



Rapid Generation of Parametric Aircraft Structural Models

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Within the aerospace design, analysis and optimization community, there is an increasing demand for automatic generation of parametric feature tree (build recipe) attributed multidisciplinary models. Currently, this is mainly done by creating separate models for different disciplines such as mid-surface model for aeroelasticity, outer-mold line for aerodynamics and CFD, and built-up element model for structural analysis. Since all of these models are built independently, any changes in design parameters require updates on all the models which is inefficient, time-consuming and prone to deficiencies. Here a browser-based system, called the Engineering Sketch Pad (ESP), is used. It provides the user with the ability to interact with a configuration by building and/or modifying the design parameters and feature tree that define the configuration. ESP is based on an open-source constructive solid modeler, named OpenCSM, which is built upon the OpenCASCADE geometry kernel and the EGADS geometry generation system. The use of OpenCSM as part of the AFRL's CAPS project on Computational Aircraft Prototype Syntheses for automatic commercial and fighter jet models is demonstrated. The rapid generation of parametric aircraft structural models proposed and developed in this work will benefit the aerospace industry with coming up with efficient, fast and robust multidisciplinary design standardization of aircraft structures.

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Nomenclature

| | |
|---------|---|
| BEM | Built Up Element Model |
| BRep | Boundary Representation |
| CAD | Computer Aided Drafting, Drawing, Design, Development |
| CAPS | Computational Aircraft Prototype Syntheses |
| EGADS | Engineering Geometry Aircraft Design System |
| ESP | Engineering Sketch Pad |
| MDAO | Multi-Disciplinary Analysis and Optimization |
| MSA | Mid-Surface Aero |
| OML | Outer Mold Line |
| IML | Inner Mold Line |
| OpenCSM | Open-source Constructive Solid Modeler |
| UDP | User-Defined Primitive |

I. Background

In the design, analysis and optimization of aerospace vehicles and structures, it is absolutely crucial to generate the geometry fast and in a robust way. For a given geometry, the number of structural solutions to support the design are unlimited. However, there is only one solution which could lead to the minimum weight for the structure. To realize this, a single common consistent parametric description of the design against different disciplines is necessary.

In Multi-Disciplinary Analysis and Optimization (MDAO) environments, it is a common practice to import the models from manufacturing design tools with usually IGES and STEP extensions. Although these structural parts and components are intended to be ultimately manufactured, the use of these extensions will create static (non-parametric) geometry models which are not intended for design optimization. Also to create a Boundary Representation (BRep), the models should be closed watertight which is extremely difficult due to the lack of a complete solid modeling geometry kernel to deal with the topology data if any.

A web browser based integrated software referred to as the Engineering Sketch Pad (ESP),¹ is used here which completely resolves the issues mentioned above. ESP is built upon the WebViewer¹ and OpenCSM² and is fully-parametric, attributed and is based on a feature-based solid-modeling system. OpenCSM in turn is built upon EGADS³ and OpenCASCADE. All of this software is open-source, freely available without licensing restrictions, and is in general use.⁴

The main objective here is to demonstrate through examples on how ESP could help the aerospace community by generation of parametric, feature-based analysis models to perform efficient MDAO. This would hopefully fill the existing gap between fully realizable 3D representations and conceptual design and thus can be used to an advantage throughout the preliminary and detailed design stage.

II. Commercial and Military Aircraft Prototype Syntheses

Engineering Sketch Pad (ESP) is used here as the design tool to generate the structure of a commercial and a military aircraft models parametrically and create the built-up-element (BEM) ready for structural analysis. The input of ESP is written in a CSM file which is human readable and parsed by ESP. It is an ASCII file that contains all the information needed to create a model or set of sub-models.

To create an aircraft parametric model, 'despmtr' is used to create user input parameters and 'set' is used to create variables based on the inputs. These variables are mainly used to generate internal structures. In ESP if the user changes a parameter, the software will efficiently regenerate only those parts which are associated with that parameter.

