SIZE OPTIMIZATION OF AIRCRAFT STRUCTURES

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Abstract

Structural optimization is currently a design methodology highly needed in advanced engineering and needless to say in aircraft design.
In the paper a structural model that describes very precisely the rear part of an airplane fuselage is used to present the capabilities of size optimization.
Two different problem formulation where defined. First only stress constraints were included in the problem. In a second problem stress and strain constraint were considered. In both cases a parametric study was carried out to find out the influence of different values of upper bounds of constraints in the optimal solution.

1 Introduction

A structural design process goes through various stages before a valid structural solution is obtained. In general, starting with an initial design that tries to meet a series of constraints, the design is calculated and decided if it is a valid design or no depending on the obtained results.

If the structure does not satisfy any of the constraints imposed by the designer, the design is modified and calculated again. An iterative process is begun in this way until an accepted design is obtained.

This approach can be labeled as conventional design process and along it the designer has to apply a series of rules based on his experience in order to modify the initial design. Consequently, the result depends on the designer's capability.

With this process, the designer can obtain a valid solution, but he cannot be sure if it is the best one. The flowchart of this design methodology appears in Figure 1.

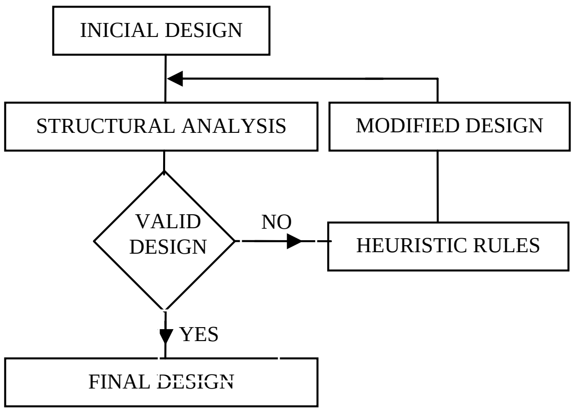


Fig.1. Flowchart of conventional design process

Throughout the process the designer know certainly which characteristics of the prototype must kept invariant and which ones are free to vary if new values of them improve the design performance.

It is also taken into account a list of requirements or limits that the prototype should retain and the main aim that the problem under study is intended for.

All this considerations can be expressed in an analytical way defining a series of terms. Those terms are the followings:

- Fixed parameters:

They are parameters considered constant in a design process. Those parameters can be grouped in vectorial form as:

$$\mathbf{p} = (p_1, \ldots, p_k)$$

- Design variables:

They are parameters considered variable in the design process. In the same way as the previous one, they can be grouped in a vector as:

$$\mathbf{X} = (x_1, \ldots, x_n)$$

- Design constraints

They are restraints that the designer knows that the prototype must accomplish. These constraints are usually structural responses and depend on $\mathbf{X}$ and $\mathbf{p}$. They can be expressed in a form:

$$\mathbf{g}(\mathbf{X}, \mathbf{p}) \leq \mathbf{0}$$

- Objective function

This is a property that a designer wants to improve in the design and it can be expressed analytically as $F = f(\mathbf{X}, \mathbf{p})$.The objective is to either minimize or maximize this function depending on the needs.

From these definitions, the approach for obtaining the best solution problem can be formulated by defining the vector of design variables $\mathbf{X}$ that minimize or maximize (depending on what needs to be improved) the objective function $F = f(\mathbf{X}, \mathbf{p})$, while fulfilling the set of constraints, $\mathbf{g}(\mathbf{X}) \leq \mathbf{0}$.

The method to solve this type of problem is called Optimization Method and substitutes the heuristic rules that a designer has to go through in a conventional design process. The corresponding flowchart appears in Figure 2.

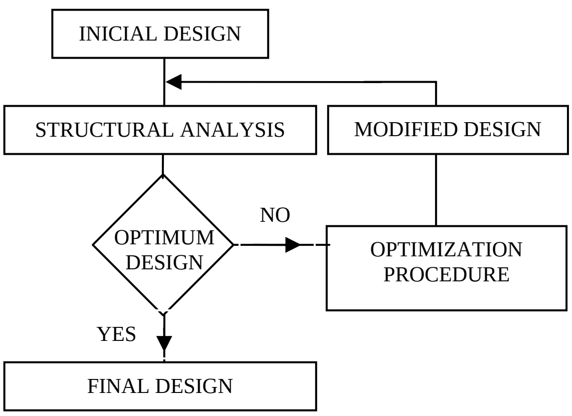


Fig.2. Diagram of optimum design process

2 Design of aircraft structures

Competitiveness on aircraft design requires being as efficient as possible and one of the objectives for engineers is to create aircrafts as lighter as possible.

