Multilevel Optimization of Aerospace and Lightweight Structures

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Abstract

The design and optimization of aerospace structures is a very complicated task. The complexity of the structural configuration, combined with a wide range of possible loading and boundary conditions leads to the need for a multilevel optimization approach.

Over many years the specialist panel design code VICONOPT has provided a fast and efficient tool for the analysis and design of typical aerospace structures such as longitudinally stiffened wing panels. Procedures are based on an 'exact' strip algorithm which allows critical buckling loads and natural frequencies to be determined with absolute certainty. A significant advantage of this approach over finite element based procedures is the dramatically reduced computation time required. When integrated into a multilevel optimization environment the software thus becomes particularly valuable.

Following a general introduction to VICONOPT, this paper describes the newly developed computer program Viconopt MLO, which acts as a windows interface between the widely used finite element program MSC/NASTRAN and VICONOPT. The software allows the specification of multilevel optimization models, but can also be used as a pre-/post-processor for conventional single level VICONOPT models.

1 Introduction

The economic performance of an aircraft depends very much on its overall weight. It is important to minimize structural mass, in order to reduce fuel consumption and hence the operating costs every time the aircraft flies. Modern aircraft design therefore increasingly utilizes high performance materials with high strength to weight ratios, such as carbon-fiber reinforced composites. This, when combined with efficient analysis and optimization tools, can lead to significantly increased stiffness, strength and reliability, while reducing the weight of structural components and systems.

The optimization of aerospace structures, such as fuselage sections and aircraft wings, however represents a very complex task with literally hundreds of design variables. It is therefore not surprising that, despite the dramatic increase in computational power over the past twenty years, optimization is still best carried out as a multilevel process. Traditionally, the structure is therefore optimized at two or more levels.

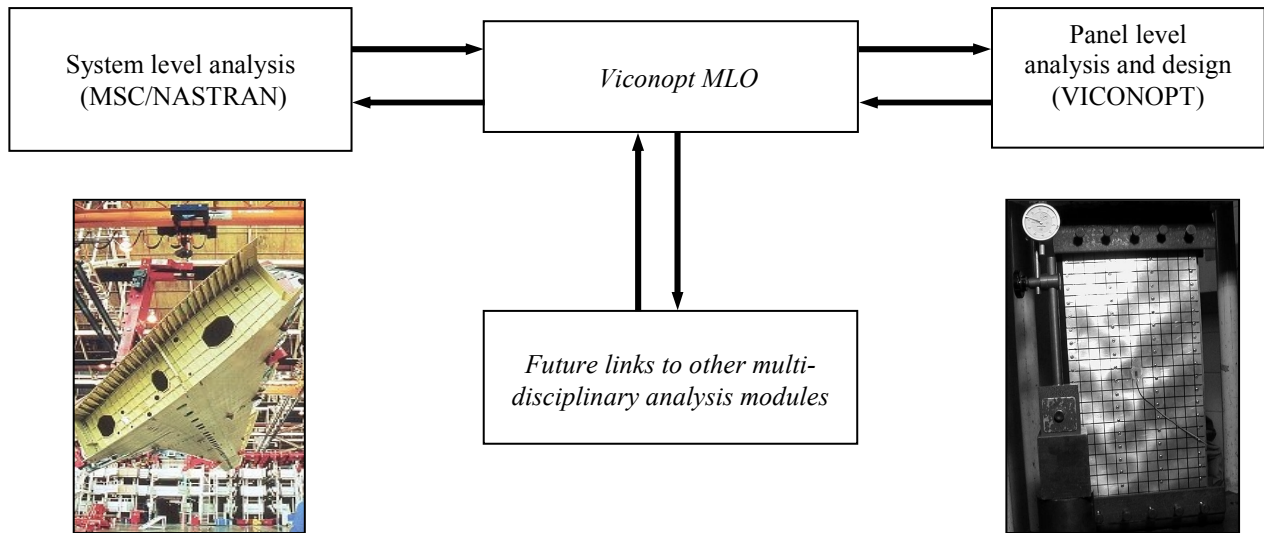Based on recommendations made by a GARTEUR (Group for Aeronautical Research

Figure 1. Multilevel nature of the optimisation procedure for an aircraft wing.

and Technology in Europe) Action Group [1], Viconopt MLO has been developed as a windows interface between the well established analysis and design software packages VICONOPT [2] and MSC/NASTRAN [3]. This new software provides an easy-to-use, fast and flexible integrated analysis and design environment, and allows the structural optimization of typical aerospace structures, such as composite aircraft wings, to be carried out as a multilevel activity (Figure 1).

