

# A KNOWLEDGE BASED APPROACH FOR AUTOMATED MODELLING OF EXTENDED WING STRUCTURES IN PRELIMINARY AIRCRAFT DESIGN

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## Abstract

This paper introduces the concept of the ELWIS model generator for Finite Element models of aircraft wing structures. The physical modelling of the structure is extended beyond the wing primary structures, to increase the level of accuracy for aircraft which diverge from existing configurations. Also the impact of novel high lift technologies on structural masses can be captured already in the early stages of design by using the ELWIS models. The ELWIS model generator is able to create structural ANSYS Finite Element and Multi Body Simulation models of the following components: the wing box, the wing fixed trailing edge including flap tracks, the wing movable trailing edge (flaps and ailerons), the spoilers, the engine pylon and the main landing gear, if attached to the wing. In order to enable trade studies on configurational level, the high number of required design parameters for the 3D model is derived from a minimal set of input parameters by making use of knowledge patterns for the individual components and technologies. A robust, CAD-free method is employed leading to model generation times which are well suited for preliminary design. This paper focuses on the generation of the structural models as one component of a wide MDO approach for overall aircraft design.

## 1. INTRODUCTION

In preliminary aircraft design, a vast number of design parameters have to be determined. Therefore, fast computing methods are required for this stage of aircraft design. However, high accuracy is another important, usually conflicting, requirement, which is not well coped by today's pre-design methods e.g. for secondary wing components. These components consist mainly of high lift systems and control surfaces and account for typically 30 to 40% of the total wing mass. At the same time, the high lift system drives the required wing area for a defined aircraft landing mass and speed as well as the take-off performance and noise. Thus, high lift technology has a significant influence on the over-all performance of configurations but is not sufficiently captured by today's pre-design methods.

The state-of-the-art in preliminary wing-mass estimation can be divided into two classes: empirical and physics-based methods. Empirical methods correlate the known masses of existing aircraft to their design parameters. This approach is well suited for the performance sizing of similar aircraft. But leaving the design space of the knowledge base or analysing the impact of novel technologies requires physical rather than statistical methods. In the majority of physics-based studies on preliminary wing design, models are used employing the beam or shell theory for primary structural wing components. Secondary structures are still captured via empirical correlations; hence these methods are called semi-physical. Two essentially different approaches can be identified:

### 1.) *Fraction of other masses:*

Estimating the mass of secondary structures as fraction of other masses is a very simple method, as the detailed geometry of the structures has not to be taken into account. Howe [1] computes the mass of a wide range of different secondary wing structures as fraction of the maximum take off weight. Kessler et al. [2] multiplies the wing box weight with 1.5 to estimate the total wing weight, while Perez et al. ([3] and [4]) multiplies the weight of the load carrying structure with 1.85 to compute the wing weight. A similar approach is chosen by Ardema et al. [5] where the load carrying structure is multiplied with the two factors 1.3442 and 1.7372. There are more authors, using this approach, but not publishing their multiplication factors, as e.g. Klatte [6].

### 2.) *Area weights:*

Those methods describe the weight of the secondary wing structures with respect to their size. Some of those methods modify the area weight with respect to the load the area has to carry. The approach that is chosen in the preliminary aircraft design tool PrADO [7] makes use of one user defined area weight for the leading edge and one for the trailing edge. On the aerodynamic side, PrADO already has an explicit representation of the high-lift system [8], but not on the structural side. The NASA tool FLOPS [9] is using one gross weight based area weight [10] for all secondary structures. FLOPS is e.g. used by Gur et. al. [11] to compute the wing secondary masses of truss braced wings. The subroutine FAME-ACSS [12] of the Airbus inhouse tool FAME-W ([13], [14] and [15]) for preliminary wing design is primary based on area weights and area loading and delivers accurate results for conventional configurations ([12] and [16]). FAME differs from the other methods, as it splits the secondary structure up in 22 mass groups (e.g. flap, aileron, spoiler, etc.) and

is using one equation for each of the 22 groups. The methods of FAME-ACSS are also used by Hürlimann ([17] and [18]) in combination with higher fidelity analysis.

The two approaches mentioned above can be used, to optimize the cruise shape. But an optimization of e.g. rear spar positions or flap size is not feasible using the *fraction of other masses* method. An optimization using the *area weights* method is only possible within a limited design space, as those methods are restricted to the design space of the constituting knowledge base. Different materials, technologies or designs beyond the database of the empirical knowledge patterns can only be analysed if the user already knows the new area weights from detailed higher fidelity analysis.

Novel structural concepts such as multi-spar flap layouts or the introduction of composite materials require extending higher level structural modelling to the entire wing, as it is becoming state-of-the-art for the primary wing structure. But those models require a large amount of additional user-defined inputs that can hardly be handled by an aircraft designer in preliminary design.

To enable the aircraft designer to analyse and optimize a very wide range of novel and state-of-the-art wings, including the secondary structures, a new method resp. tool chain is under development at DLR. At the heart of the new tool chain the model generator ELWIS (Finite Element Wing Structure) is developed. ELWIS can create a structural ANSYS Finite Element and Multi Body Simulation model including the following components: the wing box, the wing fixed trailing edge structure including flap tracks, the wing movable trailing edge structure (flaps and ailerons), the spoilers, the engine pylon and the main landing gear, if attached to the wing. To ensure the usability by overall aircraft design engineers in preliminary design, a knowledge based approach is chosen, to reduce the amount of user defined input parameters. Therefore several features of the FE-model are generated automatically, based on implemented engineering knowledge.

First, this paper gives an overview of the ELWIS model generator. This is followed by a detailed description, how the skins, ribs and spars of the basic wing, the spoilers and the trailing edge devices (TEDs) are generated. Afterwards, the modelling of the additional structures (flap tracks, engine pylons, landing gears, etc.) is explained. Finally the model preparation for the following optimization, the created ANSYS input files and the processing time of the CAD-free approach in ELWIS is described.