ESP Master Model usually contains one or more user input design parameters. These parameters could be 1-D single value or $n \times n$ Matrices. These parameters can be 'set' using 'set' command to interconnect or can directly be given by user in ESP's Graphical User Interface. They are used to input values in command arguments. Another way of using parameters is using them in if/else loop or set them as Flag.

To be able to create computational grid to be used in Computational Fluid Dynamics (CFD) or other 3D field analysis tools, the generated body has to be watertight. To ensure this, ESP uses constructive solid modelling process which guarantees the model to be realizable solids. But, for global and local structural analysis, ESP can generate non-manifold sheet bodies as thin structural plates or wire bodies. These sheet structures are necessary to generate BEM models enabling the designer to perform structural analysis using quad shell elements.

The ESP model of a military fighter aircraft with different number of ribs, spars and wing tip angles along with the associated design parameters are shown in Figure 1 and Table 1, respectively.

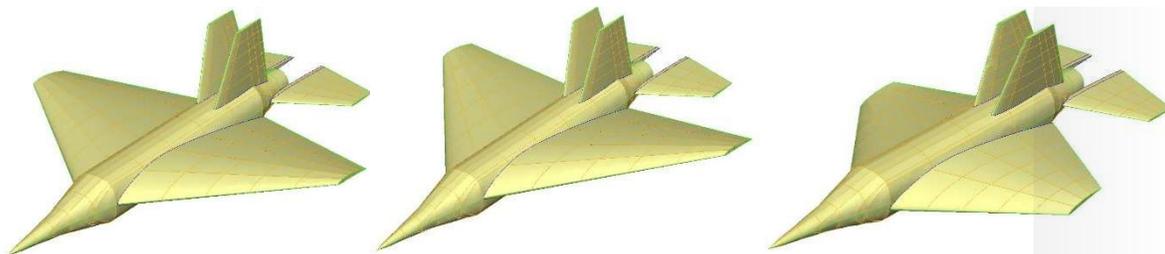


Figure 1. An ESP example of a military fighter aircraft with different number of ribs, spars and wing tip angles.

Table 1. Design parameters used to create the geometry of the military fighter aircraft.

| Parameter name | Value | Description | Parameter name | Value | Description |
|----------------------|-------|--|--------------------|-------|---|
| cone_radius | 0.25 | Radius of nose cone | series_w | 4409 | NACA profile |
| cone_length | 1.2 | Length of nose cone | AOA1 | 2.0 | Angle of attack at root |
| cockpit_length | 5.5 | Length of cockpit | AOA2 | 5.0 | Angle of attack at tip |
| cockpit_num | 3 | Frame number in cockpit | series_h | 406 | NACA profile |
| cockpit_width | 2.0 | Width of cockpit | hwing_start_length | 8.0 | Length of horizontal wing at root |
| engine_length | 4.5 | Length of engine | hwing_end_length | 3.0 | Length of horizontal wing at tip |
| engine_num | 2 | Width of engine | hwing_spars_num | 3 | Number of spars in horizontal wing |
| engine_width | 4.0 | Frame number in engine | hwing_tip | 36.0 | Horizontal wing tip leading edge distance from nose |
| spars_num | 6 | Number of spars | hwing_span | 15.0 | Span of horizontal wing |
| spars_initial_length | 20.0 | Length of wing at root | vwing_height | 6.0 | Vertical wing tip height from nose |
| spars_final_length | 4.0 | Length of wing at tip | vwing_end_length | 3.5 | Length of vertical wing at tip |
| wing_tip | 22.5 | Wing tip leading edge distance from nose | vwing_tip_dist | 33.0 | vertical wing tip leading edge distance from nose |
| wing_span | 30.0 | Span of wing | mid_ribs | 7 | Number of ribs in fuselage |
| nozzle_width | 2.8 | Initial width of nozzle | wing_ribs | 5 | Number of ribs in wing |
| nozzle_length | 3.0 | Length of nozzle | hwing_ribs | 2 | Number of ribs in horizontal wing |
| nozzle_out_radius | 1.15 | Radius of nozzle at exit | vwing_ribs | 4 | Number of ribs in Vertical wing |
| nozzle_num | 3 | Number of frames in nozzle section | | | |

The master models in ESP are defined in terms of a feature tree and a set of design parameters. This tree depicts the sequence of the operations used to create the final design which can be extracted from the CSM file and is shown in Figure 2.