The aim of this paper is to provide an introduction to VICONOPT and Viconopt MLO, and to present the underlying principles of the multilevel optimization procedure adopted.

2 VICONOPT

2.1 General Overview

VICONOPT [2] is a prismatic plate analysis and optimum design computer program, which incorporates the earlier programs VIPASA (Vibration and Instability of Plate Assemblies including Shear and Anisotropy) [5] and VICON (VIPASA with Constraints) [6].

VICONOPT covers the buckling, postbuckling and vibration analysis of prismatic plate assemblies, and also provides an efficient design tool in structural optimization. For any longitudinally invariant combination of longitudinal, transverse, in-plane shear and bending loads, critical buckling loads, undamped natural frequencies and the corresponding mode shapes can be found. Typical sections which VICONOPT can analyze are shown in Figure 2, and a typical component plate and its in-plane loading are shown in Figure 3.
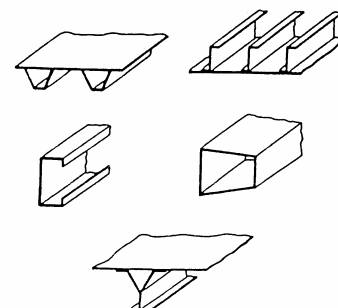

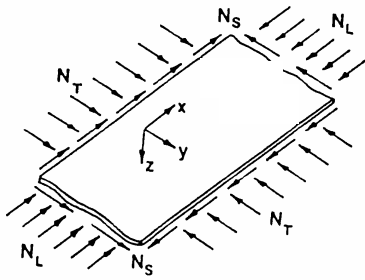Figure 2. Typical sections which VICONOPT can analyze.

Figure 3. Component plate showing in-plane loading.

2.2 'Exact' Strip Method and Wittrick-Williams Algorithm

VICONOPT analyses are based on an 'exact' strip method which assumes a continuous distribution of stiffness over the structure rather than discretized stiffnesses at nodal points, as is the case for the more widely used finite element method. The exact strip method is based on solutions to the partial differential equations which govern the in-plane and out-of-plane deformation of the component plates. Where possible, an analytical solution procedure [5] is used to determine the member stiffness matrices k_{ij}, which are subsequently assembled into the global stiffness matrix K for the overall structure. If an analytic solution of the member equation is not available the k_{ij} matrices can be found by solving the member equations numerically [7]. The global stiffness matrix K relates a finite set of displacements D at the nodes of the structure to their corresponding perturbation forces P, by

$$KD = P \qquad (1)$$

The critical buckling loads or natural frequencies of the structure correspond to the eigenvalues found by solving

$$KD = 0 \qquad (2)$$

where K consists of transcendental, and thus highly non-linear functions of the load factor F or frequency ω [8]. The solution of this transcendental eigenvalue problem requires an iterative search for values of F or ω at which equation (2) is satisfied. VICONOPT makes use of the Wittrick-Williams algorithm [9,10] which allows eigenvalues (i.e. critical eigenvalues or natural frequencies) to be found with absolute certainty. The algorithm calculates J, the number eigenvalues, which lie between zero and any trial value of F or ω. Any change in J between two trial values is equal to the number of eigenvalues lying between these trial values.

In its general form the Wittrick-Williams algorithm can be stated as

$$J = J_0 + s\{K\} \qquad (3)$$

where $s\{K\}$ is known as the sign count of K, and corresponds to the number of negative leading diagonal elements of the upper triangular matrix K^Δ obtained by applying conventional Gauss elimination, without pivoting, on the matrix K. J_0 is the value J would have if all the freedoms corresponding to K were clamped. Unless substructures are used, J_0 can be calculated as

$$J_0 = \sum_m J_m \qquad (4)$$

where the summation is over all members of the structure, and J_m is calculated for each member as the number of critical load factors or natural frequencies exceeded by the trial value, when the member ends are clamped.

