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Automatic Generation of the Structural Layout of Aircraft Rear Fuselage and Tail Surfaces including Global Finite Elements and CAD Model

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Abstract

As part of a multidisciplinary design framework developed for the preliminary design and optimisation of aircraft rear fuselage and tail surfaces, a complete structural design capability, including automatic high fidelity finite element model generation and structural sizing has been developed. Based on a parametric geometric modelling module part of the framework, the structural layout is defined using a mixture of dimensional (stringer, rib and frame pitch) and non-dimensional parameters (relative chordwise spar and spanwise rib positions, master frame positions). The structural layout definition is stored independently from the geometry and can be applied, preserving the design intent, to variations of the external geometry. The structural lay-out parameters can be changed independently from the aircraft geometry and the complete three-dimensional structural model is generated and visualised within the framework, exported to a commercial CAD package (CATIA V5) and written as a global NASTRAN finite element model (FEM). Topological details are handled appropriately (e.g., stringers run-outs are modelled following industrial guidelines) and the FEM uses a structured numbering convention and the same elements and idealization used in a manual advanced preliminary design phase.

Keywords: aircraft, MDO, structures, optimization, empennage, finite element method, CAD, CATIA.

1 Introduction

The design and analysis of aircraft structures is a key driver in the multidisciplinary design process, impacting the weight, cost, manufacturability, operability and aeroelastic response. The major aircraft components are usually designed using lightweight design principles and most structural subcomponents adopt the arrangement of a thin skin stiffened by stringers and frames or ribs. In the preliminary aircraft design process, where early availability of weight data is crucial, the structure is often modelled using simple beam theories. While this approach, when well calibrated and used by experts, provides sufficiently accurate weight and stiffness data, its applicability is limited to conventional slender structures.

Ideally a better representation of the structural layout should be used as soon as possible during the design process [1,2,3]. Coupled with a structural sizing method and a means of generating aircraft loads, access to a representation of the structure of higher fidelity would enable the identification of functional behaviour, manufacturing issues and opportunities, weight and balance and drive the design towards lower weight and costs and increased overall performance.

There are several examples in the literature of attempts to generate aircraft structural models automatically [4,5,6,7,8]. Reliance on generic CAD packages to model the aircraft external geometry and structural layout limits the freedom to code efficient finite elements meshing methods, either for lack of representation of topological detail (stringer run-outs, doors) or by the use of unstructured meshes which complicate the sizing of the structural details. Moreover, the structural layout definition is generally a manual process, preventing the implementation of a formal structural or multidisciplinary optimisation process including external geometry or internal arrangement parameters.

The following sections describe a methodology for generating the structural layout and three dimensional geometry of a conventional aircraft rear fuselage and tail surfaces. The structural layout definition can be performed in interactive mode using a graphical user interface or via a text input file in batch mode by specifying a reduced number of key parameters. The 3D structural geometry as well as a CAD model of the external surfaces and internal structure are generated automatically by a computer program referred to as MARES (Multidisciplinary Analysis of Rear Ends).

The complete global FEM generation, including an aeroelastic model, is carried out automatically by the program and, given a set of flight conditions, NASTRAN generates the external and internal structural loads. A proprietary structural sizing method then sizes the structure for strength and finally a structural weight is obtained, as well as flexible aeroelastic stability derivatives and a preliminary flutter behaviour (after augmenting the mass model with non-structural mass properties).

The aircraft external geometry, internal structure, aerodynamic and structural meshes and results, miscellaneous components (cargo, cabin) and other objects (e.g., passengers and cargo, airport equipment) can all be visualised simultaneously, enabling an unprecedented data blending and the ability to detect clashes or configuration drivers.

2 Generation of the structure of lifting surfaces

The main structure of the lifting surfaces of an aircraft (usually the wing and tail surfaces) is typically a box beam composed of stiffened cover panels, bounding and, possibly, intermediate spars and ribs. The secondary structures, i.e., fixed leading and trailing edges, are also box-like, as are usually the control surfaces. Some aeronautical structures used on lifting surfaces use sandwich panels instead of stiffened thin wall covers, but the structural layout can generally be inscribed in the box-beam type.

The following sections describe the methodology developed for the definition of a generic structural arrangement of box-beam structures and the subsequent generation of the three-dimensional structural geometry and global finite elements model.

The generation of the complete structural model is performed in two phases:

- A: Definition of a two-dimensional structural layout on a reference plane
- B: Generation of the three dimensional structural entities
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2.1 Definition of the structural layout

The structural layout of lifting surfaces is determined by the number and position of the spars, ribs and stringers. In MARES, the parameters used to describe the positions of the elements are linked to the basic trapezoidal planform and are defined in non-dimensional form. The chordwise locations are referred to *x/c*; distance in line-of-flight from the trapezoidal leading edge divided by the local trapezoidal chord. Points with *x/c* smaller than zero are located forward of the leading edge and points with *x/c* greater than 1 are located aft of the trailing edge of the basic trapezium.

The spanwise locations are given in terms of the non-dimensional span parameter, *eta*: a value of *eta*=0 corresponds to the root of the basic trapezium and *eta*=1 to the tip (Figure 1).

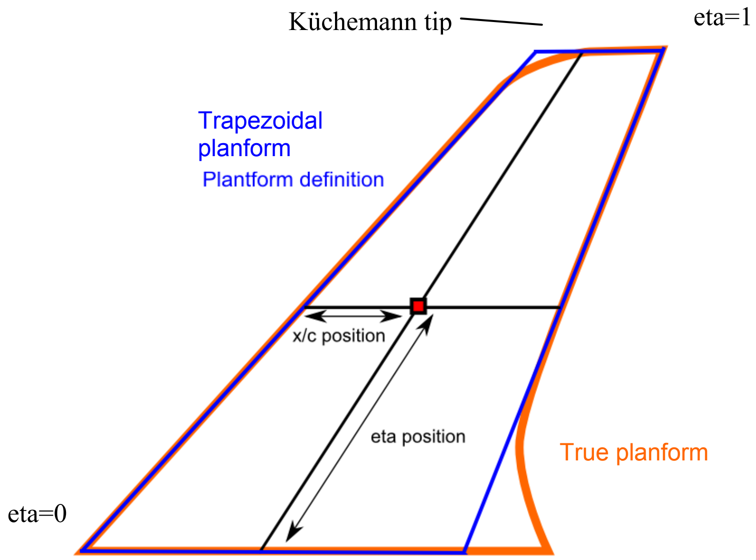

Figure 1: Planform definitions and non-dimensional planform coordinates

The main advantage of using *x/c* and *eta* as planform coordinates to position the key structural points is that the structural layout will be automatically updated when performing global modifications of the planform shape (sweep, taper and aspect ratio, reference surface). The locations of the spars, for example, are typically within similar ranges of *x/c* in most aircraft of the same type [9] and thus this is a convenient way to link the structural layout to the global geometry. Additionally, linking the locations of the key structural elements to the trapezoidal planform leaves the structure unaffected by local modifications to the leading and trailing edges such as Küchemann tips or curved trailing edges (Figure 1).

