Design of innovative composite structures by technical and economical optimization

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Abstract

Multi-disciplinary optimisation (MDO) of composite structures is fundamental in making crucial trade-off decisions and reducing the time-to-market of innovative concepts. In this contribution, the authors present an integrated optimisation approach based on genetic algorithms used in the early design phase of advanced composite components, incorporating materials & process variables as well as structural parameters. The concurrent objectives of technical performance and total manufacturing cost are computed, taking into account the technological constraints dictated by the process.

1. Introduction

From preliminary to advanced product development phases, the design of composite structures requires accounting for the strong interaction between many different disciplines due to the complexity of the composite itself. Even the conceptual design phase should include considerations about materials, manufacturing and assembly processes, structures and in service responses, in-situ monitoring. Design rules and methodologies of the future shall incorporate those different aspects in order to meet the specific demands of each particular application.

Designers usually start from the metallic solutions which have been shown to be reliable and durable. With time, expertise is gained in the field of design of composite structures, and new components are introduced based on the data acquired on the previous structures. Though being safe, such approaches usually lead to slow step-by-step progress and a limited number of concepts can be studied, they can also prevent rapid and significant technical advances. Sometimes, safety does not even justify the choice of a particular solution; it is more a question of ‘cultural resistance to change’. Moreover these solutions are sometimes shown to be heavier and more expensive than the metallic counterparts.

Consequently, there is a clear need for methods that help the designers and the engineers exploring rapidly the many different concepts without prejudice.

Hence, besides the important research effort put in the field of modelling and understanding of the composite materials at different scales, the vast array of design variables of composite structures stimulates the research and the development of design space exploration algorithms, accurate virtual testing methods and appropriate multi-objective optimisation procedures.

2. The Multi-Disciplinary Optimisation problem

2.1 The CAD centered design

Modern industrial practice dictates that the product should be described by the CAD model in order to allow for automated production methods, accurate cost analysis and to check part assemblies. In this frame, CAD should encapsulate all the pertinent information and make it available for the designers at any stages of the design process. This allows designers to make appropriate decisions and eliminates the recurrent problem of maintaining numerical data in many different formats. In such approaches, the design space can be defined upstream with much attention paid on to assembly/size constraints and manufacturing constraints, avoiding downstream problems.

2.2 The optimisation problem

Any numerical optimisation problem is described by a design space (i.e. the set of the design variables), by objectives (i.e. targeted performances) and by constraints (i.e. conditions of feasibility). In the frame of the optimisation of composite structures, the design space includes

- discrete variables such as the off-the-shelf composite materials that are available and the presence or absence of subcomponents (stiffeners, stringers, patches, etc);
- continuous variables such as geometrical parameters (angles, dimensions, etc).

In this research, the objectives are intended to be multi-disciplinary: technical and economical. Weight reduction and maximisation of the stiffness in a given zone are usually used as *technical objectives*. Other more complex objectives bringing into play various analyses (acoustic, vibration, fluid-structure interaction, CFD, thermal analysis…) could be introduced. Another key point is the economical objective of minimum manufacturing cost, based on a cost modelling tool and on the data provided by the product manager.

The most important constraints are those related to the manufacturing process. 'Manufacturing constraints' are indeed particularly relevant because they limit the design space to configurations which can really be manufactured. Damage tolerance, resistance to buckling, absence of problematic vibration modes are technical constraints related with the in-service response. Objectives of the optimisation problem can become constraints of the optimisation problem and vice versa. For instance, the objective of weight minimisation can be transformed into a constraint of maximum admissible mass so that it helps the designer to draw a part which is – at least – not heavier than its metallic counterpart.

3. Presentation of the optimisation loop

The optimisation procedure and its functioning are presented hereafter.