## 2. SURVEY OF THE MODEL GENERATOR

In the following an overview about the ELWIS model generator and the input format is given.

### 2.1. Survey of Structural Model

Within the ELWIS model generator the structural model is split into two separate groups: the *basic wing model* containing classical shell-based structures and *additional structures* that can be seen as extensions of the wing

model. After the model is created, it is prepared for a sizing in ANSYS (chapter 5).

The *basic model* includes all light weight components such as wing box, flaps, spoilers and ailerons consisting of ribs, spars and skins. ELWIS treated all light weight structures in the same way as the principal structural layout is similar for all light weight components. Therefore the movables are defined as second wing, third wing etc. The advantage of this approach is that the majority of the program code, which is written for the main wing, can be reused for all surfaces, independent from their type. Differences only occur at the 3D keypoint computation (see chapter 3.4). Due to namespace limitations, ELWIS can create a maximum of 88 different light weight components within one model.

The *additional structures* are structures that extend the light weight structure and are attached to the parent surface and potentially one other surface. Currently engine pylons, landing gears and the links between the movables and their parent (flap tracks, joints and TED drives) can be generated by ELWIS. From those components, the load carrying structure is modelled in 3-dimensional space. The model includes all hinges, joints and links, so that loads are transferred correctly between different parts and wings. Additionally, the deflection of the landing gear and the movables (TEDs and spoiler) can be simulated with respect to actuation loads.

### 2.2. CPACS Input Format

The ELWIS model generator uses the xml-based DLR aircraft parameterization CPACS (Common Parametric Aircraft Configuration Scheme) as input format. The CPACS format has been under development since 2005 and is used as common language for several disciplinary aircraft design tools at DLR and beyond. Using CPACS, it is possible to establish an overall aircraft design process, which consists of a wide range of disciplinary tools that are available at different DLR institutes. This work was started at the DLR project TIVA (Technology Integration for the Virtual Aircraft) and is currently ongoing in the project VAMP (Virtual Aircraft Multidisciplinary Analysis and Design Processes) [18].

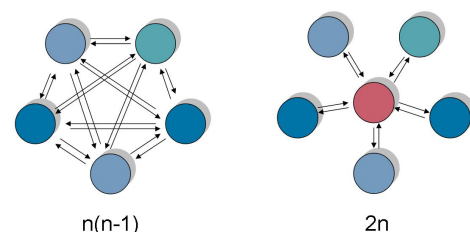


Fig. 1. Number of interfaces for interdisciplinary tool chains without (right) and with (left) common parameterisation ( $n$  = number of tools) [20]

Within CPACS, all parameters needed for any analysis of aircraft are defined, e.g. the outer geometry, structures, load cases, materials, engines, missions etc. The advantage of using one common language in an interdisciplinary tool chain is, that each tool needs only two interfaces (comparer Fig. 1) [20]. As ELWIS uses only CPACS as input, it can be easily integrated into a distributed multidisciplinary design process and be

adapted to e.g. high fidelity aerodynamic analysis or loads processes

### 3. BASIC MODEL

The basic wing model of ELWIS includes the ribs, spars and skins of all wings and movables (TEDs and spoilers). For the model generation process in ELWIS, several basic ideas of the modelling and the numbering system of key points, lines, areas etc. are taken over from the model generator PARA\_MAM. PARA\_MAM is a wing model generator developed by the DLR Institute of Composite Structures and Adaptive Systems and can be seen as precursor of ELWIS [21].

PARA\_MAM computes a mainly quadrangular structural mesh of the skins, spars and ribs of a wing using a CFD mesh and the rib and spar arrangement as input. In PARA\_MAM, the user has to define explicitly the position of all real and virtual ribs and spars. Virtual ribs and spars are used to define the borders of the skin segmentation. The segmentation of ribs and spars is defined by the surface segmentation along the ribs and spars. The number of elements in each segment is defined by an element size input parameter. In PARA\_MAM it is also possible to create wing models having unconventional structural layouts and to include control surfaces with simple hinges as link to the wing ([22] and [23]). But those models require a large amount of user inputs which makes it unhandy for preliminary design.

As CPACS is a common parameterisation of various institutions and disciplines, the wing geometry is described using neutral parameters that are not specific for one tool or discipline. Therefore no virtual spars and ribs and no CFD mesh is given as input. In the first step, ELWIS computes the planform of all areas and afterwards the ribs and spars are placed in the planform to get a 2-dimensional structured grid. In a third step, the 2-dimensional grid is interpolated within the outer shape of the wing. Finally the element properties of the areas are defined and the different areas are assembled into one model.

The wing definition in CPACS is not limited to conventional wings. It is possible to define nearly all possible wing shapes (e.g. box wings, splitting wings, strut braced wings...). The structure, control surfaces, landing gear position etc. are defined using relative coordinates in spanwise ( $\eta$ ) and chord ( $\xi$ ) direction. For well-defined relative coordinates, the wings have to be split into several wing parts, the so called 'component segments'. Within each component segment, e.g. the wing structure can be defined using the relative coordinates. For conventional wings only one (the whole wing) or two component segments (wing and winglet) may be used. For a strut braced wing the wing and the strut may be defined as different component segments. ELWIS handles each component segment and each movable as separate lifting surface. Those surfaces are assembled to one model at the very end.

#### 3.1. Planform

The aerodynamic shape of the wing in CPACS is defined by airfoils that are placed within the 3-dimensional space.

Each airfoil can be rotated around all 3 axes, so that airfoils that do not face in flight direction can be defined. The connectivity between the airfoils is given by segments that are spanned between two airfoils each. ELWIS creates triangular elements between each two neighbouring airfoils as definition of the outer shape. These elements are later used for the 3-dimensional key point computation of the upper and lower skin.