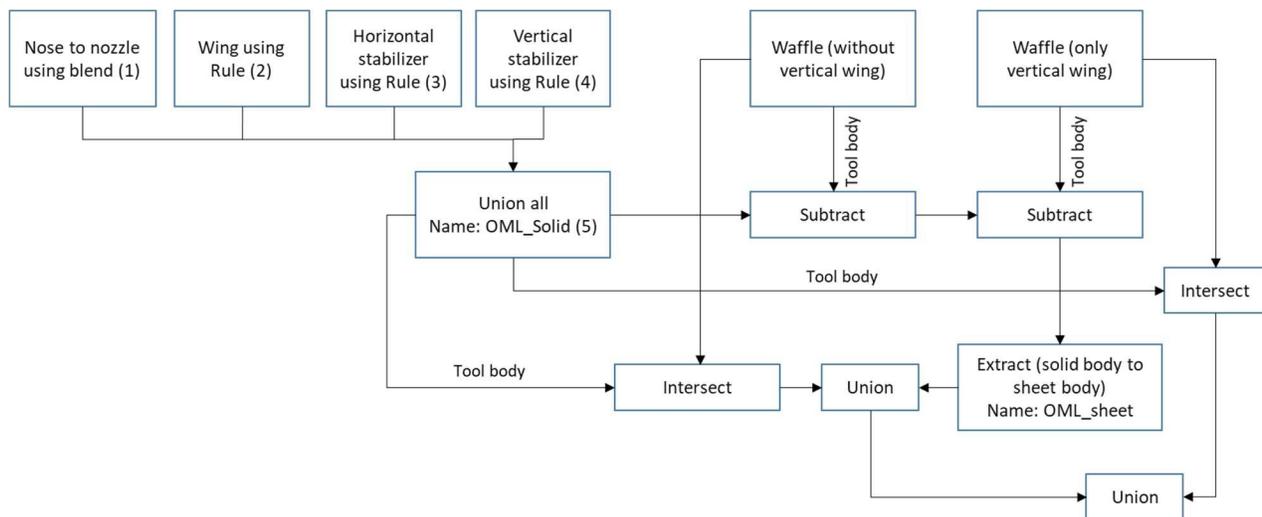


Figure 2. The ESP tree structure to generate a military fighter aircraft.

In this tree structure, each part contains of several steps. These steps are called ‘Branches’. Each part starts with generation of standard primitives which includes Box, sphere, cone, cylinder, or torus. Some primitives are used to join sketches such as extrude, rule, blend, revolve, sweep, or loft. And some are User Defined Primitives (UDP) such as ‘Naca’ and ‘supell’ (super ellipse). ESP arranges bodies in a stack order approach. This means that a given command is being operated on the last generated body or the last two bodies in case of the Boolean operations.

Figure 3 shows some key steps in generation of the fighter aircraft model. Figure 3a demonstrates the OML which is made from geometric user input parameters. Figure 3b shows a parametric waffle structure which upon its intersection with the OML will generate the internal structure of the aircraft (see Figure 3c). This structure is fully parametric and one can easily and efficiently change the number, thickness and the shape of the internal structures.