In this paper a concept of the rear part of an aircraft was considered to demonstrate the capabilities of structural optimization techniques.

Figure 3 shows a typical configuration of aircraft fuselage. Essentially it is composed by:

Skin: The most external structural part, made of composite shell elements stiffened by some longitudinal stringers of the same material. The skin only takes membrane forces.

Frames: Internal transversal stiffeners that work as frames to maintain the external shape of the fuselage. They are aluminum shells stiffened with stringers.

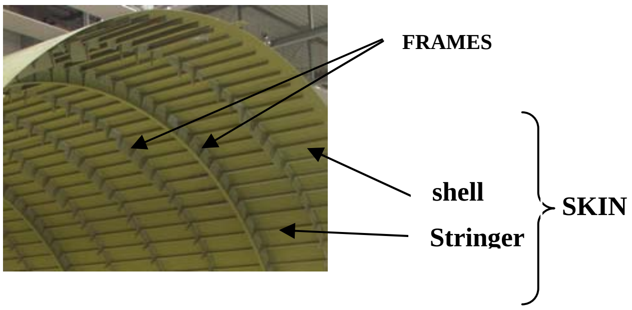


Fig.3. Aircraft fuselage

This common configuration was considered in the structural model shown in Figures 4 and 5 that describes quite accurately the rear part of an aircraft fuselage.

The model contains also the VTP. With regards the HTP it was considered statically connected with the fuselage, and therefore its influence is included through the forces induced in the fuselage by the HTP in each loading case. The geometric model was converted in a finite element mesh composed of bar and shell elements. Many loading cases were, up to a number of 21, taken into account to reproduce quite realistically the existing requirements in aircraft design.

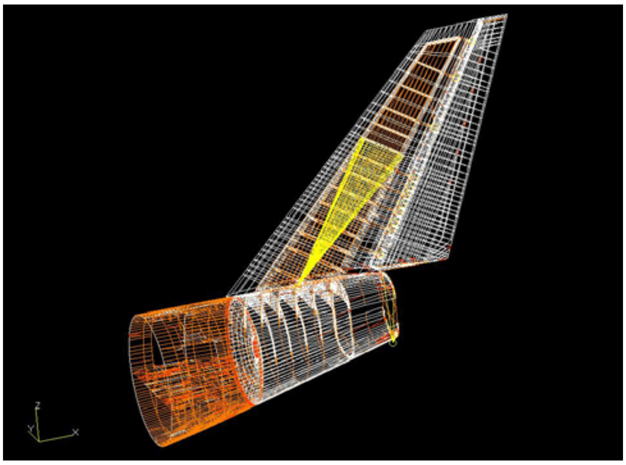


Fig.4. Rear part of aircraft

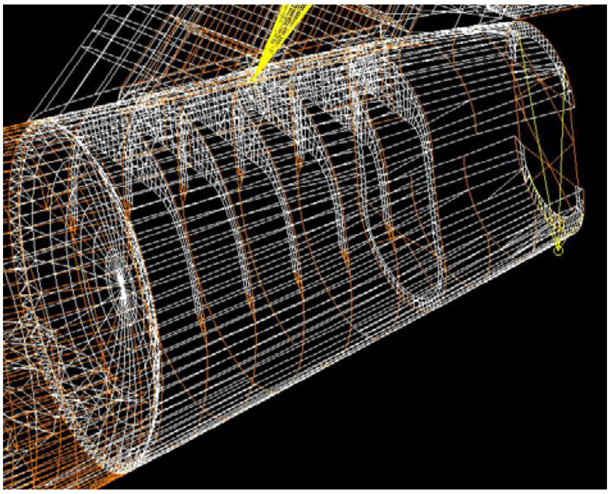


Fig.5. Detail of rear part of aircraft

Two different optimization problems were generated based in this structural model. Both of them contain a quite large member of design variables and constraints, therefore, this case can be representative of the current capabilities of design optimization techniques.