Afterwards, the 3-dimensional planform of each component segment is computed in ELWIS so that the  $\eta$  and  $\xi$  coordinates are defined. In the second step, the planforms of the spoilers and the TEDs are computed, which are defined as cut outs of the parent wing. The inner and outer borders of the movables can either head in flight direction or can have skew borders. Similar to the coordinate system of the component segments, each planform of a movable defines a  $\eta/\xi$  coordinate system for all further definitions related to the movable (e.g. ribs and spars of the movable). By referencing to another TED, instead of the main wing, as parent of a TED, double and triple slotted flaps can be created.

#### 3.2. Spars

ELWIS creates a structured mesh on skins, ribs and spars using mainly quadrilateral elements. In the created FE model, one element is created on each area of the surface. Therefore no external meshing algorithm would be needed for the wing surface. The element borders of the skins in chordwise direction are defined by the spar positions. Beside the real spars, there are several more virtual spars that have to be created to get a proper surface grid. As only the real spars are defined explicitly by the user, ELWIS automatically creates several different virtual spars automatically, to ensure a proper structured mesh. In detail, the following spars are generated (compare Fig. 2 and Fig. 3):

- 1) *Virtual spars at the leading and trailing edge*: usually no real spar is defined at the leading and the trailing edge of the wing; therefore a virtual spar is inserted as forward and rear end of the structured grid.
- 2) *Real spars*: Real spars that are defined by the user in CPACS. The spars are defined by several points on the planform which are connected to spars. Those can start and end at any position of the wing. In addition spars can cross either by defining the crossing point as spar definition point or without defining the definition point. In the second case ELWIS detects the coordinates of the crossing point and inserts the new spar definition point.
- 3) *Virtual spars at cut outs due to spoilers and TEDs*: at the positions, where the spoilers and TEDs are placed, the skins have to end. Therefore element borders have to be placed at those positions. ELWIS automatically creates virtual spars at these positions, if the skin cut outs is not equivalent with a real spar (which can be defined in CPACS). The cut outs can optionally be defined in CPACS. If it is not defined, ELWIS automatically defines the needed spar positions.
- 4) *Virtual spars due to material definition of the skins*: in CPACS it is possible to define different materials in different parts of the skins and spars. The borders of those areas can either be real spars and ribs or can be defined using  $\eta/\xi$  coordinates. In the second case

virtual spars are inserted by ELWIS to ensure that the material properties of the elements are correct.

- 5) *Virtual spars due to intermediate structure*: similar to the definition of regions of different material properties, it is also possible to define a so called intermediate structure, which is a filling structure (e.g. honeycomb structure) between the upper and lower skin.
- 6) *Virtual spars due to element size*: virtual spars are inserted to ensure a specific element size in chordwise direction for the ribs and skins. The element size can optionally be specified by the user. If the element size is not specified, ELWIS defines a proper element size by itself.

In front of and behind the center wing box, the secondary structures are deleted. But for this cut out, no additional virtual spars are inserted. This is due to the fact that the cut out is always along real the front and rear spar.

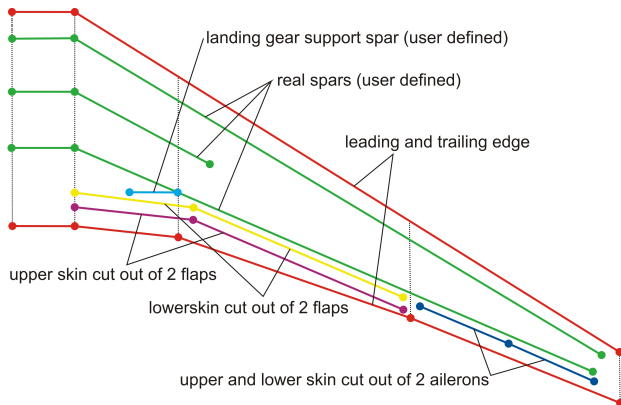


Fig. 2. Virtual and real spars to be place in the wing

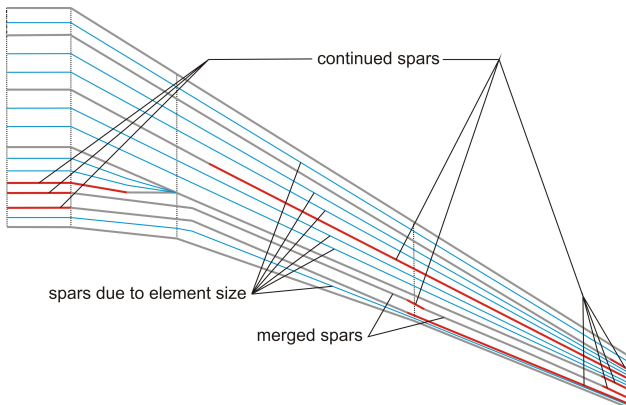


Fig. 3. Spar layout of the structured surface grid

The spars mentioned under point 2 to 5 can all start and end at any position of the wing, not necessarily at the root and the tip. Therefore those spars are to be continued virtually to the root respectively tip automatically by ELWIS. This also works properly if the root and/or tip is not heading into the flight direction as it might e.g. be the case for the aileron or flap bodies.

If two spars are merging (comp. landing gear support spar and rear spar in Fig. 2) the spars are continued on each other, so that a 'double-spar' appears. Those spars are detected later and one spar is deleted before the ANSYS output is created. This works for any number of spars with coincidence positions. At the position where the spars are

merging, triangular elements are created instead of the quadrilateral element at the rest of the wing.

ELWIS checks if two or more spars can be merged together to one spar. This is the case, if either a virtual spar is equivalent to another virtual or a real spar, or if two spars are defined in different spanwise areas and their chordwise positions are similar. An example is shown in Fig. 2 and Fig. 3 where the two spars for the lower flap cut out and the two spars for the aileron cut outs are merged to one spar.

After all spars are merged and continued to the root and tip, the additional spars due to the element size are created where necessary.

