

Manual of PreVABS*

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1 Introduction

PreVABS is a design driven pre-processing computer program which can effectively generate high-resolution finite element modeling data for VABS^{1,2,3,4,5} by directly using design parameters such as CAD geometric outputs and both the span-wisely and chord-wisely varying composite laminate lay-up schema for rotor blade and aircraft wing cross-sections. It has the capability of modeling sophisticated cross-sectional configurations for various composite helicopter rotor blades, wind turbine rotor blades, and aircraft wing structures. Most importantly, it has the merit of reducing dramatically the intensive modeling efforts for generating 3D finite element analysis (FEA) model which is either time consuming or impractical especially during the preliminary and intermediate design phases.

A typical comprehensive blade strength/dynamic/aeroelastic analysis process for rotor system or aircraft flight simulations during the various design stages requires realistic cross-sectional properties of rotor blades or wing structures. In addition to rotor system dynamic analysis and aeroelastic (dynamic stability) analysis, information on stress/strain distributions at critical blade sections sometimes becomes very valuable for designers to evaluate blade strength. This can be achieved by recovering the 3D stress/strain fields based on the global behavior obtained from the 1D nonlinear aeroelastic/dynamic analysis.

As shown in Figure 1, starting from the blade design configuration, PreVABS automatically models the complex cross-sectional configurations with mixed quadratic and triangular meshes based upon a few design parameters such as airfoil geometry, web positions and titling angles and chord-wisely varying composite laminate lay-up schema. The finite element modeling process is accurate up to each individual composite layer and the complete 3D structural and material information such as ply orientation, fiber orientation and ply thickness are calculated and recorded for each element. The VABS program is then used to analyze these data to obtain multiple span-wisely distributed sectional properties including structural properties (tension center/neutral axis, centroid, elastic axis/shear center, shear correction factors, extensional/torsional/bending/shearing stiffness, principal bending axes pitch angle, modulus weighted radius of gyration) and inertia properties (center of mass/gravity, mass per unit span, mass moments of inertia, principal inertia axes pitch angle, mass weighted radius of gyration). These span-wisely distributed inertial and stiffness data, combined with aerodynamic loads and boundary conditions, are fed to aeroelastic analysis tools, such as

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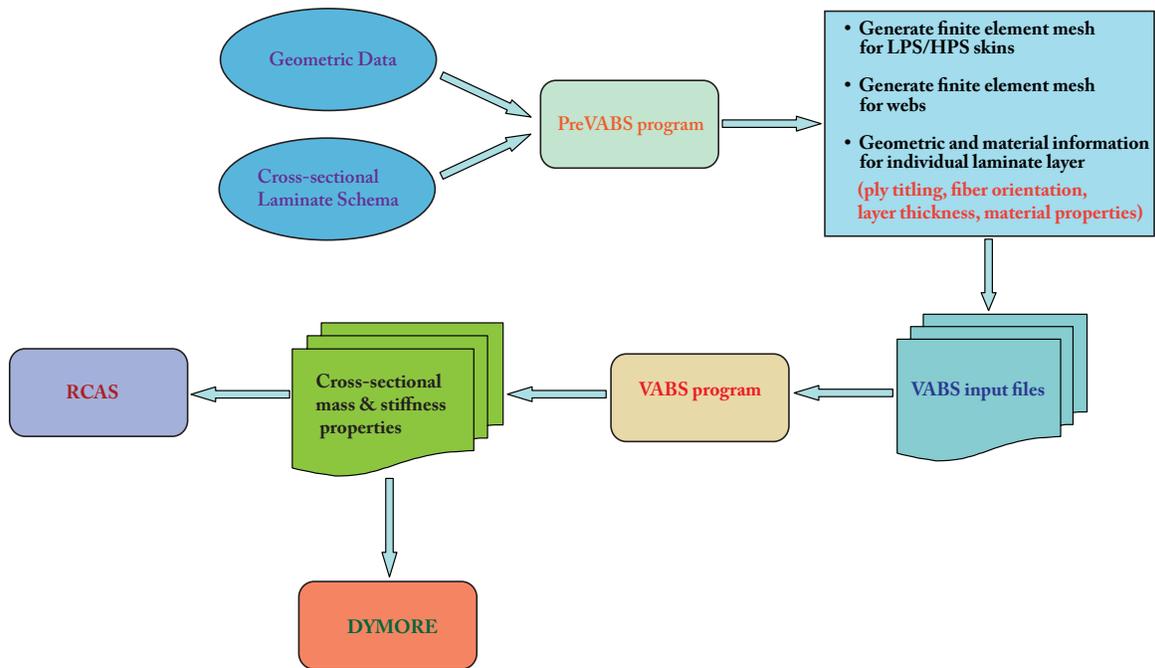