The number of structural elements, in particular ribs, frames and stringers, depend on the size of the structure. The key parameter is the rib and stringer pitch, i.e., the separation along the reference direction between these structural elements.

The rib and stringer pitch determine the buckling wavelength and thus influence the structural stability. These parameters should be determined by a weight optimisation process: reducing pitch lowers the skin weight but increases the number of stiffening elements and therefore there is a point of equilibrium corresponding to the stiffener pitch giving minimum overall weight.

There are, in fact, several considerations affecting the final structural pitch of ribs, frames and stringers although a certain trend can also be observed in transport aircraft [9]. In MARES, the pitch of stringers, ribs and frames is specified in dimensional form.

The final parameter that must be defined to complete the description of the structural layout is the stringer orientation with respect to the spars, which, in MARES, can be different in either surface of the lifting surfaces.

Once the two-dimensional structural layout has been defined, additional parameters are required in order to define the angles formed by spars and ribs with the plane of reference. At this point, the complete three dimensional structure can be generated by creating datum planes for ribs, frames and stringers. The intersection of these datum planes with the reference plane corresponds to the 2D layout and their orientation is the angle they form with the plane of reference.

The generation of the actual 3D structural elements is performed by intersecting the datum planes with the external surfaces and by trimming and "running-out" the stringers as described hereafter.

2.1.1 Structural boxes

The structures of lifting surfaces can be described by "boxes". Each box is bounded in planform by a front and rear spar and two closing ribs. The stringer pitch and orientation on each of the external surfaces can be different. There can be additional internal spars.

The simplest arrangement for the main structure of a lifting surface consists of just a single box with a front and rear spar extending from *eta*=0 to an *eta* close to 1 (the structural box generally does not extend all the way to the tip). Therefore the spar locations are given in terms of their inboard and outboard *x/c* and *eta* coordinates, requiring 4 parameters per box.

In the simplest definition, the stringer layout is the same in both external surfaces; same pitch and orientation with respect to the rear spar. The number of intermediate ribs is defined by the box rib pitch at the rear spar and their orientations are fanned out between those of the closing ribs. Alternatively, the number of internal ribs can be specified and the rib pitch will be adapted accordingly.

In order to define spar kinks or to change the orientation of the ribs or stringers, additional boxes can be defined. The complete structure will correspond to the spanwise concatenation of these boxes. The closing ribs of each box are referred to as "master ribs" (Figure 2) and their definition only requires their *x/c* and *eta* coordinates at the front and rear spars.

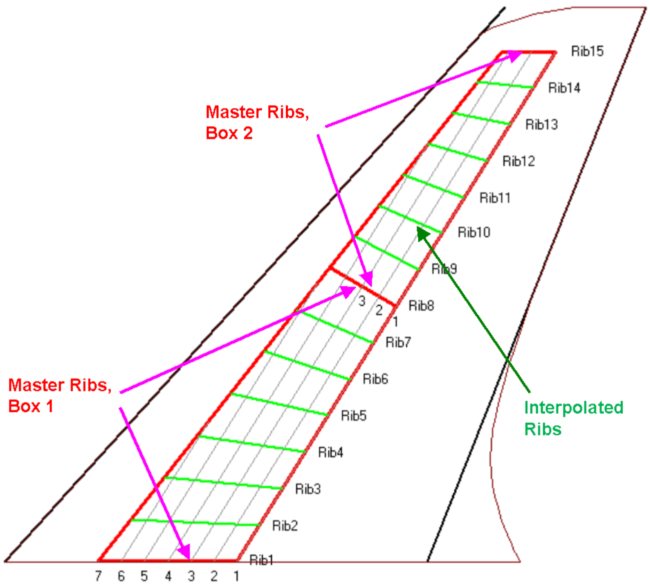

Figure 2: Definition of master ribs and boxes

2.1.2 Stringers

The information required to define the stringers layout is their pitch at the inboard and –optionally- outboard closing ribs and the angle between the aft-most stringer and the rear spar. The main complication when generating the actual stringer layout is the correct management of their topology at the stringer run-outs and their continuation between adjacent spanwise boxes.

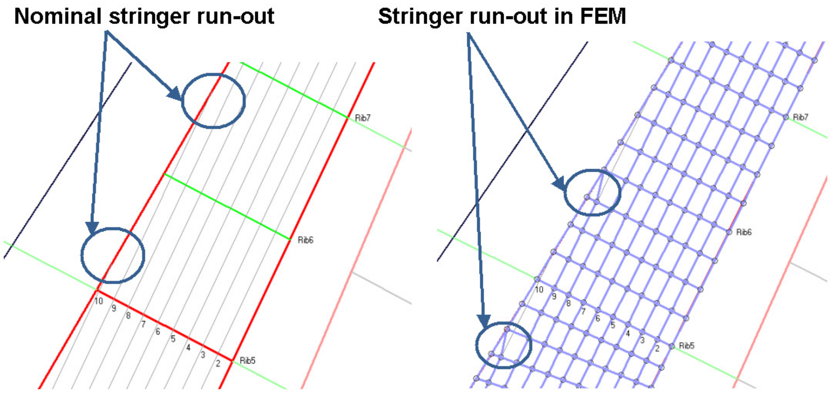

Figure 3: Nominal stringer run-out (left) and modelling of the run-out in a finite elements model (FEM) mesh with intermediate elements in the rib-bay (right)

The final stringer layout topology (the rib or intermediate rib station at which each stringer starts or runs-out) can only be calculated using the complete 3D geometry as the intersections at the external surfaces will depend on the orientations of the spars and rib datum planes.

The stringer lay-out (pitch and orientation) can be different in each elementary box and on either side of the lifting surface.