3 Design optimization with stress constraints

3.1 Problem formulation

This problem corresponded to a design taking in account 21 loading cases. Only stress constraints were included in the formulation and in order to find out the influence of the upper bound of stress, three different stress levels were considered. That means that the optimization problem was solved three times, as many as the number of the stress upper bound included in the study.

The complete formulation of the design optimization problem was defined as follows.

- **Design variables**

Design variables considered were:

- Thickness of each shell element that compose the skin

- Area of each bar element that form the bars of the skin.

The total number of design variable is 1304, and they can be classified in two groups.

- Shell thickness of the skin: 696
- Bar area of the skin: 608

- **Design constraints**

The design constraints in this phase are the Von Mises stress in the elements of the skin. This means that the resulting model after the optimization process should have stress values lower than or equal to the maximum allowed in any of the loading cases.

The considered design constraints are:

Each shell element of the skin should fulfill:

$\sigma_{von\_mises} \leq \sigma_{\max}$. (29232 constraints)

Each bar element of the skin should fulfill:

$\sigma_{von\_mises} \leq \sigma_{\max}$. (25536 constraints)

The total number of design constraints for the optimization problem is 54768.

The considered value of $\sigma_{\max}$ is not unique, as it was mentioned three different optimization cases were defined with the following upper bound limit values: 115, 160 and 300 MPa..

According with the overall number of design variables and constraints and recalling that the structural model is very accurate and the number of loading case quite important, this problem can be considered a large optimization problem and therefore its solution can be seen as an example of the optimization capabilities for real aircraft design tasks.

- **Objective function**

The objective function in this case is the volume of the skin, which is to be minimized. The problem was solved by using a commercial optimization code [4] in a environment of distributed computing with a cluster of workstations with 64 bits CPU.

3.2 Numerical results

The following graph shows the evolution of the model volume in function of the iterations for each of the imposed constraint limits, 115, 160 and 200 MPa. of Von Mises stress.

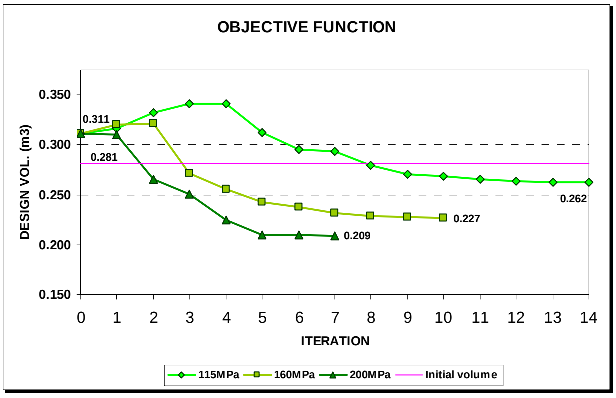


Fig.6. Objective function evolution

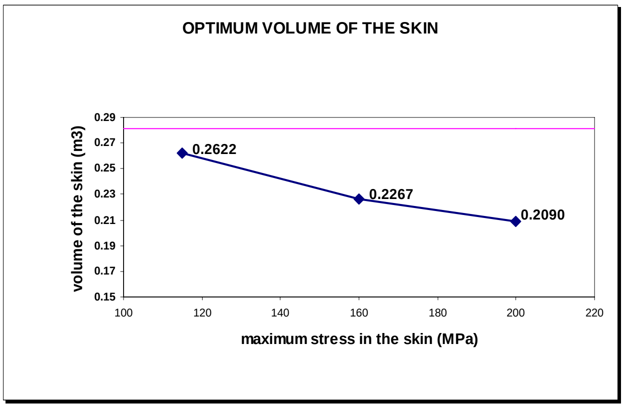
During the first iterations, an increase in volume is observed. This is because the initial design at iteration 0 does not meet all the constraints, so the procedure increases at the beginning the thicknesses and areas of the design variables. As the procedure proceeds, it redistributes the material to produce a structural scheme with less volume.

Final values of volume are smaller for each of three upper bounds. In other words the optimization process is capable of diminish the volume of material required while at the same time decreasing stress values in the structure, even for the lower upper bound of 115 MPa.