Figure 1: Precess for calculation of cross-sectional properties

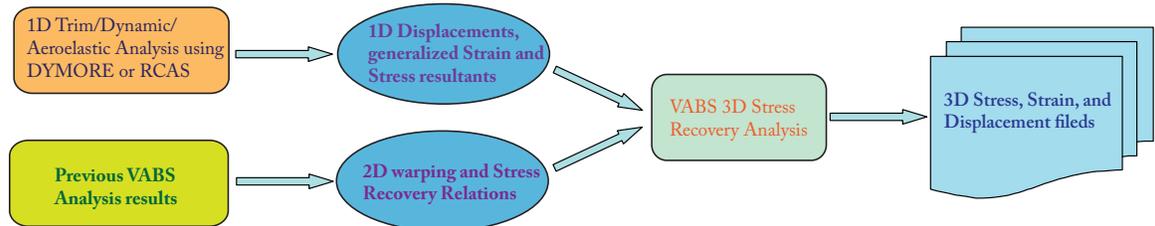


Figure 2: Precess for 3-D Stress/Strain Recovery

Rotorcraft Comprehensive Analysis System (RCAS) or DYMORE (a multi-body dynamics analysis software developed at Georgia Tech) to carry out aeromechanical analysis for the global behavior of the blade or wing.

As a result, steady-state and nonlinear time responses of structural loads and moments of the blade/wing are computed from various aerodynamic trim states and transient conditions. Subsequently, if required, the VABS recovery procedure can be used to obtain the 3D stress/strain fields. The 3D stress/strain recovery process is accomplished by inputting the calculated 1D span-wisely distributed loads/moments and displacements/rotation angles obtained by the aforementioned 1D beam analysis as well as previously computed and recorded 2D warping and recovery relations for each cross-section into VABS. Some visualization tools are needed to plot the distribution of the stress and strain field. A flowchart of this recovery procedure is shown Figure 2. This manual focuses on providing a brief tutoring on the use of the PreVABS software.

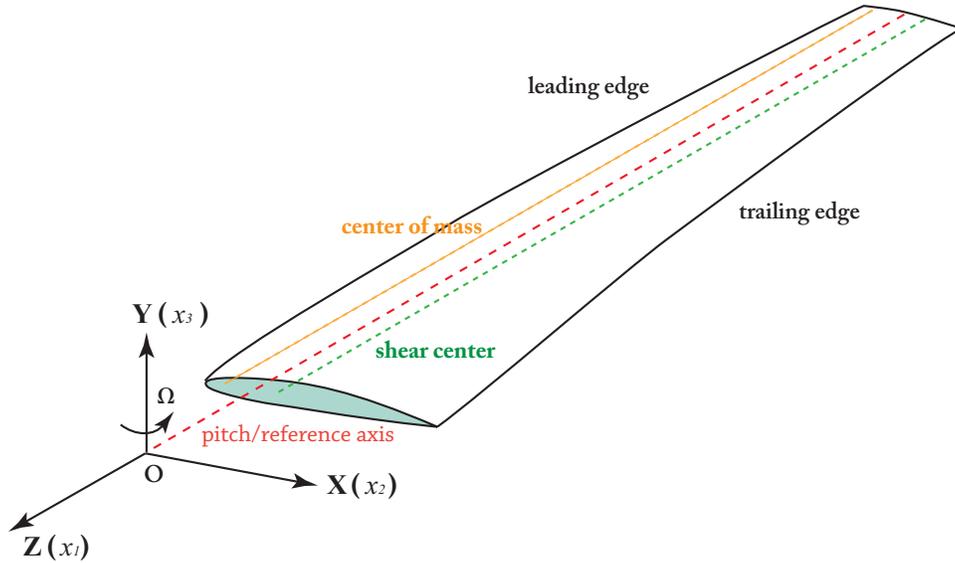


Figure 3: Schematic of VABS coordinate system

2 PreVABS Features

In contrast to most currently available rotor blade modeling tools, PreVABS, along with its analysis engine VABS, offers following features for high-fidelity modeling of sophisticated composite rotor blades:

- Automatically generates high resolution finite element meshes directly from CAD geometric data and lamina schema, dramatically reduces the primary design schedule.
- The finite element modeling is accurate up to each individual composite layer and complete 3D material and structural information are calculated and kept for VABS analysis to provide the most accurate cross-sectional analysis.
- Can model composite blades or wings with hundreds of layers.
- Can model sophisticate configurations for composite blades or wings, including both relatively flat and highly curved airfoil profiles, arbitrary web position and web titling angles, and both span-wisely and chord-wisely varying lamina schema.
- Can provide visualization for the finite element model, rigorous check of model, and user-friendly warning and error messages. These will guarantee robust and accurate modeling outputs and provide a very convenient and quick way for users to correct and modify the design data.

3 PreVABS Input Descriptions

During modeling, PreVABS requires the specification of blade's external airfoil configuration as well as the internal layup of composite laminate. The blade's external airfoil configuration can be obtained either from the output of an airfoil generation software or from some CAD tools such as Solidworks or CATIA. The chordwisely varying composite laminate schema can be specified by defying some representative key points along the outer profile of the current blade airfoil indicating the chordwise change of laminate stacks. In PreVABS, the geometric input data for cross-sectional properties calculation are defined according to a VABS

coordinate system depicted in Figure 3, where three coordinate axes x_1 , x_2 , and x_3 have exactly the same physical meaning as they are defined in VABS manual.⁶ It worth noting that if the subsequent coordinate system for 1D linear/nonlinear beam analysis is different from the VABS coordinate system, necessary transformation law must be applied both for the 6×6 mass and stiffness matrices to reflect the corresponding coordinate transformation. Interested users may refer to references^{7,8} for detailed information about coordinate transformation.

PreVABS uses three input data files for each blade cross-section analysis— (1) the airfoil geometric data file, (2) the cross-sectional lamina schema data file, and (3) the material property data file. All data files are self-explanatory with the help of the comments in the sample input files. It is worth noting that character “!” in the input files servers as a comment character and any information in the same line after “!” will not be read by PreVABS. Comments starting with “!” can occur anywhere in the input file, even after a valid input data value. Another feature of PreVABS is that it is not sensitive to the number of blank lines and blank space. Users may add any number of comment lines, blank lines, or blank spaces to enhance the readability of the input files.

3.1 Airfoil geometric data file

As can be observed from the companion example input files, the airfoil geometric data file is typically named as “section_profile_XXX...x.input”. The first input variable in this file is *prof_output_id*, a flag indicating whether or not to output dimensionalized profile data for the actually twisted cross-sections. This flag can only be specified by either ‘Yes’ or ‘No’ (not case sensitive). The next valid input data line consists of four variables, namely, CL , Θ_{twst} , $Cent_x$, and $Cent_y$, representing respectively, the dimensional chord length, the pre-twisted angle (in degrees) of the current cross-section, and the X, Y location of the reference axis. Specifically, $Cent_x$ and $Cent_y$ represent the dimensional X and Y coordinates of the origin of the reference axis, the intersecting point of the reference axis with the plane of current cross-section, in a new coordinate system (X_{af}, O, Y_{af}) , called “airfoil profile coordinate system”. The origin of airfoil profile coordinate system is coincident with the leading point of the current cross section, a point where the outer airfoil profile intersects with the chord line. The X_{af} axis of the airfoil profile coordinate system lies on the chord line and points to the trailing edge, see Figure 4.

While $Cent_x$ is always positive because the intersecting point of the reference axis is always after the leading point of the airfoil, $Cent_y$ is positive only if the intersecting point of the reference axis with the current blade cross section plane locates above the chord line. Although the dimensional chord length CL , $Cent_x$, and $Cent_y$ can be expressed in various units, the choice of units, as described in the VABS manual,⁶ must be consistent during the whole process of modeling to avoid errors. In PreVABS, the aerodynamic pre-twisted angle Θ_{twst} should always be expressed in the unit of degrees ($^\circ$). In addition, the positive Θ_{twst} angle represents a counter-clock-wise rotation of the cross-section about the x_3 axis in the VABS coordinate system (figure 3), i.e., leading edge twists down.