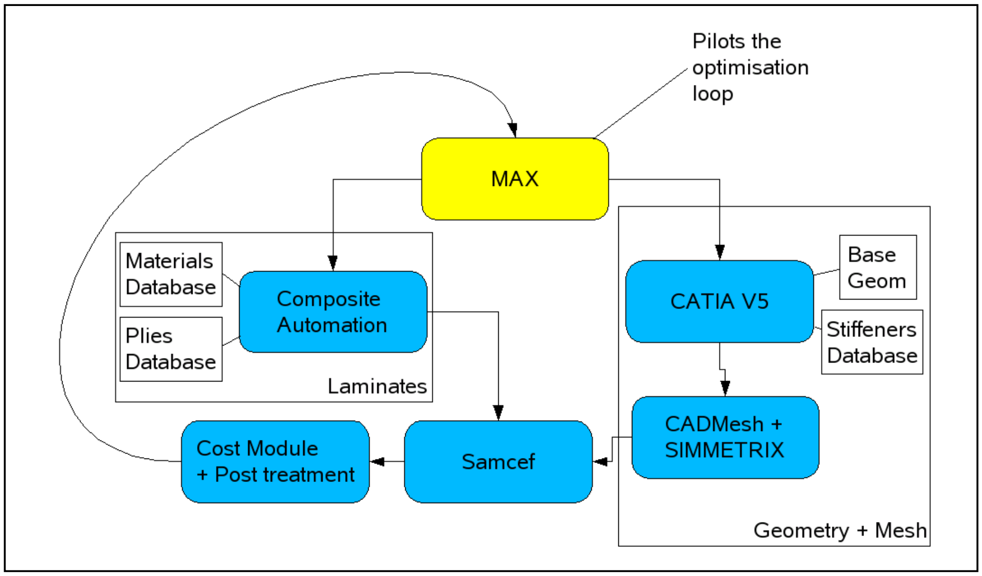

Figure 1: The Composite Optimisation Tool

The design parameters are modified based on the data file supplied by the optimisation software, Max, developed by CENAERO, which pilots the whole chain. Max is based upon genetic algorithms, enhanced by their coupling with meta-models (radial basis functions and neural network) for an accelerated convergence. Such schemes allow for the reduction of the number of calls to the complete FE model. Max can perform single or multiple-objective and multiple-constraint optimisation with the presence of a large number of discrete and continuous variables.

The CAD model is parameterised and modelled in CATIA V5^{TM}. It is directly modified with the help of the in-house library based on the commercial library CADNEXUS CAPRI^{TM} CAE Gateway, using the content of the file provided by Max.

The components and the assembly process are defined and parameterised in SEER-DFM^{TM} (Galorath Intl.) in order to compute the total manufacturing cost. Within SEER-DFM^{TM}, some manufacturing constraints can be imposed and managed by Max in order to prevent inconsistent concepts.

The final geometry is extracted from the CAD system via CAPRI^{TM} and the mesh is automatically generated using an in-house library called CADMesh, itself based on the commercial library Simmetrix^{TM}.

Depending on the nature of the problem, many different solvers can be used to compute the technical objectives. For instance, the optimisation of the stiffness (minimization of the displacements modulus) of a composite structure with safety constraints (Tsai-Hill criterion for the reference and fail safe cases) has been achieved with Samcef^{TM}. In the case of an aero-mechanical optimisation of a compressor, a general purpose FE software has been used to compute the stiffness of the composite structure (first technical objective) while another software dedicated to turbo machinery has been used to evaluate the pressure ratio or the adiabatic efficiency (second technical objective). Those two examples illustrate the possibilities of MDO in the frame of the design and analysis of composite structures with multiple technical objectives.

A library called 'Composite Automation' has been implemented at Cenaero, it contains the architecture of the computational chain, the interfaces between the different software, the tools that manage the materials database and other features.

4. Applications

The following examples illustrated in Figure 2 have been solved with the computational chain describe here above.

- The first example consists of a square stiffened panel (Figure 2, a.). In this case, the variables are:
    - the definition of the laminates used for the skin and the stiffeners (nature of the constituents, stacking sequence, number, thickness and orientation of the plies);
    - the number of- and spacing between stiffeners;
    - the shape and the dimensions of the stiffeners;
    - the number of rivets used to assemble each stiffener on the skin.

  There are two objectives: the maximisation of the stiffness of the panel, via the minimization of the displacement modulus on the skin, and the minimisation of the manufacturing cost. The manufacturing cost depends on the quantity and the nature of raw material, on the complexity of the structure (shape of the stiffeners, curvature of the panel, …), on the total manpower required, on the number and the nature of the rivets.

- A more complex test case is illustrated in Figure 2. b. This generic aircraft composite door is a simplified version of a proprietary design of DDL Consultants. It involves similar design parameters and objectives but includes several manufacturing constraints on the position and opening angles of the horizontal stiffeners. Moreover, additional constraints are integrated in the chain such as damage criteria for the reference case but also for fail safe cases. In the ideal design, the door should integrate innovative systems and mechanisms (Figure 2, c.).