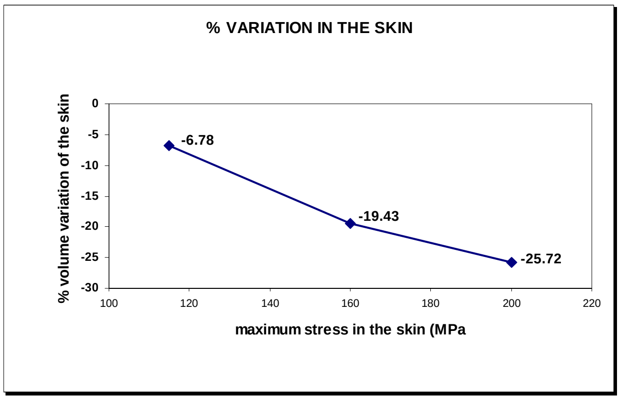
The percentages of saving for each case are:

For the upper bound of 115 MPa: 6.78%
For the upper bound of 160 MPa: 19.43%
For the upper bound of 200 MPa: 25.72%

The following figures show a series of graphs of the evolution of the optimum volume in function of the imposed constraint limits, 115, 160 and 200 MPa.

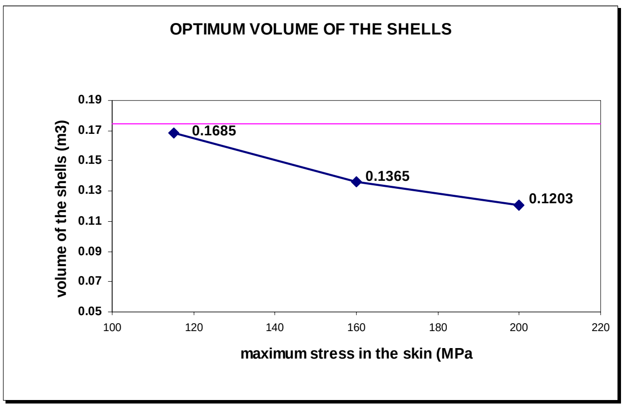


a)



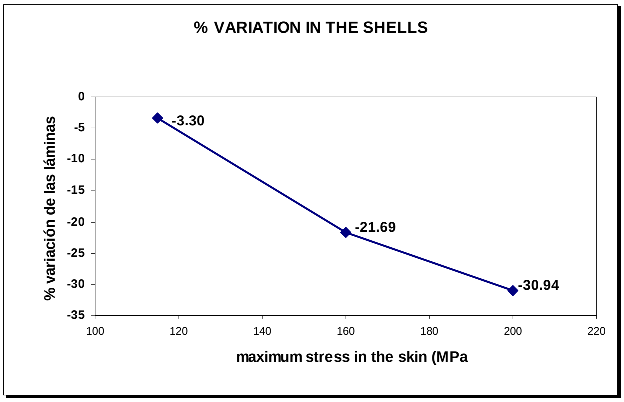
b)

Fig.7.1. Evolution of the optimum skin volume



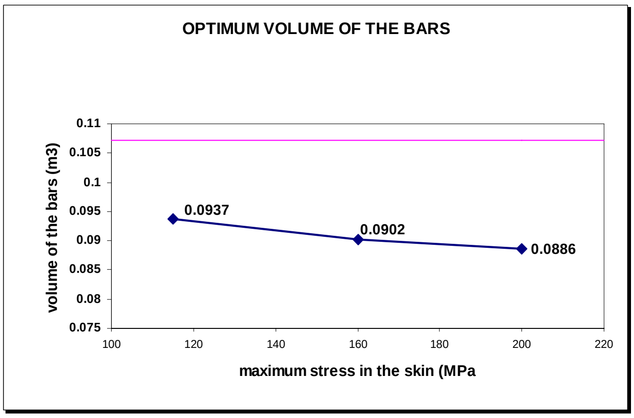
a)

Fig.7.2. Evolution of the optimum volume of the skin shell elements.

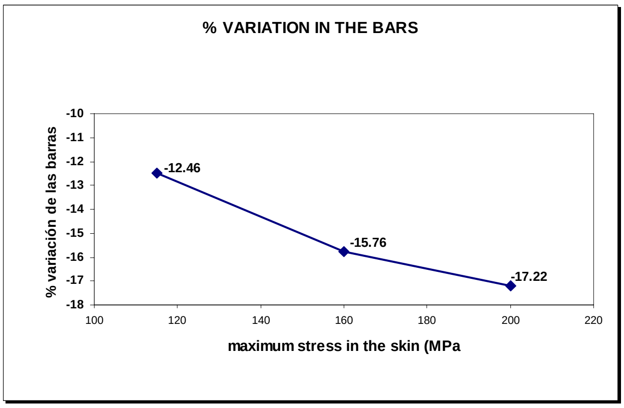


b)

Fig.7.2. Evolution of the optimum volume of the skin shell elements.



a)



b)

Fig.7.3. Evolution of the optimum volume of the skin bar elements

4 Design optimization with stress and strain constraints

4.1 Problem formulation

This new problem was defined for evaluating the variation of the solution when even a larger number of design variables is included and more sets of design constraints are also incorporated to the problem in addition of the design variable of the fuselage.