For computational efficiency, the algorithm allows the use of substructures. Their contribution to J_0 can be determined by prior application of the algorithm to each substructure, with all points of attachment between the substructure and parent structure clamped [9].
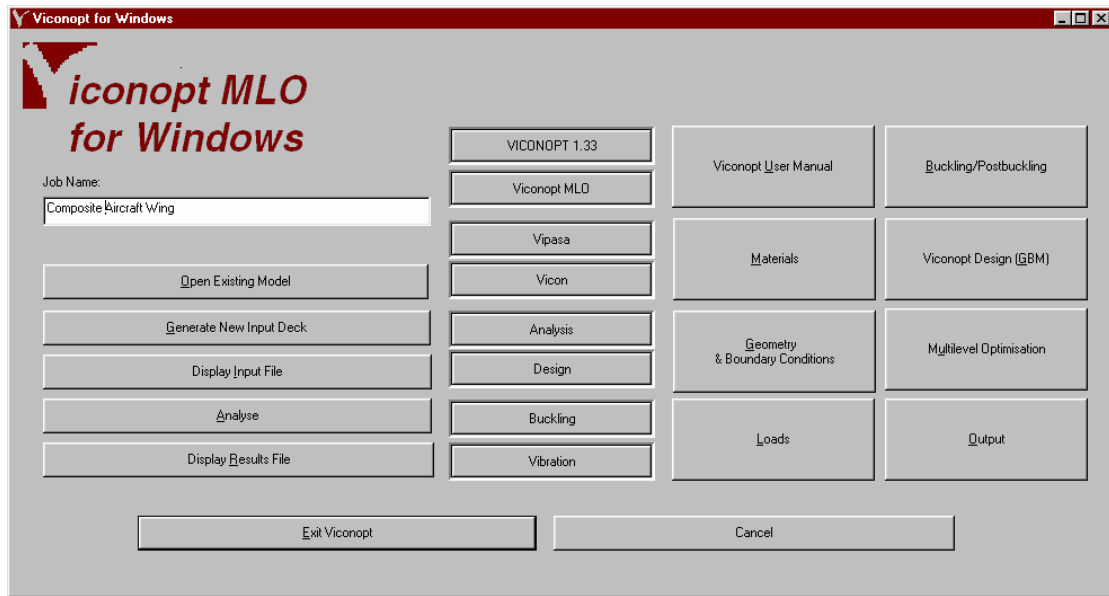
Figure 4. Viconopt MLO – main window.

2.3 VICONOPT Design Capabilities

VICONOPT has a number of design capabilities which have recently been extended to allow discrete optimization [11,12] in addition to its well proven continuous optimization features [2]. The software also allows for cost optimization [13] and discontinuous cost functions [11,12].

The continuous optimization procedures in VICONOPT are based on a gradient based optimizer [14] which features the method of feasible directions [15].

A range of different design variables can be specified. These can include breadths and thicknesses of plates or, in the case of composite structures, individual layer thicknesses and ply orientations. Equality and inequality constraints can be specified, allowing configurational and overall geometric dimensions and design variables to be controlled, or linked to each other. By means of design variable linking, geometric consistency can be maintained, while computational time is reduced due to a smaller number of independent design variables. Many composite components in aeronautical structures have a

symmetric and balanced lay-up, which can be exploited to significantly reduce the number of design variables.

VICONOPT's discrete design capability differs from various other methods, in that the discrete design phase does not interact with the continuous phase. Instead, whenever some or all of the design variables are required to take discrete values, the discrete design phase is invoked sequentially following the continuous phase, using the continuous optimum solution as a starting point. The discrete design phase consists of two stages, *sequential rounding* and *combinatorial partial enumeration* which are described in detail in Refs. [11] and [12].

3 Viconopt MLO

3.1 General

Viconopt MLO is a newly developed software package which aims to provide an efficient solution for the optimization of typical aerospace structures, such as aircraft wings. The software provides a windows interface (Figure 4) for multilevel optimization, bringing together the analysis and design capabilities of MSC/NASTRAN and VICONOPT. Particular

care has been taken to make the program as user-friendly as possible.