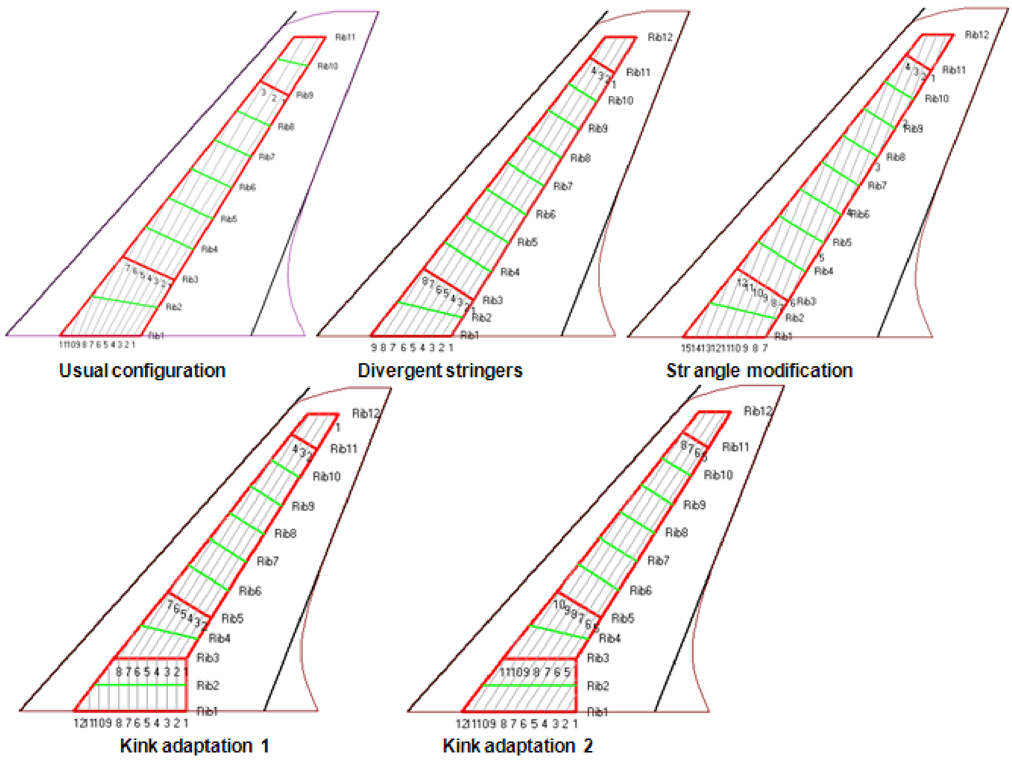

Figure 4: Different stringer lay-out possibilities

By implementation, the stringers are continuous spanwise, although kinks are allowed. By specifying different stringer pitch at the inboard and outboard closing ribs in a box, the stringers can be made converging or diverging (Figure 4).

2.1.3 Multi-spar boxes

Multi-spar boxes can be modelled by defining a web between parallel stringers on each side of the lifting surface. A discontinuous intermediate spar can be defined between any two master ribs (Figure 5).

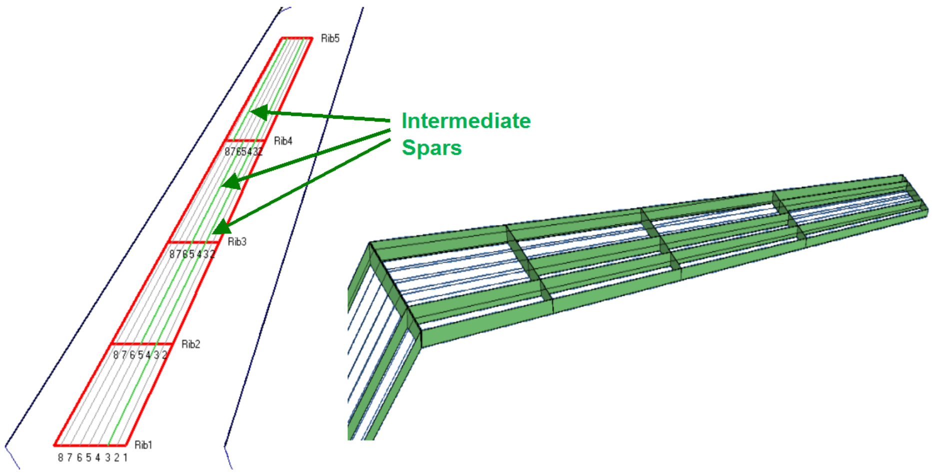

Figure 5: Multi-spar box lay-out definition (left), 3D rendering (right)

2.1.4 Control surfaces

The usual control surfaces on the empennage are the elevator, at the trailing edge of the horizontal tailplane (HTP) for pitch control and the rudder on the vertical tailplane (VTP) for yaw control. The structure of elevators and rudders is usually box-like, with at least one front spar and various ribs and stringers. As the thickness of the trailing edge tends to zero there may be no rear spar.

In MARES, the structures corresponding to the control surfaces are defined in a similar process as that used for the main boxes. The various master ribs are defined including a virtual rear spar extending aft of the real trailing edge of the tail surface. The mesh generator detects the intersections between the stringer datum lines and the trailing edge and manages the stringer run-out topology. Particular orientations can be specified for the master ribs -for example, to make them normal to the hinge axis- and these are imposed on the final geometry by a constraint solving algorithm.

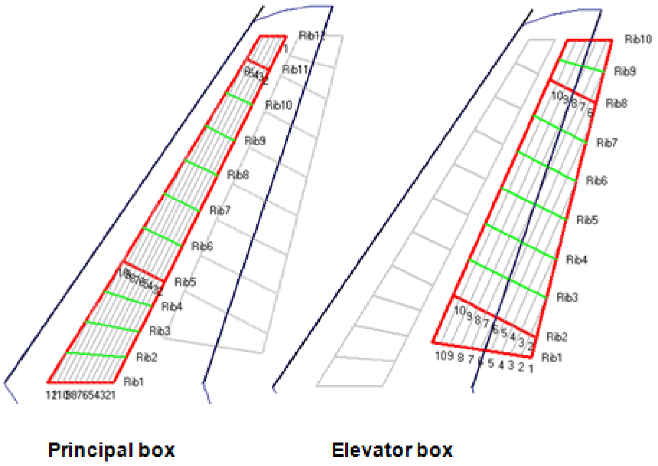

Figure 6: Definition of the structural lay-out for a control surface

2.1.5 Secondary structure

The secondary structure considered in MARES corresponds to the fixed leading edge, attached to the front spar, and the shroud covers and ribs, connected to the rear spar. Internally, the secondary structures are treated as "extension boxes" but their master ribs are subordinated to those of the principal box to which they are associated. The orientation of the extension ribs is their only remaining degree of freedom and is given relative to the corresponding master rib.

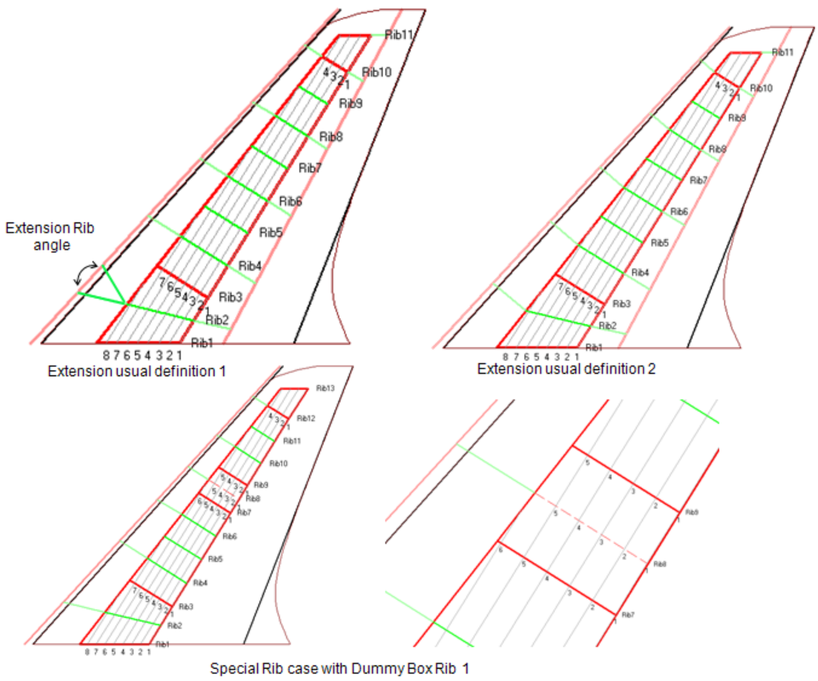

Figure 7: Secondary structure definition

2.2 3D Structure

The previous sections have described the main parameters and elements that are required for the definition of the structural arrangement. This is, in fact, a two-dimensional trace of the datum planes defining the spars, ribs and stringers on the reference plane for the lifting surface. The reference plane forms a dihedral angle with the principal planes of the aircraft and this and other geometric considerations (twist, blended tips) need to be taken into consideration to define completely the structure. Ribs, for example, tend to be defined in datum planes essentially normal to the local elastic axis of the main box. The spar datum planes tend to be perpendicular to an aircraft principal plane, but there are instances where a certain slant is required on the spars (Figure 8).