### 3.3. Ribs

Similar to the spars, also several different kinds of ribs have to be computed by ELWIS to create a proper surface grid. Again, only the real ribs are defined by the user, while all other ribs are created automatically by ELWIS. In detail, the following ribs are created (compare Fig. 4 and Fig. 5):

- 1) *Virtual rib at the root and tip*: similar to spars
- 2) *Real ribs*: those ribs are defined by the user in CPACS, where ribs are defined in sets of one or more ribs. Within one set either the rib pitch or the number of ribs in a specific spanwise range is defined. Ribs can be rotated around an axis rectangular on the planform and around an axis along the rib laying in the planform. The start and end of the ribs is at the leading or trailing edge, at a spar or if the rib is crossing another rib. Ribs can also continue after crossing each other.
- 3) *Virtual ribs due to kinks*: if there is a kink in the planform ELWIS inserts automatically a rib at this position to ensure that the geometry of the wing is represented properly. As kink, each position is assumed where an airfoil is defined. This function is optional. The user can turn it off, if e.g. real ribs are defined at the kinks anyway or if the kinks are small.
- 4) *Virtual ribs at cut outs due to spoilers and TEDs*: similar to spars
- 5) *Virtual ribs due to material definitions of the skins*: similar to spars
- 6) *Virtual ribs due to intermediate structure*: similar to spars
- 7) *Virtual ribs due to material definition of the spars*: if the material of a spar is changed, an element border is needed at this position. Therefore a virtual rib is inserted, if no real rib is defined at this position. This rib is only inserted as point and later continued.
- 8) *Virtual ribs due to beginning, ending or kink of a spar*: if a spar does not start at the root or end at the tip or if the spar has a kink, an element border is needed at this position. Therefore a virtual rib is inserted at this position, if no real rib defined there. This rib is only inserted as point and later continued.
- 9) *Virtual ribs at flap track attachment*: the flap tracks are attached at the rear spar. At the position where the tracks should be attached, key points and element borders are needed for some track types. Therefore a rib point is inserted at these positions.
- 10) *Virtual ribs due to element size*: similar to spars

As described for the spars, no rib is introduced for the cut out of the secondary structures at the center wing box, as most aircraft have a kink or a real rib at this position.

Similar to the spars, different ribs are merged to one rib. Like in Fig. 4, where the three different ribs at the inner kink (kink rib, real rib and cut out rib) are merged to one rib. Ribs that lay on each other are handled similar than spars that lay on each other. In a next step, all ribs are continued virtual to the leading and trailing edge and finally the virtual ribs due to the element size are inserted.

If two ribs are crossing each other, a chordwise element border has to be at this position. It is checked, if the spars in front of and after the intersection point are virtual and can be moved to the intersection point. If both spars can be moved the closer one is chosen. If none of the two spars can be moved, a new virtual spar is inserted. At positions, where ribs are crossing, triangular elements are created instead of the quadrilateral elements.

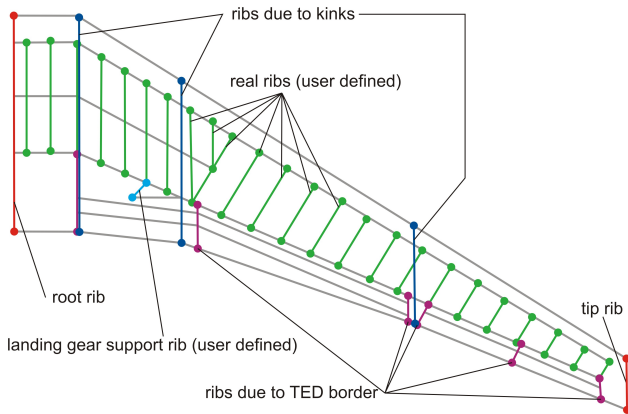


Fig. 4. Virtual and real ribs to be placed in the wing

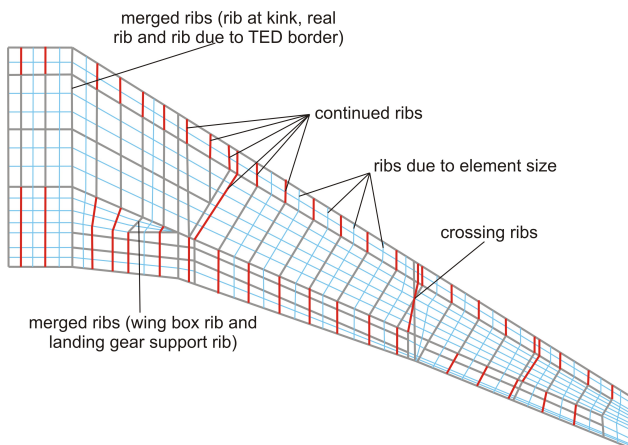


Fig. 5. Rib and spar layout of the structured surface grid

### 3.4. 3-Dimensional Key Points

After the 2-dimensional mesh is created the mesh 3-dimensional key points of the upper and lower skin are computed. If the number of elements in thickness direction is larger than one, also key points in the middle of the wing are created.

### 3.4.1. Wings

The computation of skin key points for the wing is done as follows: First the normal vector of the planform is computed for each grid point; afterwards this vector is rotated according to the rotation of the corresponding rib and spar of this point. Next the intersection point of this vector and the triangular elements of the outer shape definition is computed. To increase the processing speed, a function is implemented that guesses which elements of the outer shape definition might be crossed by the normal vector and only the crossing points with those elements are computed. This is followed by a check if the guess was true. If the guess was wrong, the guess and the crossing point computation are repeated. For most of the points the first try is correct, but especially for rotated spars and at the areas close to the leading edge 3 to 5 iterations might be needed.

### 3.4.2. Movables

In preliminary aircraft design, the exact airfoil shape of the movables (TEDS and spoilers) is unknown. This shape is later defined within the detailed aerodynamic high-fidelity optimization of the high-lift system. As the exact airfoil shape is not needed for the mass estimation, ELWIS is computing the airfoil with respect to the shape of the clean wing and some additional input parameters. For the TEDs those parameters are:

- 1) relChordUpperSkin: defines the most forward chordwise position where the aerodynamic shape of the main wing and the TED are equivalent.
- 2) relChordLowerSkin: similar as above, but for the lower skin.
- 3) relHeightLE: defines the relative height of the TED leading edge compared to the airfoil height of the main wing.