In addition to its multilevel optimization capabilities, Viconopt MLO can also be used as a pre/post-processor for conventional single level VICONOPT panel analysis and optimization. This new approach avoids the need for text input files to be generated manually, allowing models to be assembled, analyzed and optimized much more quickly and efficiently. Models can either be generated from scratch, or based on data imported from MSC/NASTRAN. The latter is a particularly useful feature, since many users typically choose VICONOPT as an alternative means for the analysis and design of structural components for which MSC/NASTRAN models already exist.

3.2 Multilevel Optimization using Viconopt MLO

Optimization in Viconopt MLO is based on a process which cycles between two levels: the system level and the panel level (Figure 1). At system level, a finite element analysis of the whole structure is performed by MSC/NASTRAN, and the loads in each of the component panels are passed to VICONOPT. VICONOPT optimizes each of the panels separately, and passes details of the new configuration back to MSC/NASTRAN. Typically, several cycles are required for convergence on a consistent optimal set of panel configurations and loadings.

Figure 5 gives a detailed flowchart representation of the multilevel optimization procedure adopted for Viconopt MLO. The MSC/NASTRAN finite element model at system level can be generated using any pre-/post-processor such as MSC/PATRAN [4], which allows the creation of a model database (.db) and the actual MSC/NASTRAN input file (.bdf) containing all the relevant finite element data. The .bdf file is submitted to MSC/NASTRAN, and two results files are created: the .f06 and .op2 files. The former

contains all the results for the finite element model in a numerical format, while the latter includes the necessary data for the graphical display of the results in MSC/PATRAN.

Typically, MSC/NASTRAN models consists of various groups containing different components of the overall structure. For instance, when modeling an aircraft wing, it is good practice to associate a different group with each individual skin panel. Each panel consists of various component plates (skin, webs and flanges). By means of property cards, different material properties (e.g. laminate lay-ups) may be defined for these individual plates. Provided that all of the structural components that will constitute plates in a VICONOPT model have been modeled as plates at the system level and have been assigned individual property cards, all the model information required to specify the optimization problems at the panel level can be translated by the 'MSC/NASTRAN to VICONOPT' converter in Viconopt MLO. Any additional parameters required to create the panel models may be specified using the pre-processing capabilities of Viconopt MLO.

Once all of the VICONOPT panel models have been set up, Viconopt MLO automatically generates the VICONOPT input files (.dat). These are subsequently analyzed and optimized by VICONOPT, and two results files (.vres and .u11) are created. The .vres files contain all of the results from the panel optimizations, as well as various other pieces of information which can be requested by the user. The .u11 file contains the optimization results, including the final values of the design variables and dependent variables in a format suitable for re-input into VICONOPT.