The next block of input data consists of the determination of the number of webs and the position and orientation of each webs. In PreVABS, arbitrary number of webs can be defined by specifying their positions and tilting angles. For each web, while its position is specified by the non-dimensional (x_{web}, y_{web}) coordinates of a point representing the intersection between the center line of the web and the chord line of the blade in the airfoil coordinate system (X_{af}, O, Y_{af}) , see Figure 4, its orientation is specified by the tilting angle (in degrees) of the center line of the web, which is measured from the positive direction of X_{af} . Since (X_{web}, Y_{web}) representing the intersecting point on the chord line, the non-dimensional Y_{web} coordinate of each web is always zero. The non-dimensional Y_{web} coordinate for each web is obtained by normalizing the corresponding dimensional X value of each web with respected to the chord length. The format of this data block is defined as:

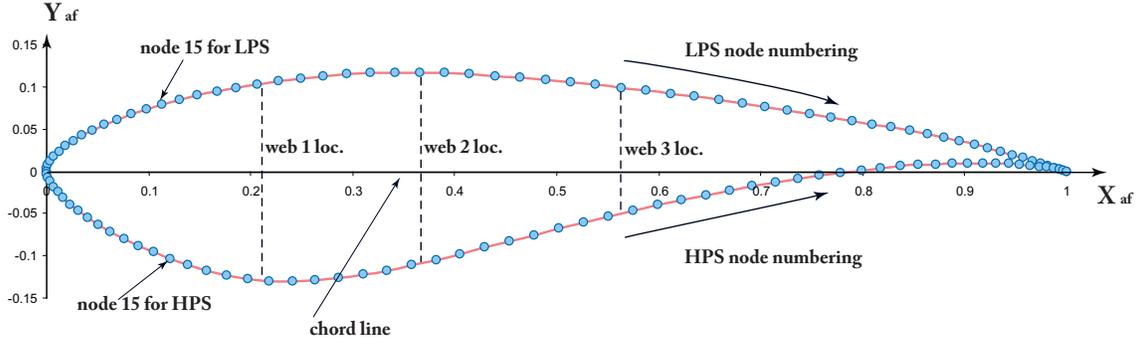


Figure 4: Schematic representation of a non-dimensional airfoil profile

```
! Nwebs
4
! x_web    y_web    tilting angle (deg)
-----
x_web1    0.0    135
x_web2    0.0    90
...
x_web4    0.0    90
```

The next two lines define whether the chord line is horizontal or tilted with a certain angle with respect to the chord line. For the currently version of PreVABS, the chord line is set to be coincident with the reference X axis, therefore, the chord line status should always be set to Regular (not case sensitive) and the chord line rotation (tilting) angle should always be set to 0 (degree).

The rest of geometric profile data describes the outer profile of the airfoil by providing the non-dimensional (X, Y) coordinates of the nodal points firstly on the lower pressure surface (LPS, or top surface) and then on the higher pressure surface (HPS, or bottom surface). The 2D (X, Y) coordinates for each node on the outer surface of the airfoil profile are also normalized with respect to the chord length CL . The nodal points on LPS and HPS are numbered separately and the numbering are based upon their ascending X values. Here, non-dimensional airfoil profile coordinate system (X_{af}, O, Y_{af}) is used to represent these (X, Y) values of the outer profile nodes, see Figure 4. For LPS, the structure of input data block is specified as: (1) the total number of LPS nodes ($Nnod_LPS$); (2) $Nnod_LPS$ lines of non-dimensional X, Y coordinates, with each line containing a pair of coordinates representing one profile nodal point. Similar data structure is repeated for non-dimensional (X, Y) coordinates for HPS nodes.

3.2 Cross-sectional lamina schema data file

The cross-sectional lamina schema data file is typically named as “Sec_Layup_Config_xxxx.input”. This file helps to define the lamina schema for webs as well as the internal lamina schema which varies along the outer profile of the airfoil. Firstly, we identify the upper and the lower surfaces, which are LPS and HPS, respectively, of the section periphery between the leading and trailing edges. Each surface can be divided into several segments, depending on the chordwise change of the laminate stacks including the variation of the total number of layers, components of materials, fiber layup orientations, etc. A segment consists of a stack of laminas specified with a given combination of material and layup information, see Figure 5. Different numbers of segments for LPS and HPS are allowed for PreVABS.