At first all key points on the skins are computed using the aerodynamic shape definition of the parent wing. In a second step the relative height of the key points of the TEDs is computed for all key points with respect to three parameters mentioned above (comp. Fig. 6). The relative height between the three points is interpolated using an elliptical slope. Finally the key point position of the TEDs is computed by scaling down the computed key point positions according to the relative height of each point.

The approach for the spoilers is similar to the approach at the TEDs. For the spoiler only the relative thickness at the leading edge is user defined. There, the whole lower skin is scaled, while the upper skin is equivalent to the outer shape of the parent wing.

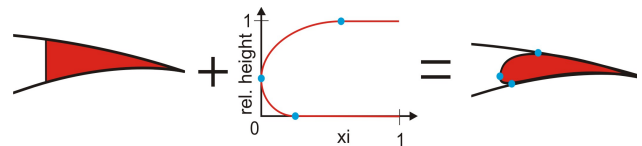


Fig. 6. Computation of 3D key points of TEDs

### 3.5. Element Properties

After the keypoint computation is finished, the element properties of the lines, areas and volumes, which are



defined by the keypoints have to be set.

### 3.5.1. Skins and Stringers

The skin and stringer elements are model as multi-layered shell elements. The material properties of these elements are defined in CPACS and introduced into the model. As multi-layered elements are used, also composite materials can be handled. If stringers are defined in CPACS, a smeared representation is computed and an additional layer on the inner side of the skin elements is created.

### 3.5.2. Ribs and Spars

Ribs and spars are modelled using multi-layered shell elements, similar to the skin, but without stringers. If the user defined properties for spar caps, those caps are modelled using beam elements, having a rectangular cross sections. The spar caps are created at the spar/skin intersection of the upper and lower skin.

### 3.5.3. Secondary Structure

The region in front of the front spar (= first real spar) and behind the rear spar (= last real spar) is interpreted by ELWIS as not load carrying structure. The element properties of those elements have to be modified in a way that those elements do not contribute to the overall stiffness of the wing. But aerodynamic loads that are applied in this area have to be transferred correctly to the primary wing structure.

Therefore the stiffness of skin elements in this region is reduced by a factor of 100. The other properties, as e.g. density or element thickness, are kept unchanged, compared to the CPACS definition. To transfer the aerodynamic loads of these elements to the primary structure, the real defined ribs kept unchanged while all virtual ribs are transferred to real ribs, having an adequate stiffness, but a density of zero and therefore no mass.

The approach described above is applied at the total leading edge and the trailing edge, where no movable is defined. At those positions where a movable is defined, the skin elements are modified similar, but the virtual ribs are kept virtual. For the load transformation a more realistic support structure is created (see chapter 4.4).

### 3.5.4. Wing Cut Outs

There are two reasons for wing cut outs: At those positions where the movables are located and at the region in front of and behind of the center wing box, where the wing is inside the fuselage. Those positions are automatically detected by ELWIS and the skin, rib and spar elements are not exported to ANSYS.

### 3.5.5. Intermediate Structure

An intermediate structure is a volumetric structure between the upper and lower skin as e.g. honeycomb. Such structures are often used at the trailing edges of wings and TEDs, or at the whole spoiler. If those kinds of structures are defined in CPACS, volumetric elements are created

created between the upper and lower skin and the material properties are set according to the CPACS definition.

## 3.6. Wing Assembly

As mentioned above, different component segments of one wing are handled as independent wings within the model generation in ELWIS. Therefore those component segments do not have a structural connectivity. To solve this issue, a module is implemented that creates rigid links between the neighbouring keypoints of the skin and spars of two component segments.

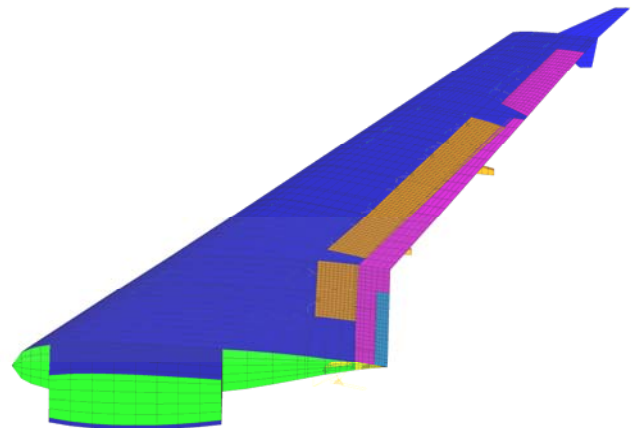


Fig. 7. wing assembly that consists of 12 areas: the main wing, the upper and lower winglet, one aileron, one single and one double slotted flap and 5 spoiler

## 3.7. Clamping

In CPACS, the root rib of the wing is defined. Optionally additional pin attachment can be defined in CPACS, if e.g. the wing-fuselage connection of a high decker configuration or the connection of horizontal and vertical tails to the fuselage is defined.

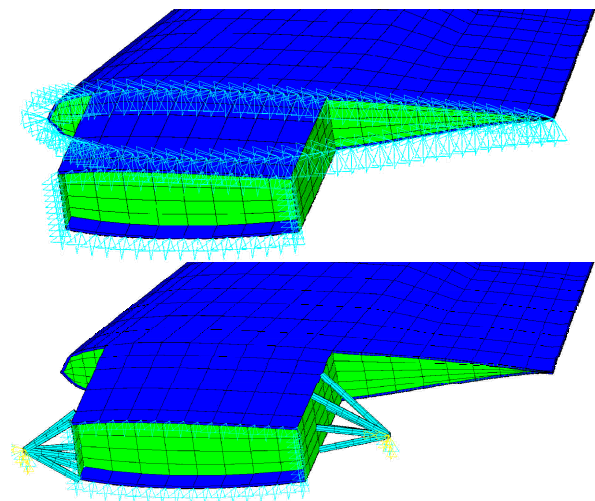


Fig. 8. Continuous clamping (up) and HTP clamping with screw jack support and rear pin (down)

If no pin attachment is defined, ELWIS clamps all nodes of the skins and spars of the root rib (also before and afterwards of the wing box) in flight and height direction, while all nodes of the skins and spars of the symmetry plane are clamped in spanwise direction. If a pin attachment is defined, beam-elements between the bolt positions and the wing skin, rib or spar are created. The exact geometry of the beams is computed by ELWIS automatically, only requiring material settings from the user. The bolts are clamped according to the CPACS definition of the blocked degrees of freedom, while all element borders at the symmetry plane of the wing are clamped in spanwise direction.

