references, assumptions or guesses made can be found in [10-11].

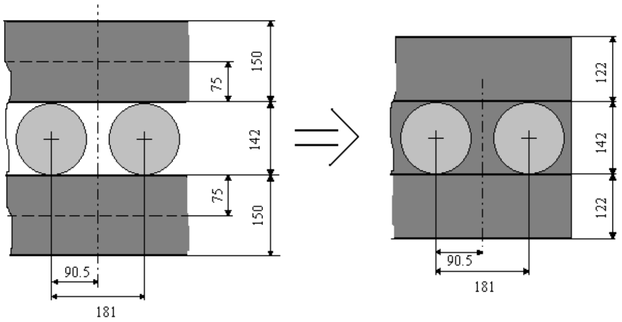


Figure 4. Material schematization before and after diffusion bonding process (dimensions are expressed in microns).

Table 1. Fibre and Matrix mechanical characteristics.

MECHANICAL PROPERTIES	SCS-6			Ti-6Al-4V		
	400 *K*	900 *K*	*RT*	400 *K*	900 *K*	*RT*
E [*GPa*]	394	365	400	103	55	110
ν	0.19	0.36	0.15	0.33	0.41	0.31
G [*GPa*]	167	137	174	40	25	43
σ_{yp} [MPa] tension yield st.	3830	3372	3450	711	382	868
σ_{yp} (MPa) compress. y. st.	–	–	–	751	403	916
τ_u (MPa) shear strength	–	–	–	516	210	600

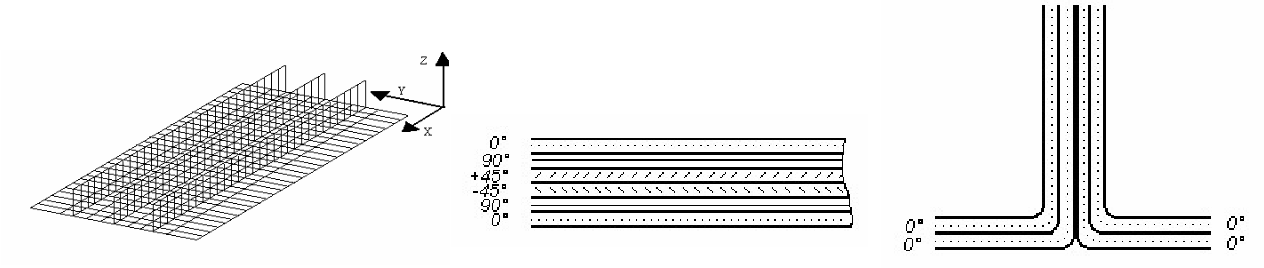
Table 2. Composite material mechanical characteristics.

PLY FRACTURE STRENGTHS (V_f=33%) (Mpa)	Ti-6Al-4V / SCS-6	
	400 *K*	**900 *K***
σ_{lT} longitudinal tensile strength	1432	1121
σ_{lC} longitudinal compressive strength	3103	3103
σ_{tT} transversal tensile strength	711	382
σ_{tC} transversal compressive strength	751	403
τ_{ltR} longitudinal-transversal shear strength	516	210

5.3 Optimization scheme

Optimization is limited to the main panel (Fig. 5b) of the air intake ramp (Fig. 5a), while fixed configurations are assumed for the reinforcing "T" shaped ribs (Fig. 1). These latter are made by the same composite material of the main panel, but with fibres disposed only along the longitudinal direction (Fig. 5c).

Two different search criteria are considered separately (§ 5.5 and § 5.6).



(a) (b) (c)

Figure 5. Air intake ramp scheme (a), example of reasonable configuration for ramp main panel (b), prefixed rib configuration (c).

5.4 Objective Scalar Function and Fitness Function for GA

In a generic multiobjective search problem (Fig. 6), there are "m" design functions, f_j, of the "n" design parameters, d_i, to be simultaneously optimized, accounting for "p" constraint violation $\bar{h}_k$.