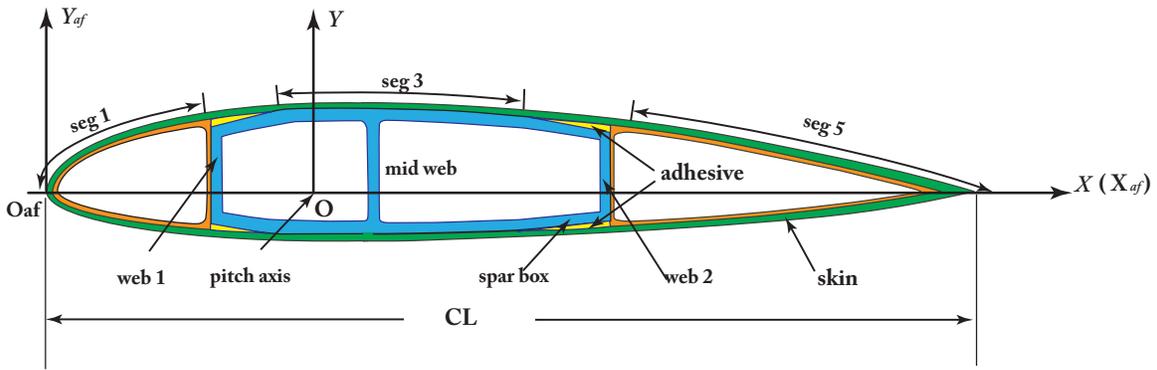


Figure 5: Sketch of a typical blade cross section

The structure of the lamina schema data can be divided into three major parts: (1) two nodal numbers indicating the start and end of each segment and its corresponding lamina schemas for LPS, (2) two nodal numbers indicating the start and end of each segment and its corresponding lamina schemas for HPS, and (3) the lamina schema for each web. PreVABS reads the schema input data exactly follow this order.

For LPS lamina schema data, its structure begins with a surface indicator, which should always be “Low_PS”, indicating the LPS part. Then, the user should define the total number of segments N_{seg_LPS} and the itemized segment numbers, for example, $1, 2, \dots, N_{seg_LPS}$. The next two input data values are nodal numbers indicating the start and end of segment # 1. The node numbering here should be consistent with that defined for non-dimensional airfoil data described in the above section. No gap is allowed between two adjacent segments, *e.g.*, the ending nodal number for the previous segment must be the same as the starting nodal number of the current segment. The next line defines the total number of composite layers in the current segment, *i.e.* N_{seg_Layers} . And the next N_{seg_Layers} lines define the corresponding layup configuration. Each line requires three parameters, namely, thk , θ , and mat_id to specify the lamina thickness, the fiber orientation, and the material id for each composite layer. This procedure is repeated until the configurations of all segments belong to LPS have been defined.

PreVABS allows the web to intersect with the LPS/HPS lamina schema within a single segment or with two or more neighboring segments as long as they have the same total thickness (not necessarily the same total number of layers). **PreVABS does not allow the situation where a web intersects with two adjacent segments with different total thicknesses.** If this situation happens, PreVABS will print out a error message and display a figure illustration to show where the problematic intersection occurs. The user can easily avoid this problem by increasing or decreasing the starting or ending nodal number of a particular segment by one or two to guarantee that each layer of the web intersects with the LPS/HPS inner boundary with the same thickness. In order to turn on the figure illustration, the user needs to set plotting flag Is_plot_area in the control parameter file to ‘Yes’ to enable the area-mesh-monitoring functionality. Specifications on how to define plotting flags and modeling parameters will be described in the next section.

Similar procedure should be repeated to determine the lamina schema and segments for HPS. The final step for defining the cross-sectional lamina schema data file is to determine the layup configuration of the web, whose data structure can be illustrated by the following self-explanatory inputs:

Example of web schema data structure:

```

! Total number of webs in this cross section
3
! (3.1) lamina layup configuration of Web 1
!=====
! Number of layers: Nweb1
58
!thickness (in)   fiber orientation (deg)   material id

0.0053           45                       1
0.0053           -45                      1
0.0053           60                       1
0.0053           -60                      1
0.0053           30                       1
...             ...                       ...
0.0053           20                       1
0.0053           -20                      1

! (3.2) lamina layup configuration of Web 2
!=====
! Number of layers: Nweb2
24
!thickness (in)   fiber orientation (deg)   material id

0.0053           45                       1
0.0053           -45                      1
0.0053           45                       1
0.0053           -45                      1
0.0053           45                       1
...             ...                       ...
0.0053           45                       1

! (3.3) lamina layup configuration of Web 3
!=====
! Number of layers: Nweb3
56
!thickness (in)   fiber orientation (deg)   material id

0.0053           -20                      1
0.0053           20                       1
0.0053           -30                      1
0.0053           30                       1
0.0053           -60                      1
...             ...                       ...
0.0053           -45                      1
0.0053           45                       1