The additional degrees of freedom corresponding to the inclination of the ribs and spar datum planes with respect to the reference plane of the lifting surface complicate the definition of the complete structure and, depending on the particular structural concept (e.g., multi-spar, kinked stringers) can lead to cases of over or under constrained definition which need to be handled by the structural model generator.

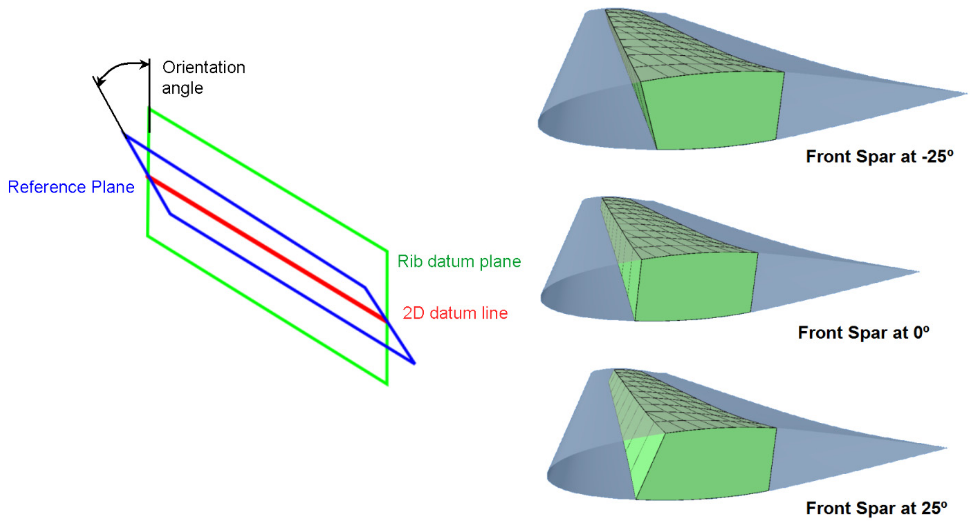

Figure 8: Orientation of rib and spar datum planes

2.2.1 Spars

The spars are beams bounding the box structure in the spanwise direction. At least two spars need to be defined for the main torsion box and one for the control surfaces. In MARES, the spars can be kinked along the span, but the spar webs must be planar between kinks. The angle formed between the spar web and the reference plane can be defined for each spanwise segment (Figure 8) and the possible degeneracies must be handled to avoid illconditioning of the structural layout. By default, the spars are normal to the plane of reference.

The intersection of the spar datum planes with each of the external sides of the lifting surface becomes the datum line bounding the ribs.

2.2.2 Ribs

The ribs are also defined by datum planes in the structural layout and their default orientation is normal to a nominal neutral axis calculated based on the spar geometry, with the exception of the inboard closing rib, which is assumed normal to the relevant aircraft plane of reference (Figure 9).

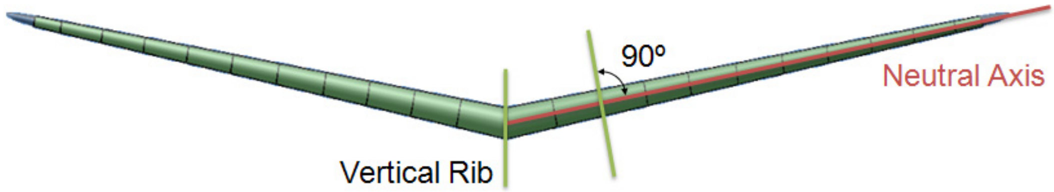

Figure 9: Ribs default orientation

The orientation of each rib can be edited individually (Figure 10) as may be required to adapt to particular load introduction directions on the structure (e.g., actuators, pylon or landing gear attachments).

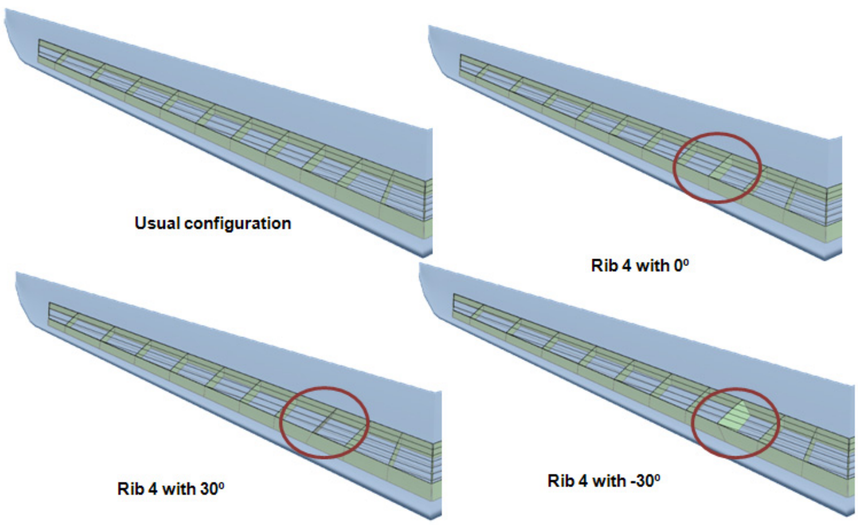

Figure 10: Orientation of individual ribs

The orientation of the ribs at the spar kinks is calculated from the orientation of the adjacent spar sections. There may be cases leading to a warped kink rib and these are tolerated but a user warning is raised as this would not lead to a meaningful structure (Figure 11).

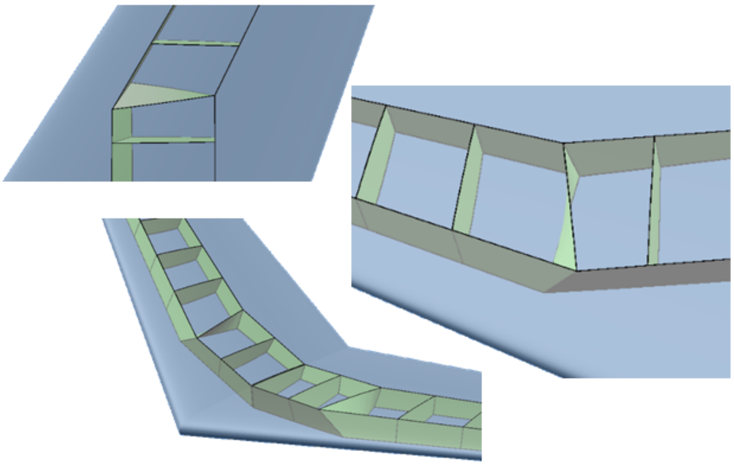

Figure 11: Rib warping at spar kinks

2.2.3 Stringers

The stringers are obtained by intersecting their datum planes with the external surfaces. The orientation of the stringer datum planes is perpendicular to the reference plane. The final structural topology, i.e., the position of the stringer run-outs, is calculated by intersecting the stringer curves by the rib datum planes, including a minimum distance check to the nearest spar.