For doing that the thicknesses of the frame elements were also defined as design variables in this problem.

For the design constraints both stress and strain constraints were taken into account. Regarding to stress constraints only an upper bound of stress was considered but, on the other hand, three different upper bounds of maximum strain were considered, and consequently leading to three different optimization problem. Again, all 21 loading cases used in the previous problem were retained. The precise formulation of the problem was as follows.

- **Design variables:**

The followings are considered as design variables:

Thickness of each of the elements that constitute the skin and the frames.

Area of each of the bar elements that constitute the bars of the skin

The total number of design variables is 2306, classified in three groups.

Shell thickness of the skin: 696

Bar area of the skin: 608

Shell thickness of the frames: 1002

- **Design constraints**

The design constraints incorporated to the formulation are membrane deformation for the shell elements that form the skin and axial deformation for the bars of the skin. Besides that stress constraints are imposed to limit Von Mises stress in shell elements of the frames.

The mentioned design constraints are:

Each shell element of the skin should fulfill: $|\varepsilon| \leq \varepsilon_{\max}$. (58464 constraints)

Each bar element of the skin should fulfill: $|\varepsilon| \leq \varepsilon_{\max}$. (25536 constraints)

Each shell element of the frames should fulfil: $\sigma_{Von\_Mises} \leq 300MPa$. (42084 constraints)

The value of $\varepsilon_{\max}$ considered is not unique, but is established in three optimization cases, using the following limit values: 1800, 2400 and 3000 microdeformations.

The total number of design constraints for each case of the optimization problem is 126084.

In this case the upper stress bound is higher than in the previous case because of that level of safety in the design in achieved by limiting the strain values and therefore preventing nonlinear phenomenon.

Recalling the numbers of the former problem it can be concluded that the new formulation has almost twice the dimension of the previous one what is an indication of its higher difficulty.

- **Objective function**

The objective function in this case is the volume of the skin and the frames, which is to be minimized. .

4.2 Numerical results

The following graph shows the evolution of the model volume in function of the iterations until it reaches its optimum value for each of the imposed constraint limits; in this case, 1800, 2400 and 3000 microdeformations.

The numerical values obtained show that this formulation requires heavier design due to the strong strain limits. Anyway, the optimization procedure again reforms very well and in a few iterations reaches the convergence producing material value savings while keeping the microdeformations values below the upper bound.

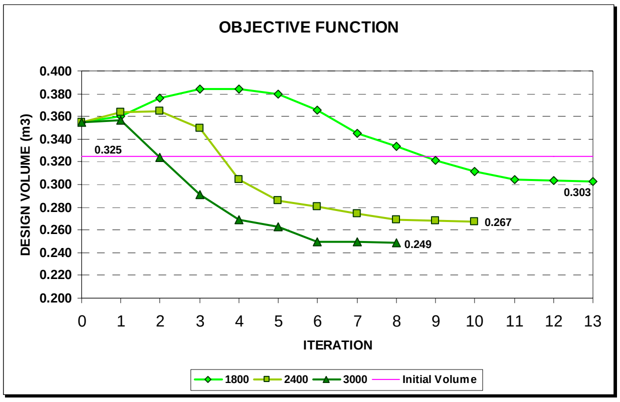


Fig.8. Objective function evolution.