The next stage uses the 'VICONOPT to MSC/NASTRAN' converter to feed all design changes made by VICONOPT back into the original finite element model, which is subsequently re-analyzed. The stress-redistributions following the design changes are determined, a new .f06 file is generated, and the .op2 file is updated to include the most
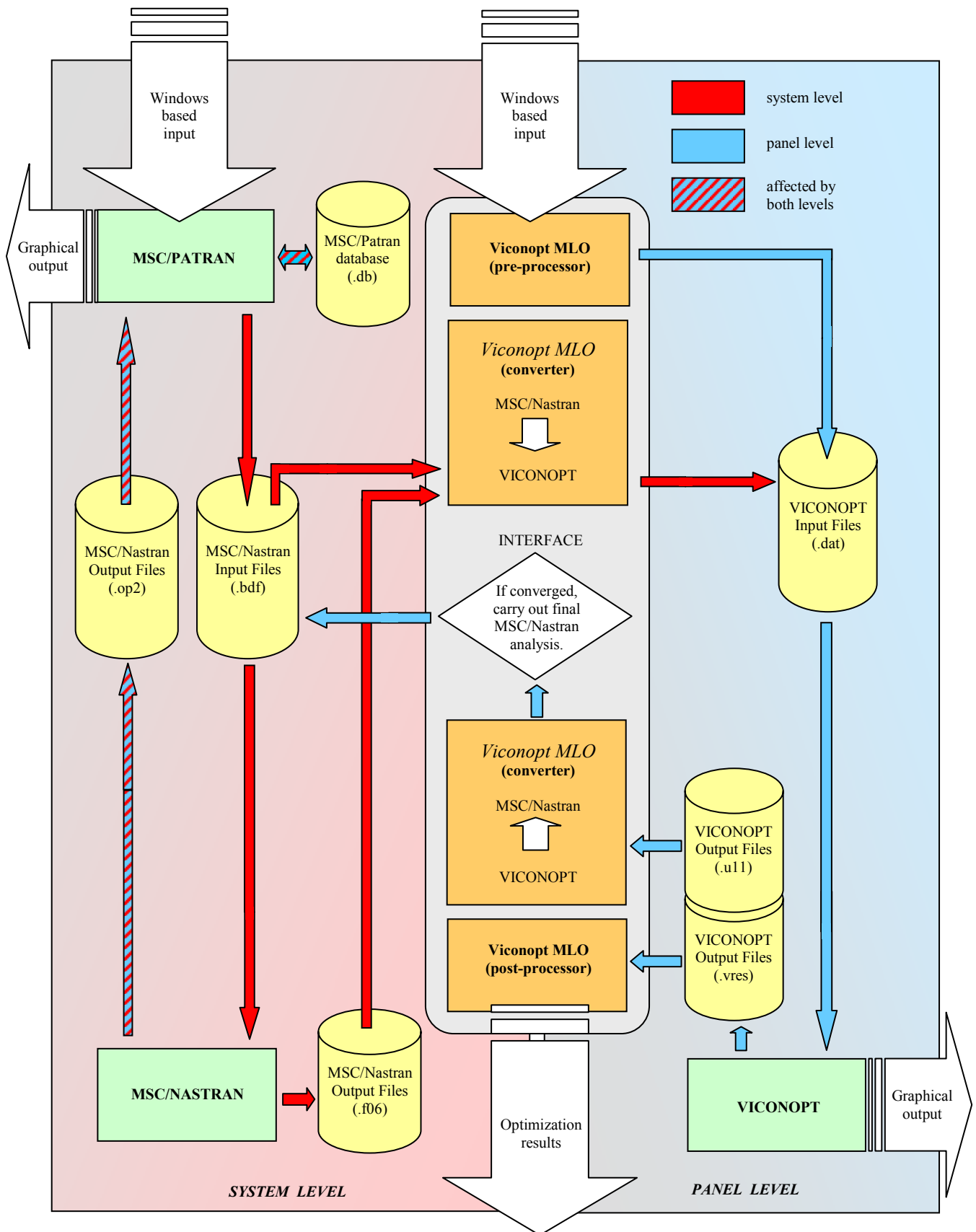
Figure 5. Flowchart of multilevel optimisation procedure in Viconopt MLO.

recent results. On the basis of the .u11 and new .f06 files, all the VICONOPT models are updated and re-optimized. Viconopt MLO repeats the above procedure until the final convergence criterion on the overall mass of the structure is achieved.

Due to the nature of the VICONOPT analysis, some approximations are necessary when generating models at panel level. Firstly, VICONOPT requires any model to have the same boundary conditions at opposite longitudinal ends. In addition, loads applied to a panel are assumed to be longitudinally invariant. For this reason, the procedure adopted for translating loads between the finite element model at system level and the VICONOPT models at panel level is based on average values for the longitudinal, transverse, shear and bending loads acting on each panel.

In its current form, Viconopt MLO does not allow design variables to be specified at the system level, and all design variable changes are made by VICONOPT at panel level. The 'multilevel' nature of the software thus mainly consists of determining the stress redistributions at system level due to the changes at panel level. However, the program has been designed in such a way that full multilevel optimization, e.g. by using the MSC/NASTRAN optimization and sensitivity analysis capabilities at system level, can be readily implemented as part of future enhancements to Viconopt MLO.

4 Applications

In order to demonstrate the capabilities of Viconopt MLO, a design study has been conducted into the multilevel optimization behavior of a composite aircraft wing [16].The wing consisted of twelve skin panels (six at the top and six at the bottom of the wing), three spars and four ribs (Figures 6 and 7). The objective was to optimize the layer thicknesses in each of the skin panels. No attempt was made to optimize the ribs and spars, which were included in the model to provide simply

supported edge conditions for the panels. To ensure adequate boundary conditions, and avoid localized stress concentrations, the wing was attached to an 'adapter' at the fuselage end, for which all degrees of freedom were clamped.