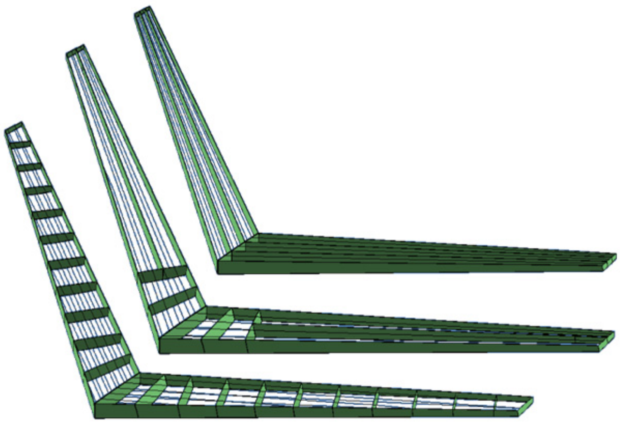

Figure 12: Examples of stringer arrangement

The same process is followed when the stringer pitch or orientations is different on either side of the lifting surface (Figure 13).

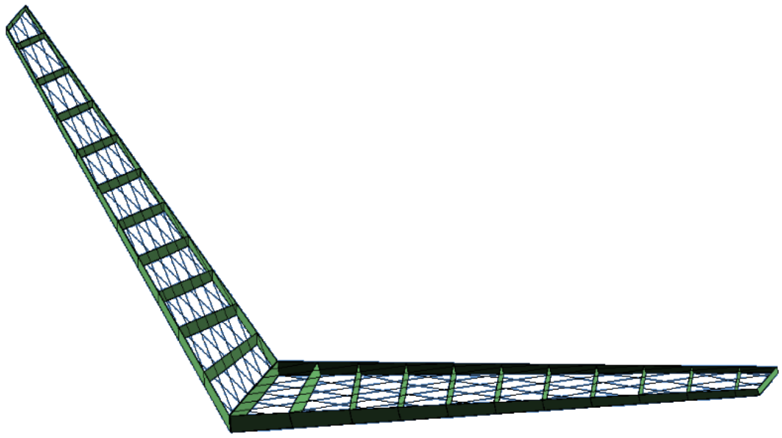

Figure 13: Stringer orientation different on each side of the box

The methodology described above allows to represent with high fidelity most of the aeronautical structures usually found on existing aircraft lifting surfaces.

Particular attention has been paid to the user interface (when operating in interactive design mode) and to the data structure and format of the input file, so that the complex task of defining the whole structure of a lifting surface is simplified to the utmost.

Figure 14 shows an example of a high fidelity structure generated in interactive mode in less than 20 minutes.

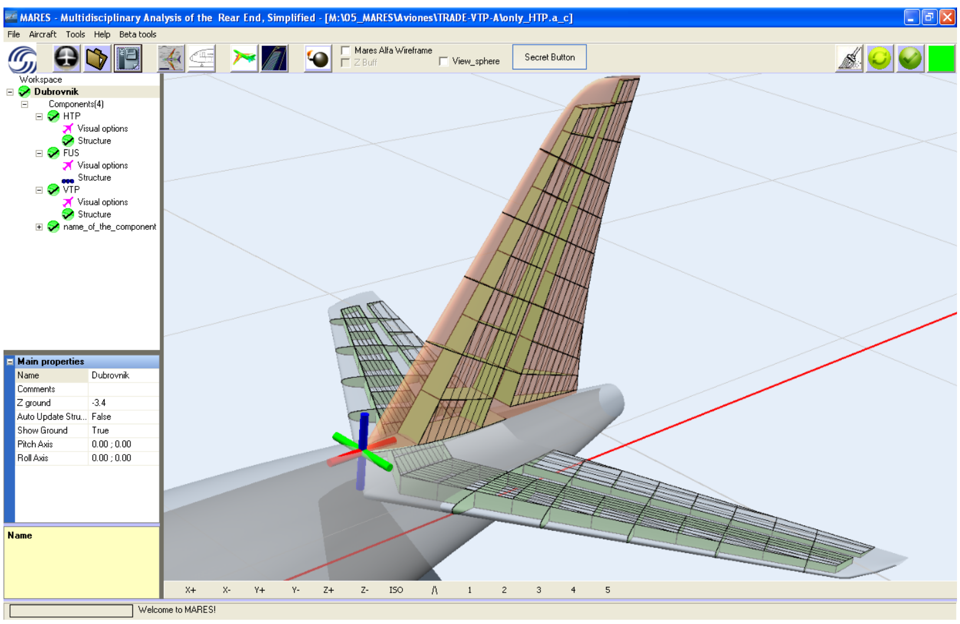

Figure 14: Final structure layout for all rear-end lifting surfaces

2.3 Global finite elements model and loads for sizing

The geometric definition of the structural arrangement is an important part of the aircraft rear fuselage and empennage design process as it affects the configuration, the location of major load inputs, and the space allocation for systems, fuel volume, assembly and maintenance.

In order to obtain the design responses from the structure required to perform multidisciplinary analysis and optimisation (e.g., mass and stiffness), three main ingredients are required:

- A finite elements model (FEM) of the structure
- A set of loads and material allowables
- A sizing method to obtain the thickness and area of the structural elements.

The following sections describe the automatic finite elements model generator implemented in MARES as well as the method to obtain loads for sizing.

2.3.1 Data for FEM generation

Once the structural arrangement has been defined in MARES all the parameters required to generate the finite elements model mesh are available. Two additional data are required in order to give more flexibility to the structural representation for sizing or loading:

- The number of elements between Ribs (Figure 15, left)
- The number of elements between the external surfaces

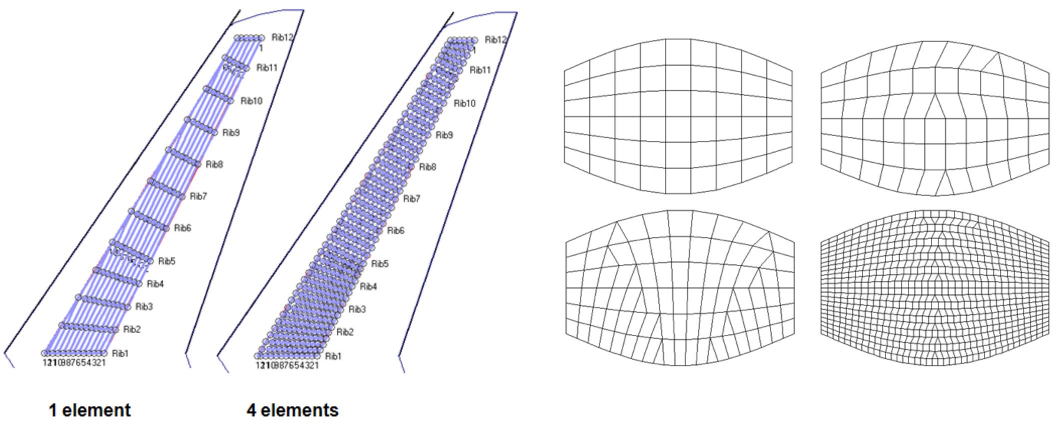

Figure 15: Different number of elements between ribs for the same structural arrangement (left), examples of unstructured "sneaking" meshes for ribs (right)