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The percentage of saving for each case is:

For the case of strain limit of 1800 microdeformations:

Skin savings: 6.67%
Frame savings: 8.66%

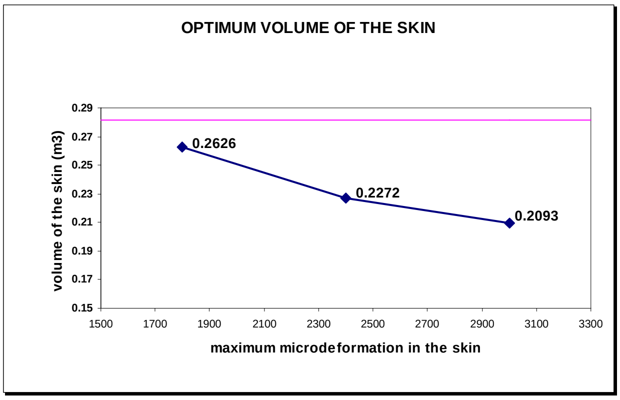
For the case of strain limit of 2400 microdeformations:

Skin savings: 19.23%
Frame savings: 9.11%

For the case of strain limit of 3000 microdeformations:

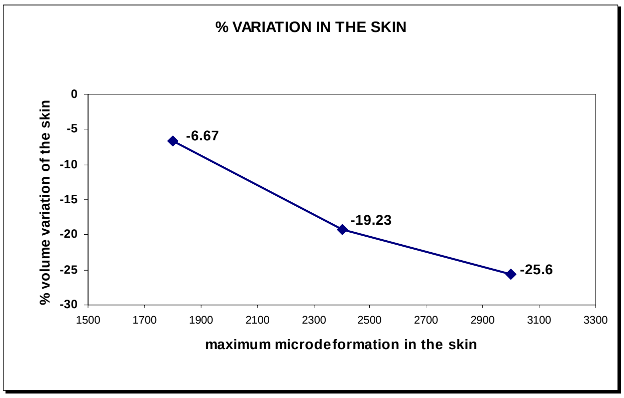
Skin savings: 25.60%
Frame savings: 9.72%

The following figures show a series of graphs of the evolution of the optimum volume in function of the imposed constraint limits, 1800, 2400 and 3000 microdeformations, for the skin shell and frame shell elements as well as the skin bar elements.



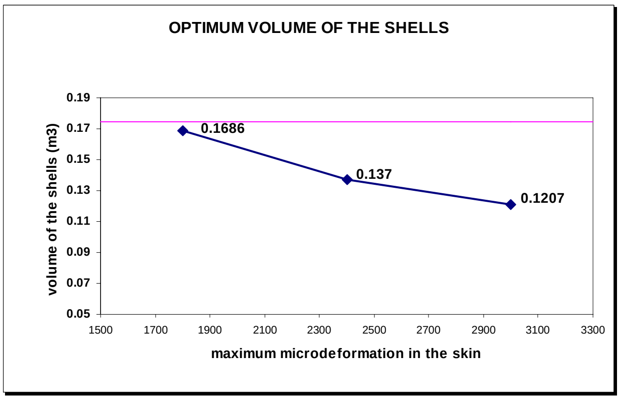
a)

Fig.9.1. Evolution of the optimum volume in the skin.



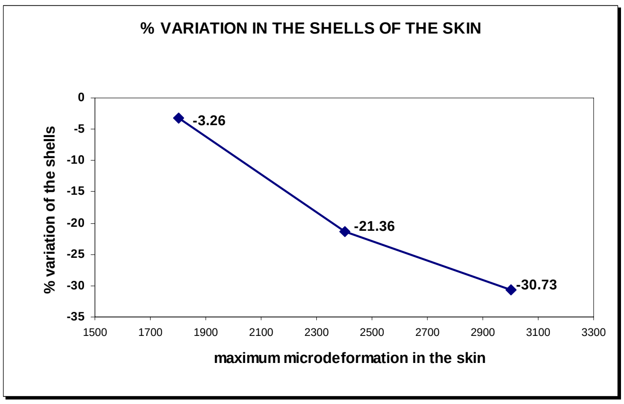
b)

Fig.9.1. Evolution of the optimum volume in the skin.



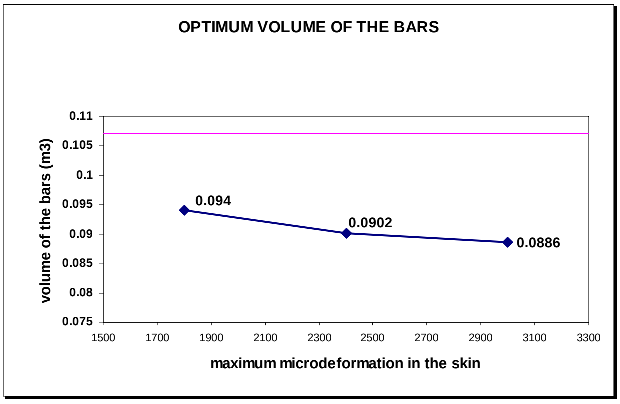
a)

Fig.9.2. Evolution of the optimum volume in the skin shells.