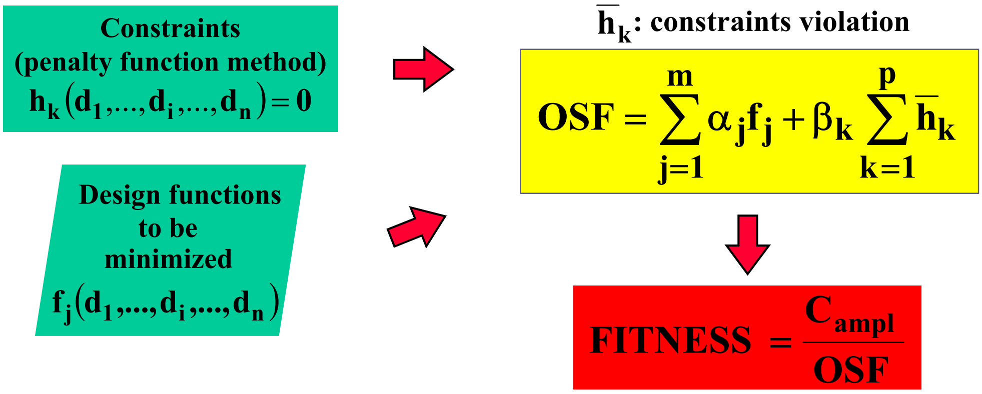


Figure 6. General multiobjective optimization problem to be solved through genetic algorithms.

Usually, if the problem is to be solved by genetic algorithms [14-15, 17], an Objective Scalar Function (OSF) is defined as a weighted sum of design functions and constraint violations (penalty function methodology, [15]). A merit or cost function (fitness), to be minimized by GA, is then derived (Fig. 6). OSF and, consequent, fitness must be accurately chosen to measure, through the finite element analysis, the soundness of every solution candidate generated by GA and to assess its aptness in answering to the problem considered. Obviously, α_j, β_k and C_{ampl} are suitably chosen weighting parameters to balance the influence of objectives and constraints and to ensure dimensional consistency in OSF expressions. In the actual problem of the aeroplane air intake ramp, two optimization goals are considered: minimum weight (§ 5.5) and maximum stiffness (§ 5.6). Owing to the difficulty of ensuring a right choice for weighting parameters inside the OSF when too many terms are present, optimization is split in two phases and the two criteria are considered independently. Results seem to confirm that these two separate searchs lead to similar conclusions.

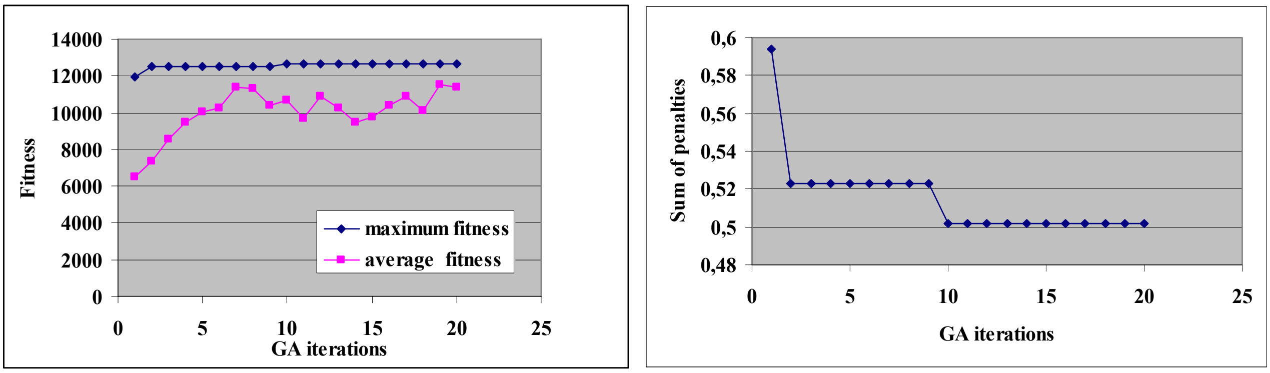
5.5 Weight optimization

First of all, a minimum weight optimization has been implemented, by utilizing a variable thickness panel, while meeting strength constraint requirements. Design parameters are fibre orientation (chosen among eight discrete angular values, technologically significant, measured about longitudinal laminate reference direction: -60°, -45°, -30°, 0°, 30°, 45°, 60°, 90°) and the number of plies inside the air intake main panel. Then, the proposed OSF is:

$$\boxed{\begin{array}{l} \alpha = 2 \cdot 10^{-5}\ \mathrm{mm}^{-3} \\ \beta = 10 \\ \mathrm{FITNESS}_1 = \dfrac{10^2}{\mathrm{OSF}_1} \end{array}}$$

$$\mathrm{OSF}_1 = \alpha\ V + \beta\ \frac{\sum_{i=1}^{\mathrm{NLAYR}/2}\left[\left(Q_1^{max}(i)-\frac{2}{3}\right)^2+\left(Q_2^{max}(i)-\frac{2}{3}\right)^2\right]}{\mathrm{NLAYR}/2} \qquad (2)$$