The box FEM mesh is structured for the spars and covers and uses quadrilateral elements where possible to represent the skins and the spar and rib webs. Triangles are only used at the stringer run-outs and in the particular case where there are different number of stringers on either side of the rib. In this case, an unstructured mesh is generated with an specific "sneaking" algorithm designed to minimise the number of triangles introduced in the mesh and distribute them in an optimum way.

2.3.2 Model testing with unit loads

The finite elements model is written into a text file with Nastran format by MARES. The generation of models for other solvers would only entail a change of format, the topology would be invariant.

The Nastran input file contains the FEM mesh topology: nodes and elements with their connectivity. By default, all the shell elements are written with a constant thickness and the 1D elements with constant beam properties. A different material is used for each component i.e., ribs, spars and covers.

A multipoint constraint element (MPC) is defined at each rib for point load introduction. This is the usual method to load box structures when the external loads are available.

In order to perform a test run on the model, a unit load case is also written in the input file, as well as all the required cards setting the analysis type and parameters. The test input file, as written by MARES, can be run directly in Nastran.

An example of a conventional tailplane FEM generated and rendered in MARES is shown in Figure 16.

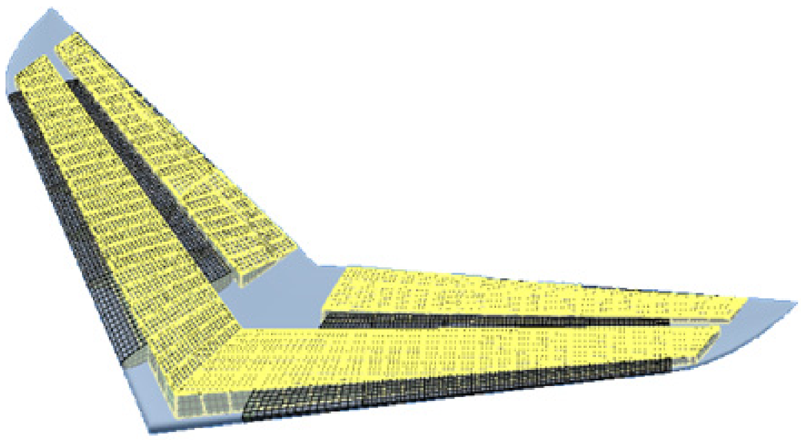

Figure 16: Global FEM of a conventional tailplane rendered in Mares

The same model, as seen once imported in a finite elements model pre and post processor is shown in Figure 17 (left). The results of the analysis for the unit load case (Figure 17, right).

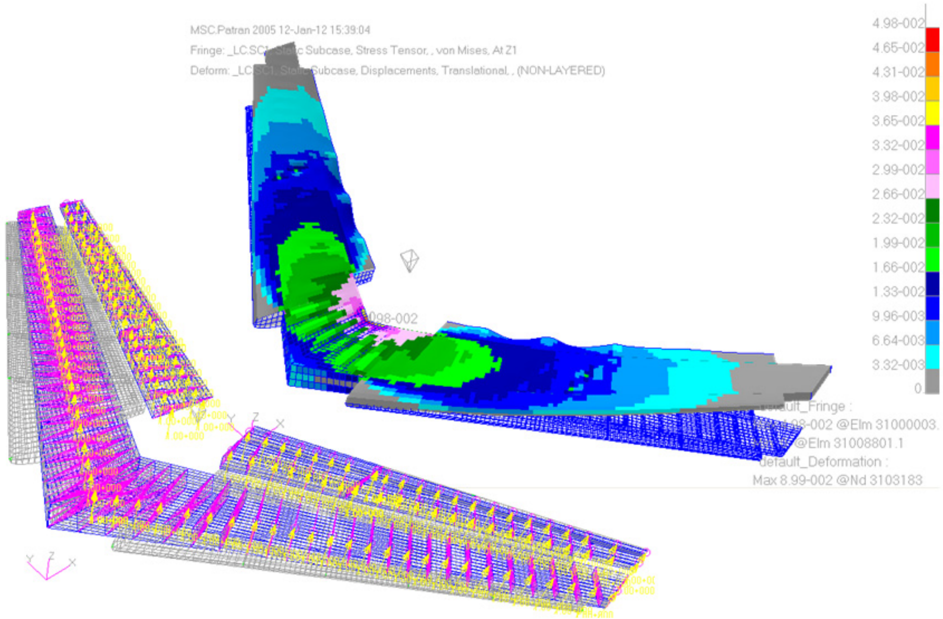

Figure 6: Conventional tail surface FEM, including multi-point constraints and unit loads (left). Results of FE analysis for unit load test case (right)

2.3.3 Aeroelastic loads

In the preliminary design phases, access to a full set of external loads to size the structure is difficult. An alternative approach is to generate the loads directly on the finite elements model by coupling the structural deflections to an aerodynamic mesh and specifying the flight conditions in terms of angle of attack and yaw, deflection of the control surfaces, rates of aircraft rotation, load factor, Mach number, dynamic pressure and any other relevant flight parameter.

The aerodynamic forces, if transmitted to the structure, will generate internal loads suitable for sizing. The inertial loads will arise as a consequence of the mass of the FE model (which should include the non-structural mass) and the accelerations specified in the flight conditions for the load case. Following an iterative sizing process, where the loads are updated after every sizing loop, the final mass and stiffness distribution will be consistent with the internal loads.

The methodology described can be implemented in Nastran using a static aeroelastic solution (SOL144). The aerodynamic model is based on a doublet lattice method (DLM) and the aero mesh is coupled to hard points in the structure, representative of the global displacements. Examples of the aero-structural coupling can be seen in Figure 18.