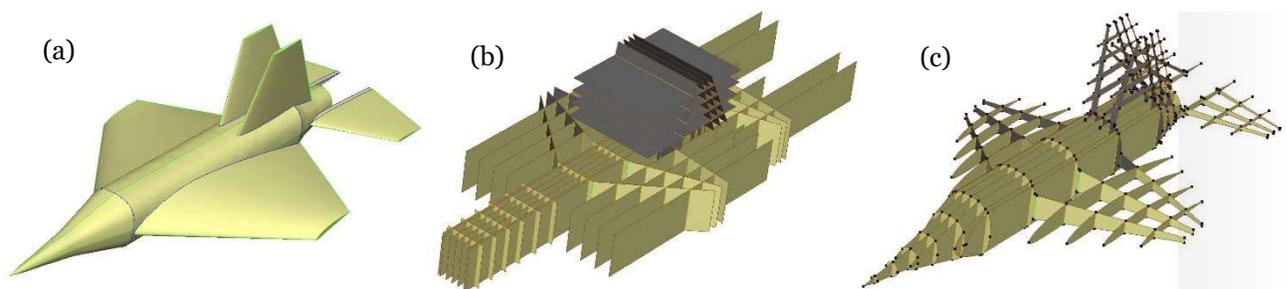


Figure 3. Parametric generation of the OML and the internal structure of a fighter plane in ESP.

The internal structure is created using Waffle UDP which takes a group of crossing lines in X-Y plane and extrudes them up in Z direction to create a non-manifold group of Faces. The waffle is then subtracted from the OML, which enforces the outer sheet Body to be scribed by the faces of the waffle.

Table 2 shows the design parameters used in building the parametric model of the commercial aircraft. The three models shown in Figure 4 are different in terms of the configuration of their internal structures. The design parameters of each model have been depicted in Table 3. To create a new model with a new set of design parameters, one needs to vary the relevant design parameters. The new ESP model takes about 10 - 15 minutes to regenerate which will result in a fast and accurate multidisciplinary design optimization platform.

Table 2. Design parameters used to create the geometry of the commercial aircraft

| Parameter name | Value | Description | Parameter name | Value | Description |
|----------------|---------------|--|----------------|-------|---|
| Fuse | [23x4] matrix | Dimensions of the fuselage(x,y,z1,z2) | xroot_v | 13.2 | Distance of root of horizontal stabilizer from nose |
| noseList | [2x4] matrix | Curvature of nose cone in three directions | zroot_v | 0.4 | Distance of root of horizontal stabilizer from central plane of plane |
| series_w | 4409 | NACA profile, location and orientation data for the wing | area_v | 9.6 | Area of the vertical tail |
| wing | [3x5] matrix | x,y,z, chord length & angle of attack of 3 profiles in wing | taper_v | 0.3 | Taper ratio of the horizontal tail |
| series_h | 406 | NACA profile for the horizontal stabilizer | aspect_v | 3 | Aspect ratio of the vertical tail |
| xroot_h | 14.5 | Distance of root of horizontal stabilizer from nose | sweep_v | 45 | Swept angle of the vertical tail |
| zroot_h | 0.2 | Distance of root of horizontal stabilizer from the central plane | stringers_no | 4 | Number of stringers in one half plane (this ensures even number of stringers) |
| aroot_h | 0 | Angle of attack of the horizontal tail at the tip | fore_frames_no | 6 | Number of frames between nose and wing |
| area_h | 0.78 | Area of the horizontal tail | aft_frames_no | 7 | Number of frames between wing and vertical stabilizer |
| taper_h | 0.55 | Taper ratio | ribs_no | 8 | Number of ribs |
| aspect_h | 3.7 | Aspect ratio of the horizontal tail | iribs_no | 3 | Number of ribs in the region joining the wing and fuselage |
| sweep_h | 25 | Swept angle of the horizontal tail | hribs_no | 6 | Number of ribs in the horizontal stabilizer |
| dihed_h | 3 | Dihedral angle of the horizontal tail | vribs_no | 6 | Number of ribs in the vertical stabilizer |
| twist_h | 2 | Twist angle of horizontal tail | spars_no | 2 | Number of spars |
| series_v | 404 | NACA profile for the vertical stabilizer | | | |