In Eq. (2), V is the global volume (comprehensive of the “T” shaped ribs), corresponding to the main optimization goal of minimum weight. The second term of Eq. (2) corresponds to strength constraints (penalties). In this expression, $Q^{max}(i)$ is the maximum value, calculated inside the i-th ply, for the Tsai-Hill strength parameter [5, 7]. For safety, it must be always lower than one. A limit of 2/3 (corresponding to a safety factor of 1,5) is assumed here. Actual implementation of FEM numerical program [12] allows to analyze only symmetrical laminates so that half laminate is considered. Therefore Q_1^{max} and Q_2^{max} are Tsai-Hill parameter values determined, respectively, for the i-th ply and for its symmetrical one. To ensure a significant comparison between virtual individuals inside GA, constraint terms are divided by half of the layer number (NLAYER/2). Together with OSF of Eq. (2), best values for α, β and C_{ampl} weight parameters and final fitness expression to lead GA are reported. With the assumed values for weighting parameters, a variation of 10% of each constraint term corresponds to a variation of about 2% for the volume. In Fig. 7, fitness and sum of penalties against GA iterations are shown for the weight optimization phase. An optimum number of plies equal to 6 results from this optimization [10]. Results for reinforcement angular orientations are not reported because they are practically coincident with those outcoming from stiffness optimization (§ 5.6 and Fig. 8).



(a) (b)

Figure 7. Weight optimization: fitness (a) and sum of penalties (b) against GA iterations.

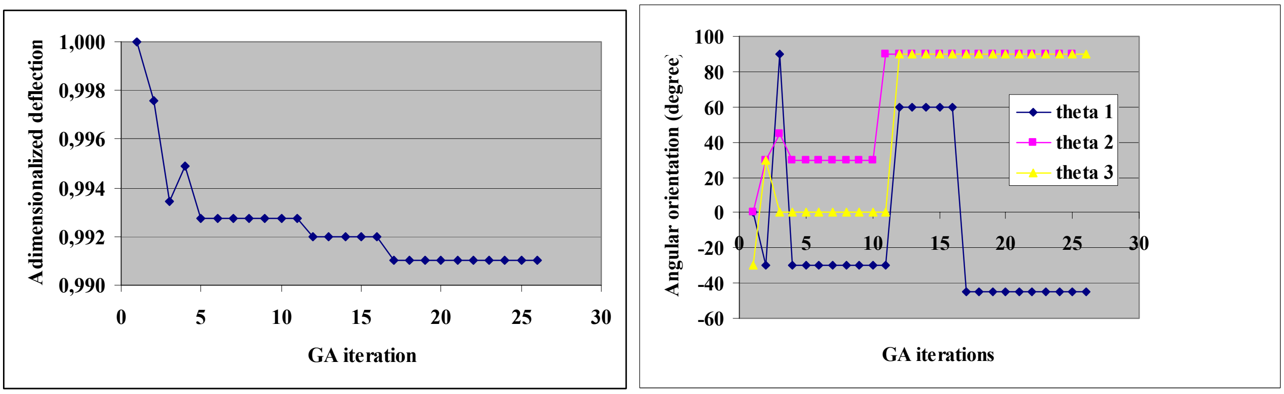
5.6 Stiffness optimization

Afterwards, maximization of the panel stiffness is assumed as optimization goal. A constant thickness panel (with six plies, as obtained during the former search) is considered, while orientation angles are left free to vary again among eight discrete angular values measured about a prefixed laminate reference direction: -60°, -45°, -30°, 0°, 30°, 45°, 60°, 90° (as before). The corresponding proposed objective functions is:

$$\boxed{\begin{array}{l} \alpha = 2 \cdot 10^{-9} \\ \beta = 4{,}5 \\ \gamma = 2{,}5\ \mathrm{mm}^{-1} \\ \mathrm{FITNESS}_2 = \dfrac{2 \cdot 10^5}{\mathrm{OSF}_2} \end{array}}$$

$$\mathrm{OSF}_2 = \alpha\, e^{\gamma\, w_{max}} + \beta \sum_{i=1}^{\mathrm{NLAYR}/2}\left[\left(Q_1^{max}(i)-\frac{2}{3}\right)^2+\left(Q_2^{max}(i)-\frac{2}{3}\right)^2\right] \qquad (3)$$