#### 4. ADDITIONAL STRUCTURES

All structures that are attached to one or more areas of the wing model are called additional wing structures in this paper. All links between movables and their parents (the main wing or another movable) and the beam structure to support the trailing edge secondary structure are called additional wing structures. But also structures that are usually not seen as part of the wing are modelled as additional wing structures, because they are directly attached to the wing and do introduce a significant load to the wing. Namely those structures are the engine pylon and the wing mounted main landing gear.

All additional structures are modelled mainly automatically, based on the design principles of existing aircrafts. Therefore engineering rules are implemented into ELWIS how those structures are to be generated. ELWIS only asks for very few user inputs, to enable the overall aircraft engineer to create a detailed model quickly and easily.

##### 4.1. Tracks and Actuators

In this chapter, all kinds of links between a movable and the corresponding parent are described. The 3-dimensional geometry of the links is created automatically based on implemented engineering design rules, wherefore only very few input parameters from the user are needed. Beside material settings, only the type of the link mechanism and the 3-dimensional deflection path of the movable are needed as input.

Currently a total of 13 different track types and subtypes can be created by ELWIS. The currently implemented track types cover most of the track types that are used in state of the art civil transport aircraft. A further extend of this database is possible at any time, if needed. In detail the following track types are implemented (compare Fig. 9):

- 1) Dropped hinge flap track with box beam design; attached to parent rear spar and more forward; rotary drive attached to parent rear spar
- 2) Similar to 2, but track only attached to parent rear spar
- 3) Link/track mechanism with upside-down front link and straight track; attached to parents rear spar and more forward; rotary drive at parents rear spar (used at e.g. A320 [24])
- 4) Link/track mechanism with straight track and drag strut; attached to parents rear spar and more forward; rotary drive at track (used at e.g. A330/340 [24])

- 5) Similar to 4, but with drive at parents rear spar
- 6) 4-bar linkage; attached to parents rear spar and more forward; linear drive attached to track (used at e.g. A321, B777, B767 [24])
- 7) Simple hinge for aileron and spoiler attachment
- 8) Simple linear actuator as aileron and spoiler drive

For track types 1 to 6 an additional “fuselage track type” is implemented. This track type is a representative for the most inner track that is attached to the fuselage instead of the parent wing. Those track types offer the same kinematic features than the normal track types, but are clamped, instead of the connected to the parent wing. The clamping is placed at the position, where the movable part of the track is connected to the fixed part of the track.

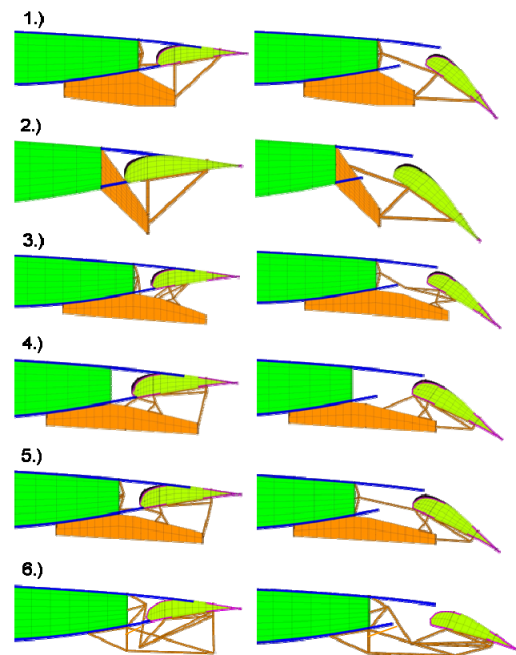


Fig. 9. 2-dimensional few on track type 1 to 6 in retracted (left) and extend configuration (right)

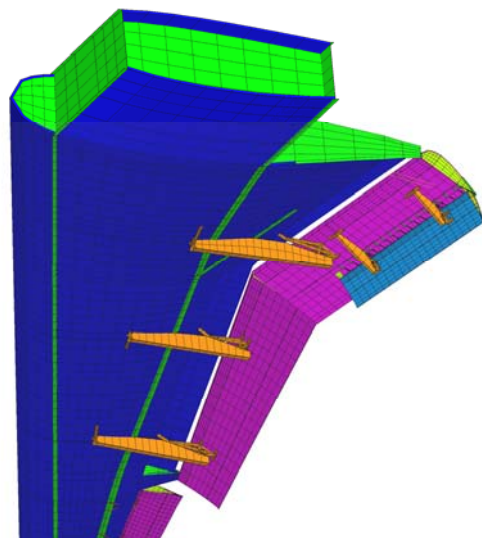


Fig. 10. Wing with several extended flaps (inner track of first flap not shown)