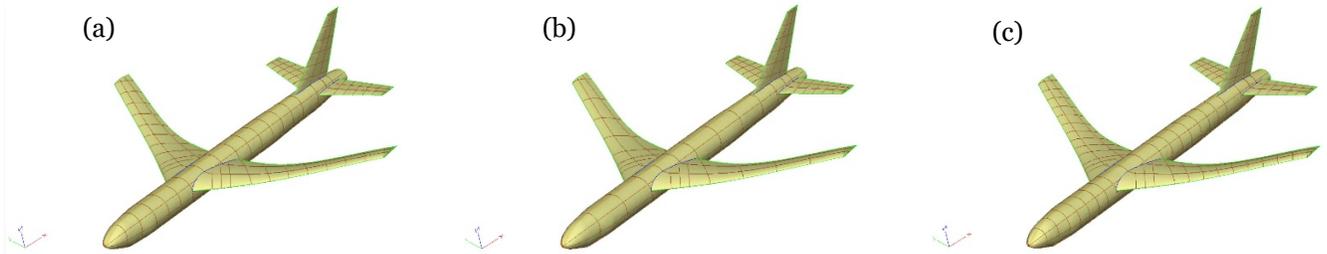


Figure 4. Parametric generation of the OML and the internal structure of a commercial plane in ESP.

Table 3. Design parameters used to generate different internal structures

| | Number of ribs in the wing | Number of fore frames | Number of aft frames |
|-----------|----------------------------|-----------------------|----------------------|
| Figure 4a | 8 | 6 | 7 |
| Figure 4b | 5 | 3 | 4 |
| Figure 4c | 10 | 8 | 8 |

Figure 5 shows different stages of the model generation process. Figure 5a depicts the Outer Mold Line (OML) of the aircraft which is the union of all the skins of the plane. Figure 5b is an extruded waffle to generate some of the internal aircraft structure which upon its intersection with the skin OML will result in the internal structure of the plane. The waffle for the vertical tail is intersected separately with the vertical tail and then is unioned with the main waffle. Figure 5c shows the union of the two horizontal and vertical waffles with only the two central stringers. The remaining stringers are intersected with the fuselage, rotated and then unioned with the waffle, thus forming the final internal structure of the aircraft (see Figure 5d). The waffle structure is then subtracted from the OML to scribe it. This divides the OML into different skin panels intersected by the waffle. The scribed OML is then unioned with the internal structure and the Inner Mold Line (IML) is subtracted from the model. The resulting final model is shown in Figure 5e.