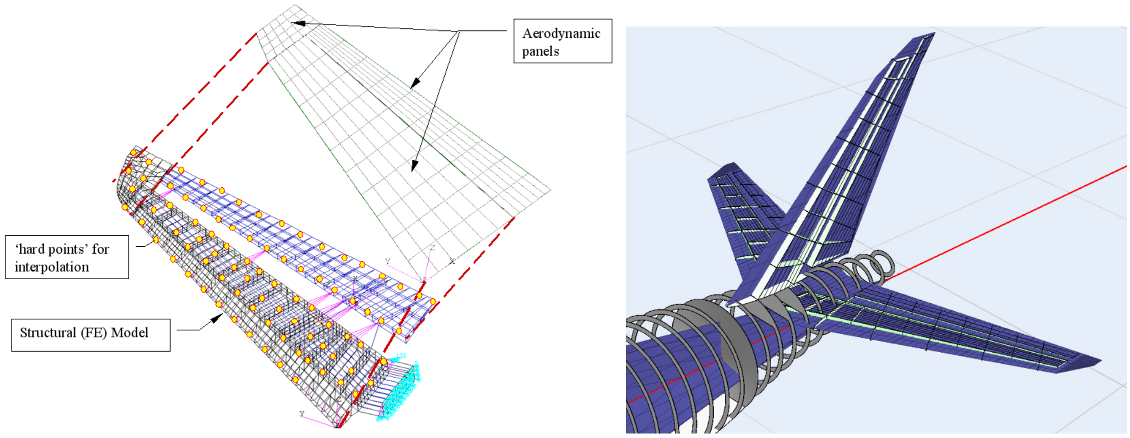

Figure 18: Aeroelastic model for loads generation. Coupling of the DLM mesh with structural hard points (left) and automatically generated aerodynamic mesh on fuselage and tail surfaces (right)

The DLM mesh is automatically generated by MARES based on the reference geometry for the fuselage and lifting surfaces (Figure 18, right).

The flight conditions to specify the relevant load cases for structural sizing may be based on “book cases” or can be based on previous knowledge on load relevant manoeuvres of similar aircraft. In general, it is easier to define the flight conditions likely to correspond to a critical loading case than the actual external loads, particularly as these depend on the structural sizing, thus the circular dependency.

The structural sizing process is not described in this paper but is based on an optimality criterion method which enables to update the model properties during every aeroelastic loading loop. An example of the thickness map of a sized tailplane structure is shown in Figure 19 (left).

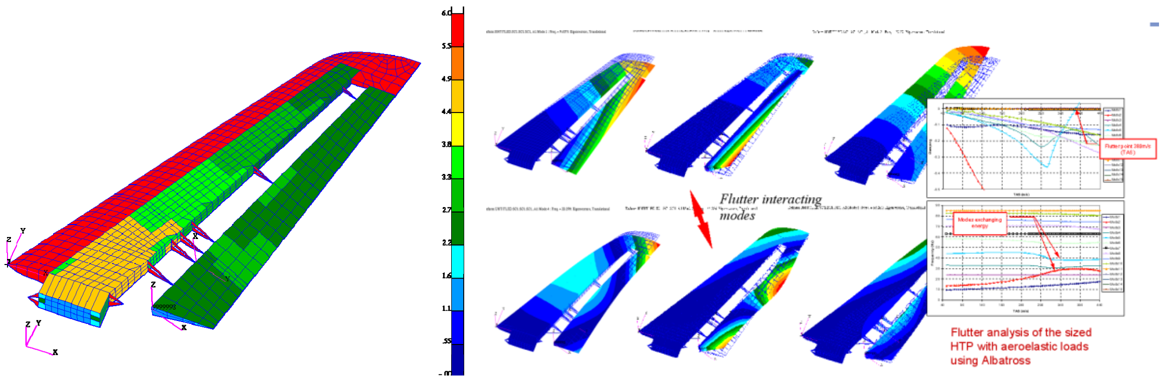

Figure 19: Tailplane structure automatically sized using aeroelastic loads (left). Flutter modes and v-g plot of the sized tailplane (right)

Through the structural sizing process the properties of the structure are obtained i.e., thickness of isotropic shell elements, lay-up of composite components, beam properties of 1D elements. Therefore, the structural mass is a by-product of the sizing process, as well as the global stiffness of the lifting surface. The latter is an important consideration in the design of tailplanes as it determines the flexible aeroelastic derivatives (particularly relevant for the effectiveness of stabilising surfaces) and their flutter response. Figure 19 (right) shows the flutter modes and v-g diagram for a tailplane sized using the process described above.

3 Rear fuselage structure

The empennage in the conventional aircraft configuration is attached to the rear fuselage, normally an un-pressurised section or the aircraft. The vertical and, particularly, the horizontal tail surfaces introduce concentrated loads into the rear fuselage and the structural analysis is complicated by the large cut-out required to allow the trimming motion of the horizontal tailplane and the need to represent properly the load diffusion into the pressurised section of the fuselage.

The classical semi-monocoque fuselage structure consists of an arrangement of frames and stringers. The frames tend to be perpendicular to the longitudinal aircraft axis and equally spaced in the pressurised section and can be slanted in the non-pressurised rear section.

The stringers run parallel to the aircraft longitudinal axis in the cylindrical part of the fuselage. The stringer pitch is measured in the circumferential direction. The cabin floor and window plank define the location of two key planes containing stringers. The datum planes for the rest of the stringers are obtained by interpolation between the key planes in the pressurised part of the fuselage. In the rear fuselage, the stringers are obtained by interpolation of a radiation of planes passing through the intersection of the stringers of the pressurised section with the datum plane of the rear pressure bulkhead. The stringer pitch is variable in this fuselage section and intermediate stringer run-outs occur when the distance between stringers is less than a specified value.

The user interface for the definition of the fuselage structural layout is shown in Figure 20 and an example of the fuselage geometry and FEM in Figure 21.

4 CAD model of the external geometry and structure

Once the external aircraft surfaces and internal structure have been generated internally in MARES, it is possible to generate a CAD model in order to perform manual modifications or refinements and to distribute the concept externally in a standard geometry format.