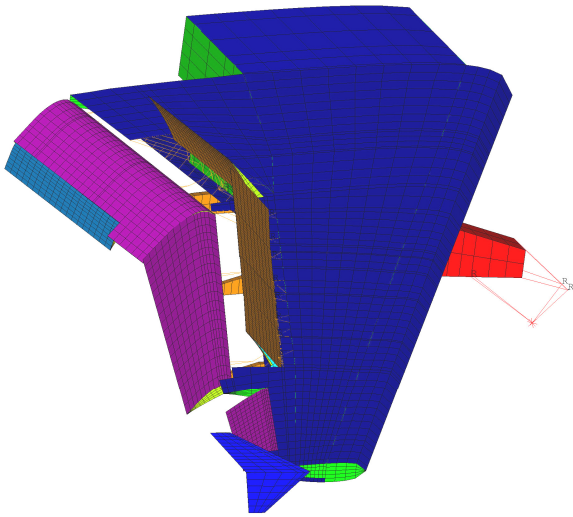


Fig. 11. Wing with engine pylon and extended aileron, TEDs and spoilers

## 4.2. Engine Pylons

At current civil transport jet aircraft two different pylon-to-wing and two different pylon-to-engine attachments can be seen (comp. [24]). All 4 resulting pylon types can be generated by ELWIS. Similar to the flap tracks also the generation of the engine pylons is done automatically by ELWIS, as the design rules, how an engine pylon is to be designed, are implemented in ELWIS. Beside different material settings, only some engine geometry parameters, the 3-dimensional engine position and the information, which wing and engine the pylon should connect, is needed. Note, that only the load carrying structure of the pylon is created and no aerodynamic fairings.

The engine itself is modelled as mass point at the engines centre of gravity, where in the successional analysis the engine thrust force can be attached. The engine mass point is linked with rigid links to the hinges, connecting the pylon and the engine.

The two different pylon-to-wing attachments are:

- 1) The pylon is attached to the wing front spar with two shackles and one spigot fitting; the pylon has a box beam design between the forward and the rear wing attachment; at the rear attachment the pylon is attached to the two load carrying ribs with one triangular shackle (comp. Fig. 12 upper row).
- 2) The forward pylon attachment is at the front spar of the wing with two joints and two upper links; the rear attachment to the load introduction ribs is done using a drag strut (comp. Fig. 12 lower row).

The two different pylon-to-engine attachments are:

- 1) The pylon is attached to the engine by bolts and the inner side of the fan casing and at the rear part of the core engine (comp. Fig. 12 left column).
- 2) The pylon is attached to the engine by bolts at the outer side of the fan casing and at the rear part of the core engine; additional two tangent links are established to carry the thrust forces (comp. Fig. 12 right column).

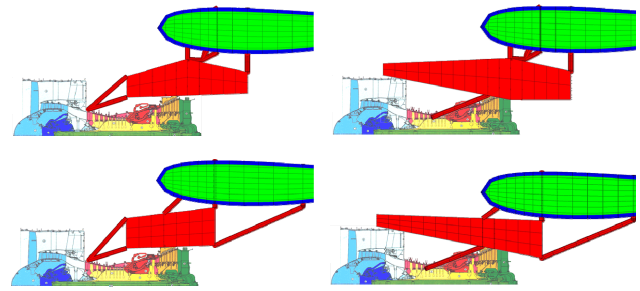


Fig. 12. 4 different engine pylon types, that can be created by ELWIS (CFM65 cutaway from [26])

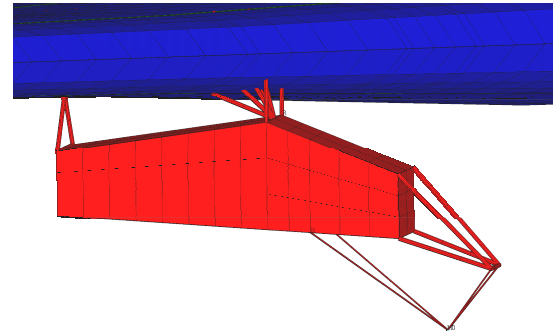


Fig. 13. Engine pylon attached to the wing

## 4.3. Landing Gear

At current civil transport jet aircraft, the main landing gear (MLG) is attached to the wing. ELWIS generates the MLG structure as additional wing structure. Similar to the creation of the engine pylon structure, ELWIS creates the geometry almost automatically. Therefore, several engineering rules are implemented, how the MLG structure has to be generated. Beside material settings, ELWIS only needs MLG position on the wing, the total length, the number of wheels and the information to which spars the landing gear is attached.

Currently three options are implemented, how the main landing gear can be attached to the wing:

- 1) MLG is located between two spars. In this case the pintle-strut of the landing gear is connected with beam elements to both spars.
- 2) MLG is located behind or in front of one spar. In this case a shell structure, similar to the landing gear support spar and rib, is created automatically. The pintle-strut is connected with beam elements to the spar and the newly created shell structure.
- 3) Attachment using a rear support beam. If a rear support beam should be used, it is automatically created as a double-T beam. The MLG is attached to the rear support beam and the rear spar. As no fuselage is modelled, the inner end of the rear support beam is clamped.

Independent from the wing attachment type, the MLG can be created with one or two side struts. For MLGs having one side strut also a drag strut is created. If two side struts are created, no drag strut is created. The shape of the boogie and the number of axels are created with respect to the user defined number of wheels.



The MLG is created in deployed position. But as ELWIS creates ANSYS multi body models, including joints and actuators, the landing gear can retract dependent on the load case. Some examples of landing gears in deployed and retracted position can be found in Fig. 14.

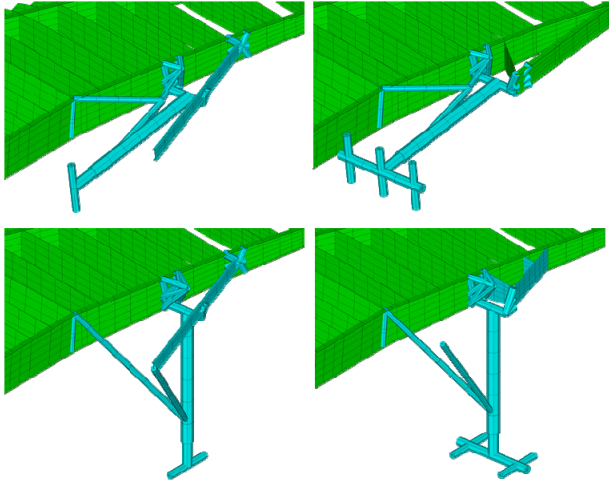


Fig. 14. Example landing gears: retracted MLG with rear support beam and one side strut (up/left); retracted MLG between rear spar and LG support spar and one side strut (up/right); deployed MLG with rear support beam and two side struts (down/left); deployed MLG attached with shell structure to rear spar and two side struts (down/right)

#### 4.4. Fixed Trailing Edge Support Structure

As mentioned above, the stiffness properties of the skin elements of the secondary structures (behind the rear spar) are extremely reduced by ELWIS. In the area, where no movables are located additional ribs are inserted (comp. chapter 3.5.3). But where a movable is located, an additional support structure is automatically created. This structure consists of beam elements and is similar to the structure used at some commercial airliners.