In Eq. (3) w_{max} is the main goal corresponding to the maximum laminate deflection obtained by FEM. α, β, γ are, again, weight parameters suitably chosen to balance the influence of the main objective and the constraints. Q_1^{max} and Q_2^{max} are, as before, the Tsai-Hill parameter values determined for the i-th ply and for its symmetrical one. An exponential expression is introduced to ensure right balance between goal and constraint terms. Together with OSF of Eq. (3), best values for α, β, γ and C_{ampl} weight parameters and final fitness expression to lead GA are reported. With the assumed values for weighting parameters, a variation of 10% of each constraint term corresponds to a variation of about 1,5% for the exponential term corresponding to laminate maximum deflection. In Fig. 8, adimensionalized deflection and optimal angular (*theta*) distribution of plies inside the panel are shown as a function of GA iterations. In Fig. 8b, only half laminate is considered, as already told, and angular orientation are recorded starting from inside towards outside (*theta 1* is the reinforcement angular orientation of the layer nearer to the laminate middle plane, while *theta 3* corresponds to the outermost layer). GA results (obtained as those corresponding to the best fitness in 20 independent runs of GA, as recommended in literature [15]) seem to suggest that reinforcements in the innermost ply must be disposed at -45 degrees while, in the outermost plies, they must be placed across laminate longitudinal direction.

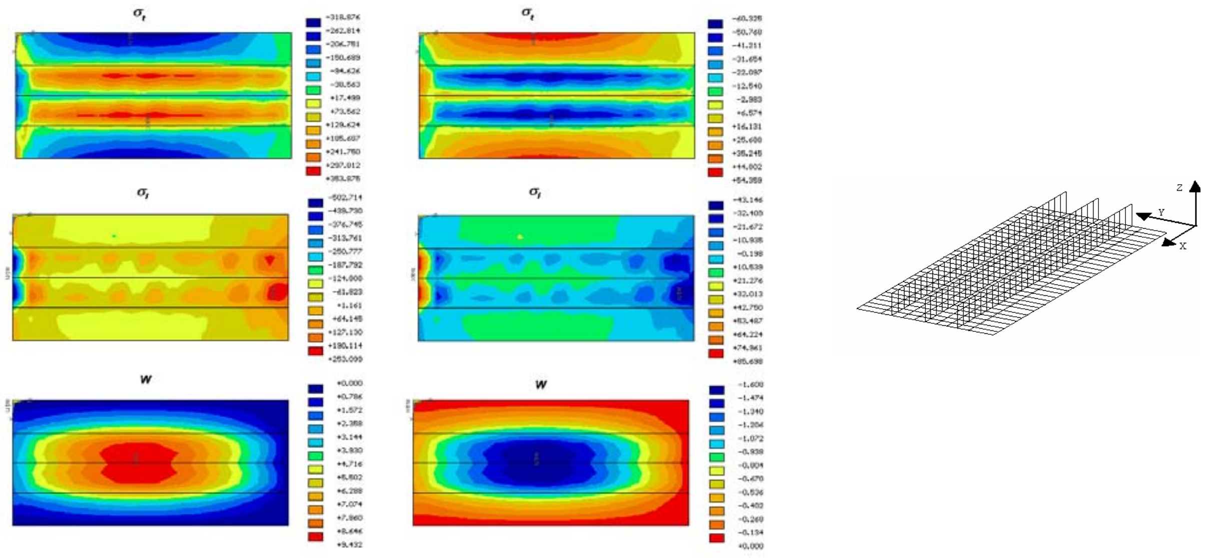


(a) (b)

Figure 8. Stiffness optimization: adimensionalized laminate deflection (a) and reinforcement angular orientation (b) against GA iterations.