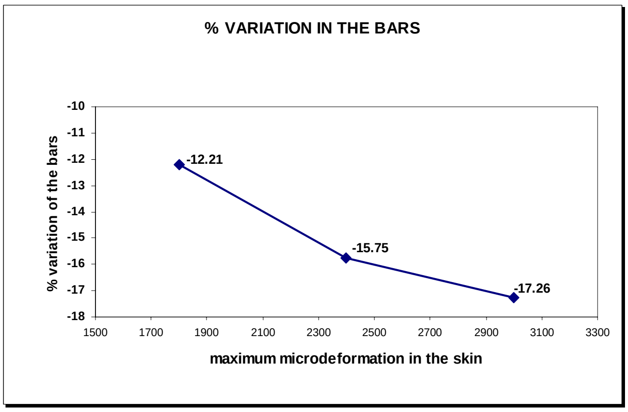


b)

Fig.9.2. Evolution of the optimum volume in the skin shells.

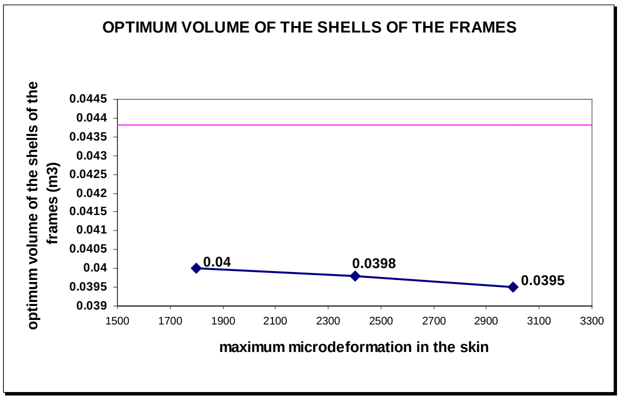


a)



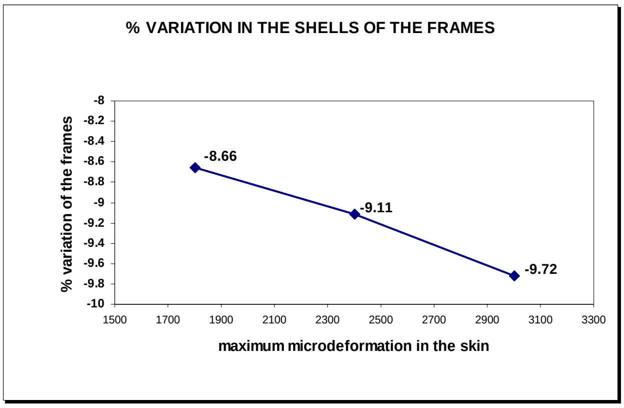
b)

Fig.9.3. Evolution of the optimum volume in bar elements.



a)

Fig.9.4. Evolution of the optimum volume in the frame shell elements



b)

Fig.9.4. Evolution of the optimum volume in the frame shell elements.

5 Conclusions

1. A structural model describing quite adequately a rear part of an aircraft subjected to an important number of loading cases has been used to demonstrate current day design optimization capabilities.

2. Two different problems of structural optimization have been defined containing thicknesses of membrane elements and cross-area of stiffeners as design variables and there fore creating formulations of structural size optimization.

3. A first problem with 1304 design variable and 54768 stress constraints was formulated and solved in a few iterations. A parametric study was also worked out by modifying the upper bound of stress limit to observe influence of this change in the optimal solutions.

4. A second problem containing more design variable and both stress and strain constraints was also defined producing a case with 2306 design variables and 126084 constraints. As before, convergence of the optimization problem was achieved in a short number of iterations. Again a parametric study by adopting three different upper bound of strain was worked out to observe the evolution of the optimal design.

5. A quite important ratio of material savings was obtained in both problem and for the complete set of the values of upper bound considered.
The optimization procedure, in all cases, achieved to reduce the amount of material and decrease stress and strains of the elements.

References

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