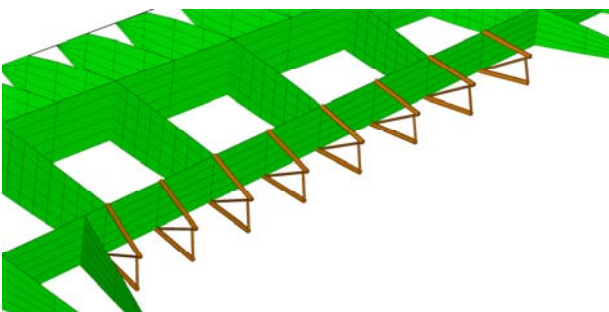


Fig. 15. Fixed trailing edge support structure

### 5. MODEL OPTIMISATION SETTINGS

ELWIS prepares the structural model for a sizing, which is performed later in the analysis tool chain. Therefore all load carrying structures are split into several sizing areas. For each sizing area, a set of 16 parameters, which describe how this area should be sized, is allocated.

Those parameters describe e.g. the sizing criteria, whether the stringer angle should be optimized or whether the material thickness should be optimized. Those parameters are either user defined or set by ELWIS, if the value is obvious; e.g. there is no need to optimize the material orientation, if the wing consists of an isotropic material.

For the definition of the sizing areas of the wing and movable bodies, the user can choose between different options. Currently three options are implemented:

- 1) no optimization and therefore no sizing areas
- 2) one sizing area between each rib and each spar
- 3) one sizing area between each rib and the front and rear spar

For the additional structures, currently three options are defined:

- 1) no optimization and therefore no sizing areas
- 2) one sizing area for each area (shell) or line (beam)
- 3) one sizing area for similar areas or lines, e.g. the whole box beam structure of the track in one sizing area

### 6. ANSYS INPUT FILES

ELWIS creates four different APDL-input files for ANSYS. The first input file includes the total wing geometry of the model as e.g. key points, lines, areas, element settings, materials and clamping.

The second input file contains an APDL script that generates one rigid body element for all trailing edge devices. This element is used for the nonlinear multi body computation of the flap or spoiler deflection, instead of the flexible multi element movable body. If a flap deploys and no aerodynamic load is applied, the flap body is not loaded wherefore the body can be replaced by a rigid element. This is reducing the computation time dramatically.

The third input file contains the APDL script to move the movables and the landing gear in the position required according to the load case description. For those computations, the flexible body of the parents and other movables are deselected and all additional structures, which are attached to the parent, are clamped. Then, the flexible bodies of the movables are replaced by the rigid body as described above. After the computation is finished, all flexible bodies are reselected and the rigid bodies deleted. Finally the complete model geometry is updated with respect to the computed deflection to get a new model with e.g. extended flaps or deployed landing gear.

The fourth APDL file is the input file for the structural sizing algorithm SARS (Structural AeRoelastic Sizing). SARS is a development, based on the structural sizing tool S\_BOT (Sizing roBOT) [21], [22] of the DLR Institute of Composite Structures and Adaptive Systems. This file includes the material limits, the load case description and some specific SARS input parameters.

### 7. PROCESSING TIME

One of the main motivations for the CAD-free approach in ELWIS is the processing time. For a wing including one

engine pylon, one landing gear, two flaps and one aileron ELWIS computes 0:46 min, ANSYS needs 2:37 min to load the model, 0:14 min to create the rigid bodies and 1:59 min to deflect the TEDs in landing configuration. The last step has to be repeated for each configuration that is needed according to the load case definition.

If one considers, that the total analysis time, including sizing and loads computation, took several hours, it is obvious, that the time for the model generation has no nameable influence on the total analysis time. This is different at the CAD/CAE based approach by Hürlimann ([17] and [18]), where a parametric associative CATIA V5 model of the wing box, the landing gear and the engine pylons is used. As shown in [18] the model total model generation time is roughly 10% of the total analysis time for a study with eight load cases.

## 8. CONCLUSION AND OUTLOOK

This paper describes in detail, how a very detailed finite element shell/beam model can be created in early aircraft design stages. The ELWIS model generator, can create detailed finite element and multi body analysis models of the primary wing structure, aileron bodies incl. hinges, flaps and flap tracks, spoilers, landing gears and engine pylons. The complex structures of the model (as e.g. flap tracks) are generated almost automatically by ELWIS. Therefore a knowledge based approach is chosen and a wide range of engineering rules are implemented. This enables the aircraft designer to analyse wing models beyond the typical design space also in early design phases, within a good range of accuracy. Finally the advantage of the chosen CAD-free approach, compared to a CAD based approach, is demonstrated.

The next steps in the development of the multidisciplinary aircraft analysis tool chain are in first place the sizing algorithm SARS, which is under development. Next, methods for the load estimation (aerodynamic, landing gear, engine and fuel loads) will be developed resp. introduced into the multidisciplinary tool chain. Finally the whole tool chain will be integrated into the aircraft design process that is under development within the DLR project VAMP.

## ACKNOWLEDGEMENTS

The author would like to thank Frank Klatt from the Technical University of Hamburg-Harburg for his support in developing and programming the landing gear model.

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