6. Optimization results

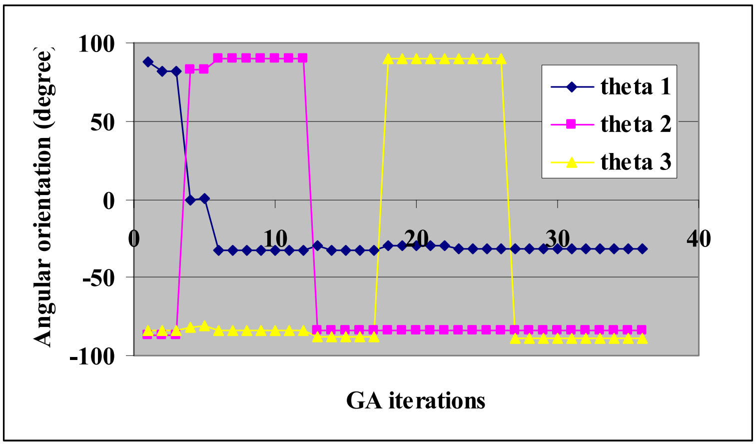
In Fig. 9, typical results obtained by FEM numerical module for the laminate under predicted loadings are shown (uniform pressure to simulate loading is applied, respectively, along positive and negative z-axis directions). Longitudinal stresses (x-axis), transversal stresses (y-axis) and laminate deflections (z-axis) are reported.



p>0 (loading along +z) p<0 (loading along -z)

Figure 9. Longitudinal stress, transversal stress and laminate deflection FEM maps for ramp external surface.

During stiffness optimization (§ 5.6), a check of the soundness of optimal reinforcement angular orientation (tailoring) predicted by GA is performed. A pseudo-continuous angular value distribution about the reference laminate longitudinal direction is simulated allowing a choice among 256 uniformly distributed angular values in the range between -90 and +90 degrees. This is performed to ascertain that discrete prefixed angular values (§ 5.5 and § 5.6) do not mislead GA, compelling its search to reach non optimal values. Results are shown in Fig. 10. Optimal angular values are, respectively -32, -84 and -89 degrees about reference longitudinal direction, starting from the middle plane towards outside. Result trend is similar to that found in § 5.6 (Fig. 8), where optimal values



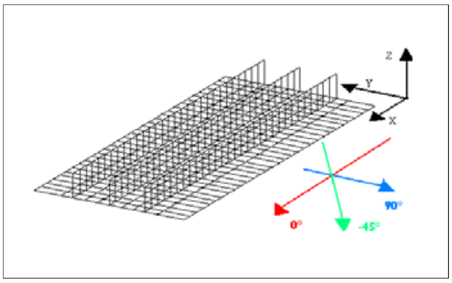


Figure 10. Angular orientation against GA iterations (pseudo-continuous angular distribution).

were -45°, 90°, 90°. The two searches are fully comparable because fitness expression, Eq. (3) and the number of independent runs of GA (equal to 20) are the same. The solution string -32°, -84° and -89° corresponds to a higher value of fitness than the former (-45°, 90°, 90°). The slight discrepancy between the two approaches observed for the innermost layer (that nearer to laminate middle plane) is effectively due to the conditioning suffered by GA algorithm, owing to the forced choice among discrete value of angular orientations. Technological considerations can help in the selection of the definitive composite material tailoring option.

7. Discussion and conclusions

A numerical program, developed in Department [12] composed by FEM and GA modules is utilized to analyze and optimize an air intake ramp for an hypersonic aeroplane prototype.

In the optimized configuration, outer laminate layers are oriented perpendicular to laminate longitudinal axis, while inner fibres are oriented at -45° (or -32° in the pseudo-continuous stiffness optimization phase of § 6). By a theoretical point of view, this configuration seems trustworthy and compatible with the chosen structural constraints (§ 4.1). Obviously technological opportunities can suggest different well balanced configurations (for example with ±45° reinforcement orientations for the innermost layers).

The proposed GA methodology, with well suited penalty functions, appears to efficiently face weight and stiffness optimizations for the proposed component in composite material. Notwithstanding authors refer often to optimized results in § 5 and § 6, for the aim of accuracy, it must be evidenced that GA does not exactly find optimum but only near optimal configurations [11, 15]. This is, however, widely satisfying for almost all practical situations.

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