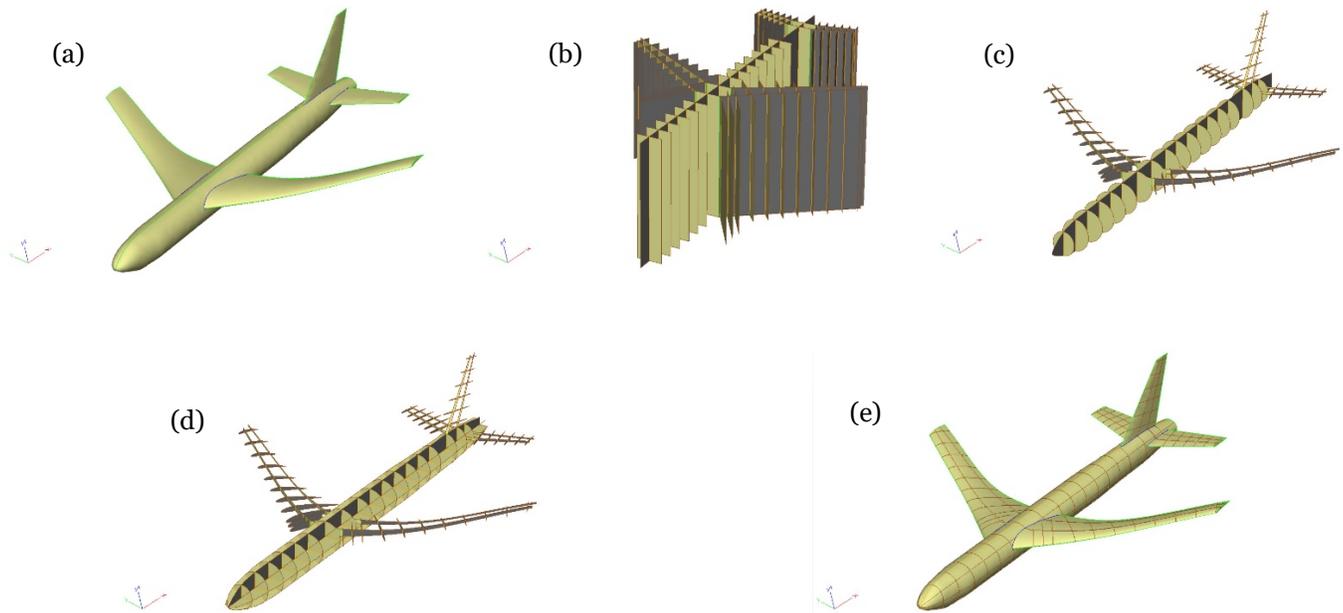


Figure 5. Parametric generation of the OML and the internal structure of a commercial plane in ESP.

Table 4. Design parameters used to create the geometry of the detailed parametric wing

| Parameter name | Value | Description |
|----------------|-------|---|
| series_w | 4409 | NACA profile of the wing |
| area | 10 | area of the wing |
| aspect | 6 | aspect ratio of the wing |
| taper | 0.7 | taper ratio of the wing |
| sweep | 20 | sweep angle of the wing |
| nrib | 5 | number of ribs in the wing |
| xfirst | 0.2 | percentage distance in the chordwise length of the first spar |
| xlast | 0.75 | percentage distance in the chordwise length of the last spar |
| nspar | 3 | number of spars in the wing |
| nstiff | 3 | number of stiffeners on the wing panel |
| depth | -0.01 | depth of the stiffener |
| angle | 45 | angle of the runoffs at the ends of the stiffener |

More intricate details about the wing such as the stiffeners can be modelled using the UDP stiffeners. Stiffeners are critical in the conceptual design as they are responsible for the stability of the model under buckling. UDP stiffener enables generating runoffs at both ends of the stiffeners. Figure 7e demonstrates the entire wing with all individual panels stiffened.