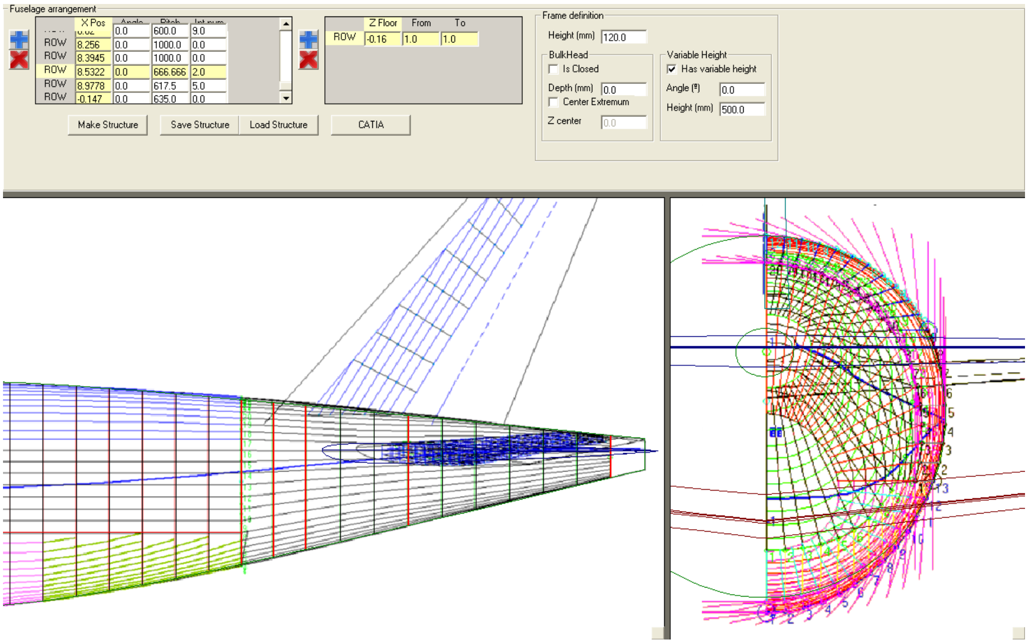

Figure 20: Definition of master frames, floor and window plank lines

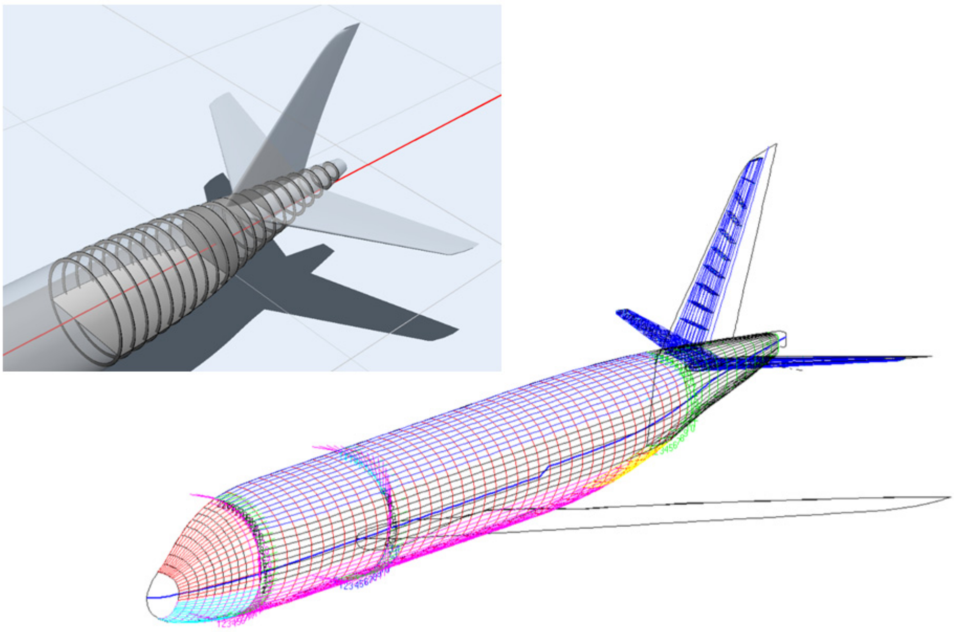

Figure 21: Fuselage structure rendered in MARES (top), FEM mesh topology (right)

The generation of the CAD geometrical entities is performed automatically by MARES via the application user interface of CATIA V5. The external surfaces are created using an equivalent geometric CAD entity to the data structure used internally in the MARES numerical geometry engine.

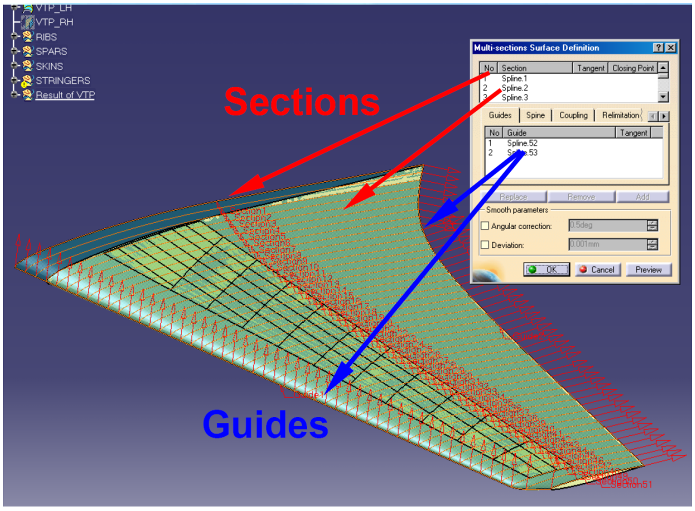

Figure 22: Example of lifting surface and internal structure as generated in CATIA by MARES.

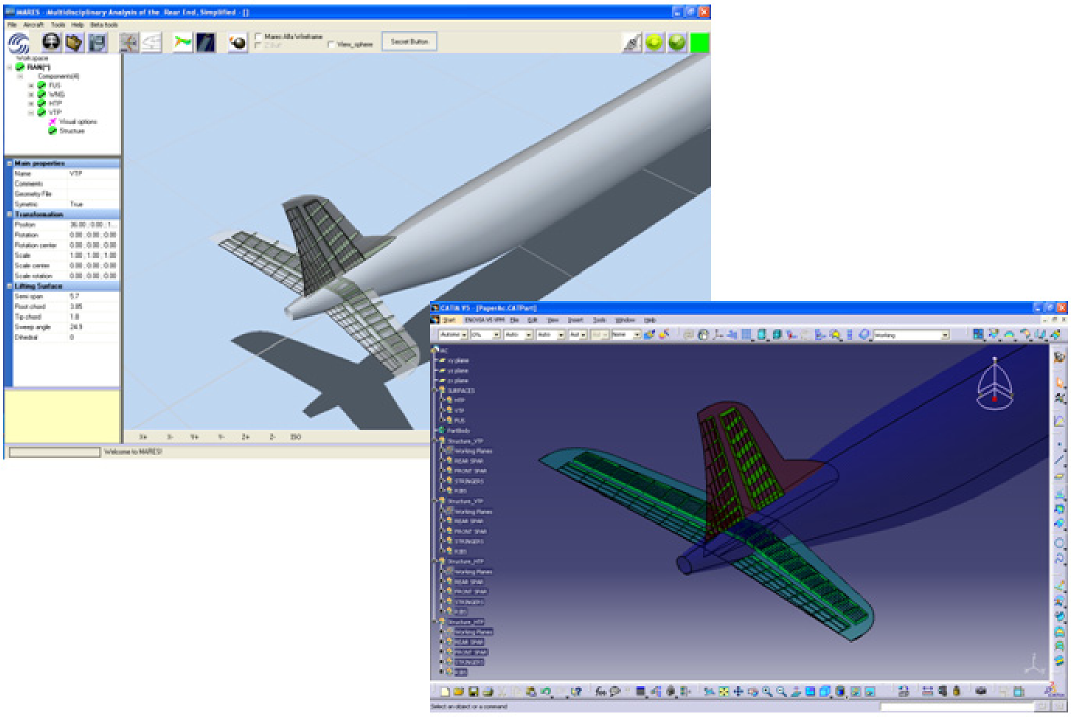

Figure 23: Geometry and structure as rendered in Mares (left) and equivalent CAD model in CATIA V5, generated automatically by MARES (right)

The structure is generated by creating the structural datum planes and calculating their intersection with the external surfaces, replicating the same operations carried out by MARES. This process enables manual edition of the datum planes and other entities in the CATIA tree, which is populated with the named geometrical entities and their hierarchical operations.

An example of the comparison of the geometry and structural models as rendered in MARES and the resulting CAD model is shown in Figure 23.

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