High strength carbon-epoxy was used as the material for all the component plates. Symmetric lay-ups were assumed for all plates (-45°/45°/90°/0°/90°/45°/-45°), but with different thicknesses for skin, webs and flanges, giving a total of 144 design variables.

Two different load cases were considered, one subjecting the wing to a uniform uplift, and the other twisting the wing about its longitudinal axis.

Although the model at system level was very large (29,280 elements with 126,860 degrees of freedom) and a large amount of data had to be transferred between the different levels, the multilevel optimization process required less than six hours to complete on a PC (Pentium III, 1000 MHz, 1024 MB RAM) due to the efficiency of Viconopt MLO. After three optimization cycles, the loads acting on the individual panels, as well as the panel masses had converged reasonably well, and the convergence criterion for the mass of the overall wing had been met. Prior to the automations of Viconopt MLO, this multilevel process would have required a substantial amount of manual data manipulation.

Ref. [16] provides a detailed discussion of the numerical results and the convergence behavior of the overall process.

5 Concluding Remarks

For many years, a range of aerospace companies have used VICONOPT for the analysis and design of prismatic plate assemblies. While much research has been carried out to continuously enhance the software to include the latest developments in
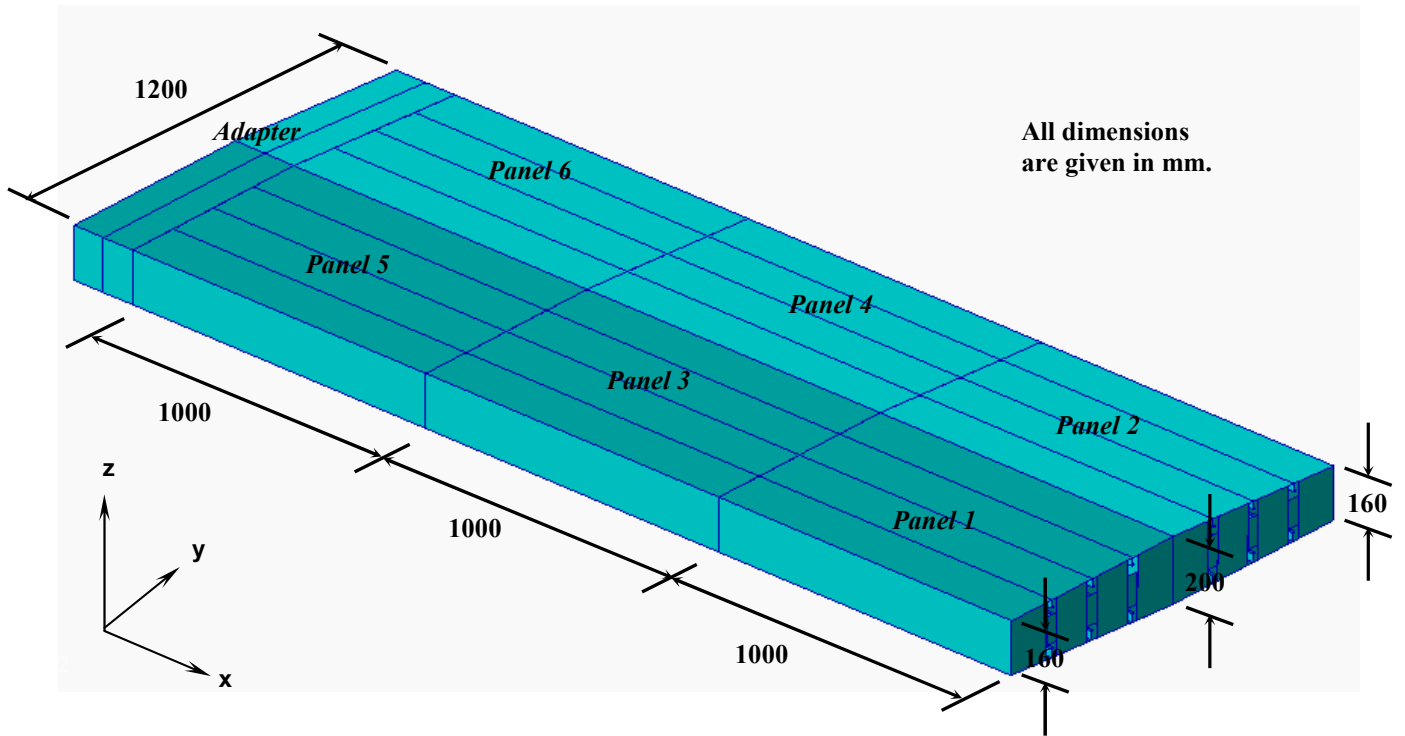
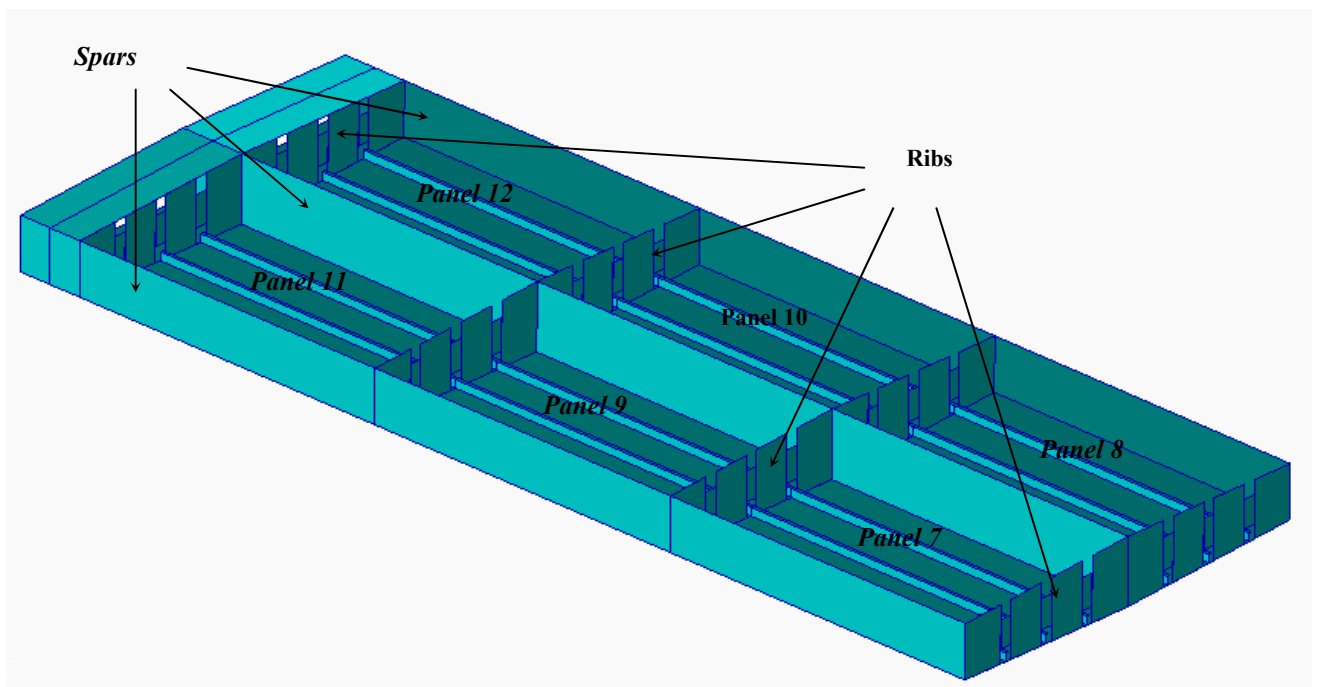Figure 6. Composite aircraft wing (top panels).

Figure 7. Composite aircraft wing (bottom panels, spars and ribs).

the field of structural analysis and optimization, VICONOPT did not previously provide a windows-based user interface. Input files had to be generated manually, which was inevitably prone to errors and very time consuming. Over the years, this has been pointed out by various industrial users as an important area for future improvement.

Viconopt MLO has been developed as a windows based interface, linking the commercial finite element package MSC/NASTRAN and the specialist panel design code VICONOPT. This new software enables multilevel optimization of plate assemblies, using a finite element model of the overall structure at one level, and separate VICONOPT models of the component structures at a second level.

Viconopt MLO is based on widely accepted standards for good windows software design, and particular care has been taken to make the program as user-friendly as possible. In addition to providing a tool for multilevel optimization, the software can also be used as a pre-/post-processor for conventional VICONOPT models.

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