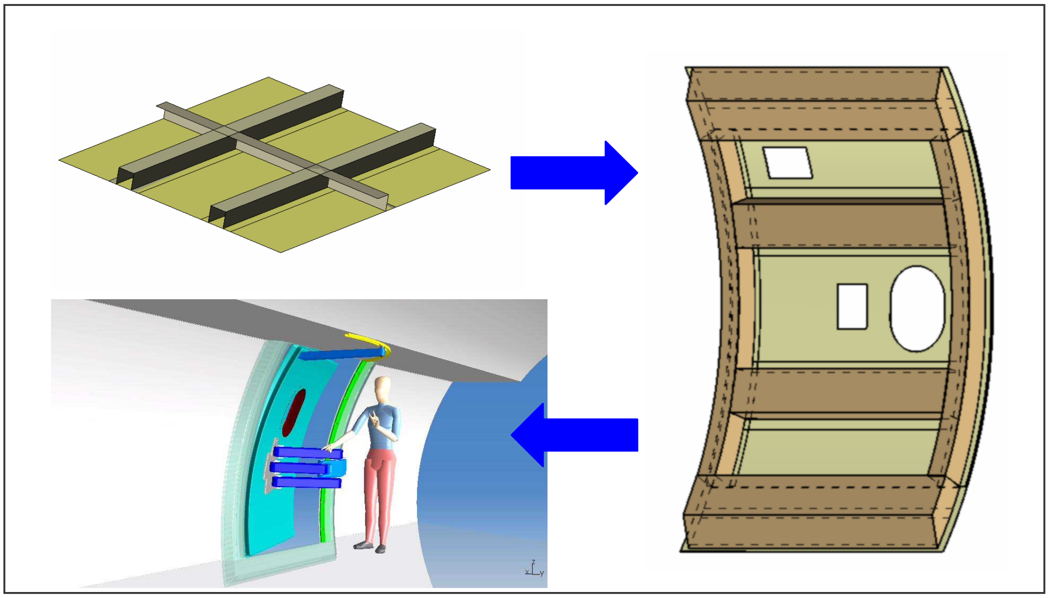

Figure 2: CAD representations of a) a generic stiffened panel (with hat and Z-section stiffeners), b) a generic composite airplane door, c) a complete composite door with integrated opening mechanism (b. and c. copyright DDL Consultants)

The result of a numerical optimisation is the Pareto front which is the set of designs that are not dominated by other configurations. For instance, for a given budget, the Pareto front provides the stiffest structure and vice versa. For a given stiffness, the Pareto front provides the least expensive solution. The following Pareto front is the one generated for the squared stiffened panel.

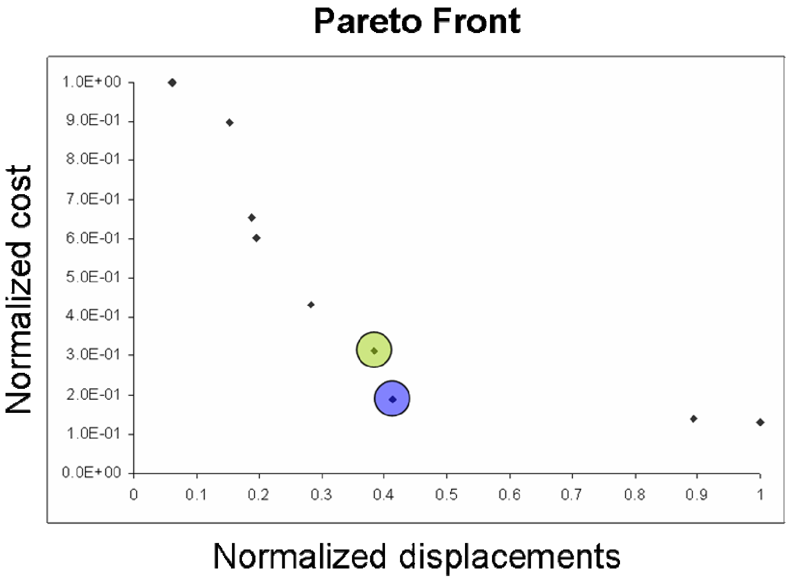

Figure 3: Pareto Front of the square stiffened panel

At the end of the automated procedure, it is observed that the points of the Pareto front involve very different sets of design parameters. For instance, thirteen design parameters are modified between the two points highlighted on the Pareto front (green and blue). On the contrary, in a manual iterative procedure of improvement of the design, an engineer would only change one or two parameters at the same time. An engineer could thus probably not anticipate the significant change between these two points which are at first sight very close on the Pareto front. Selecting designs from the Pareto front allows for conservation of the optimum.

The second important aspect of the front is that it encapsulates all the optimum design families. It allows the designer and the product manager to choose for the best design with reference to the targeted objectives. For instance, if the maximum admissible cost is reduced during the last stages of the design process, the product manager can select on the Pareto front an individual which enables him to decrease the cost with reference to his new economical objective.

5. Conclusion

An integrated multi-disciplinary optimization approach, seen as a part of a virtual composite product development procedure, has been developed. It allows for direct access to the CAD. It involves technical and economical objectives that help the designers making crucial decisions during concurrent design approaches. It is now being applied to various aerospace structures and aeroengines components. Short terms prospects involve for instance the incorporation of more refined damage models, the integration of draping simulation software, the introduction of more advanced manufacturing constraints.

Acknowledgement

The present work was made possible thanks to Walloon Region (Belgium) and European ERDF funds obtained under contract number EP1A122030000102. The authors are grateful to A. Langridge and Galorath International for providing the SEER-DFM software.

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