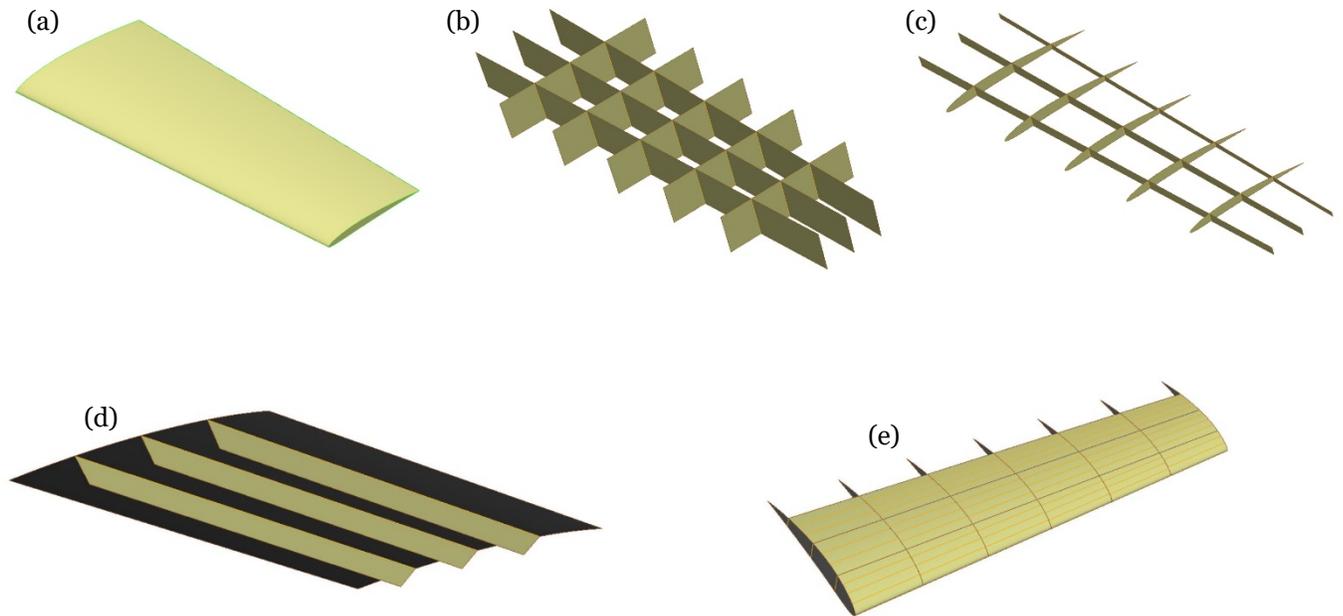


Figure 7. Parametric generation of the OML and the internal structure of a detailed wing in ESP.

III. Integration with the Analysis Tools

One of the main advantages of ESP is its capability to generate BEMs which could be robustly imported by structural analysis tools such as NASTRAN. To demonstrate this, the parametric generated model of the wing of the fighter was discretized into structured quadrilateral mesh using ‘createBEM’ UDP in ESP (see Figure 8). This mesh structure will provide a platform for performing structural analysis.

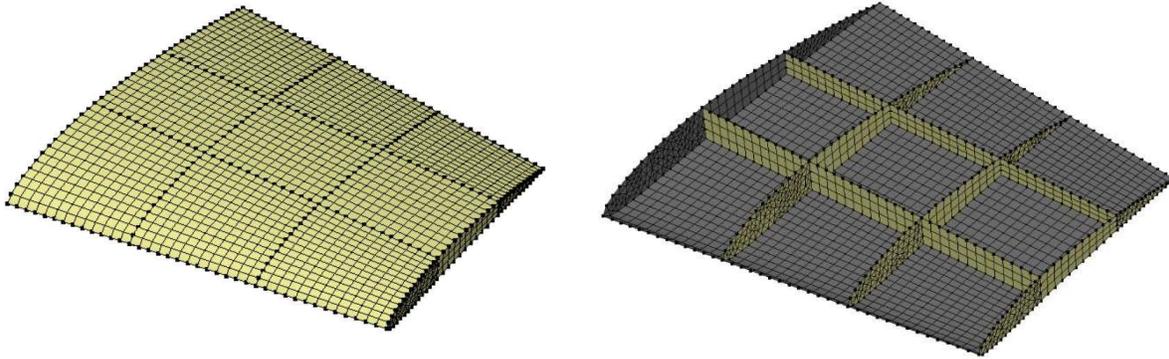


Figure 8. the parametric meshed model of the wing of the fighter in ESP.

IV. Conclusions

The CAPS program set out with the goal of having a single source geometry capability that could provide inputs to multi-fidelity, multi-physics solvers in a quick and efficient way. We are currently working on elaborating this capability by rapid generation of commercial and military aircraft prototypes to be used in conceptual design, multi-disciplinary design optimization, and high fidelity physics simulations (notably absent is CAD assemblies and three view drawings). The main advantage is that the models are parametric, attributable and have geometric sensitivities associated with the parameters. Finally, this paper will include the steps involved in creating rapid models of two commercial and military aircrafts as well as a detailed wing where the user-intensive generation of the BEM and interface connections are automated via the CAPS infrastructure.

V. Acknowledgement

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