```

3.3 Material property data file

The material input data file is typically named as “Material_xxxx.input” and an example of material input file is listed bellow. Its first two lines consist of six flag variables for VABS analysis, namely, *Timoshenko_flag*, *recover_flag*, *curve_flag*, *oblique_flag*, *trapeze_flag*, and *vlasov_flag*. The meaning of these variables is exactly the same as those defined in the VABS manual⁶. Please note: if *curve_flag* is set to be ‘T’, one additional line providing three real value inputs representing the pre-twist rate (k_1) and curvatures (k_2 and k_3) should be specified. As shown in the explanatory material input file, three different kinds of material

block can be defined, *e.g.*, the isotropic block (*ortho_flag* = 0), the orthotropic block (*ortho_flag* = 1), and the anisotropic block (*ortho_flag* = 2). The user may refer to the VABS manual for the more detailed definition on these three kinds of material data block.

Example of material input date file:

```

! VABS analysis flags
!=====
! Timoshenko_flag  recover_flag
T                    F
! curve_flag      oblique_flag      Trapeze_flag  Vlasov_flag
F                    F                    T                    F
!(k1(deg/in),k2,k3)
! input this line when curve_flag is ture
!=====
! Material Properties
!=====
! Total number of material ids
3
! Material Properties
!=====
! Material ID1      ortho_flag1
1                    1
! E1              E2              E3 (lb/in2)
2.059e7             1.42e6             1.42e6
! G12            G13            G23 (lb/in2)
8.7e5              8.7e5              8.7e5
! ν12           ν13           ν23
0.2                0.2                0.2
! Density ρ (lb - sec2/in4)
1.4763e - 004
!=====
! Material ID2      ortho_flag2
2                    0
! E
0.26E + 10         .3000000000E + 00
! Density ρ (lb - sec2/in4)
1.0d0
!=====
! Material ID3      ortho_flag3
3                    2
11.0e7             12.0e7             13.0e7             14.0e7             15.0e7  16.0e7
22.0e7             23.0e7             24.0e7             25.0e7             26.0e7
33.0e7             34.0e7             35.0e7             36.0e7
44.0e7             45.0e7             46.0e7
55.0e7             56.0e7
66.0e7
! Density ρ (lb - sec2/in4)
2.0
...                ...                ...

```

4 Running PreVABS

PreVABS is distributed in the form of PreVABS_V#_Release.zip for Windows operating systems, with # denoting the version number. The current version is PreVABS II. This release package contains an executable file— “PreVABS_V2.exe” (representing PreVABS version 2) and an example containing four exemplary input files to run a real blade modeling. Among these 4 input files, there is a main control input file named as “Control_input_file.txt”. It contains all modeling and plotting parameters as well as the file names for the other three input data files. By executing “PreVABS_V2.exe”, PreVABS will pump out a message asking the user to type in the name of the main control input file. In this example, the user should type “Control_input_file.txt”. However, the user may change this control file name to any name he/she prefers.

4.1 Parameters in control input file

The first three input parameters in the control input file are (1) the file name for sectional profile (outer surface); (2) the file name for cross-sectional chordwise layup configuration (lamina schema file); and (3) name of the input file for material properties. The data format for these three input data files has already been described in previous sections and they may serve as templates for users to generate new blade models in the future. The next step for users is to define a output file name for PreVABS. This output file is also the input file for the subsequent run of VABSIII.

In addition, there are several plotting and modeling parameters which controls the displaying and meshing process during the modeling of the blade cross-section. A detailed explanation of these variables are provided and listed below:

- **plot_profile:** a flag indicating whether or not to plot the rotated and shifted dimensional outer airfoil profile. This value can be set to ‘yes’ or ‘no’ and it is not case sensitive.
- **Is_plot_area:** a flag indicating whether or not to plot the coarsely meshed areas before conducting the refined finite element meshing. It can be used to monitor and verify the modeling process. This value can be set to ‘yes’ or ‘no’ and it is not case sensitive. This variable is especially useful to check whether or not a web intersects with the skin segments with different thicknesses.
- **plot_glbelm_mesh:** a flag indicating whether or not to plot the final finite element meshing result. This value can be set to ‘yes’ or ‘no’ and it is not case sensitive. It is recommended to set this variable to be ‘yes’ to provide a final confirmation of the modeling process of PreVABS.
- **Rel_mesh_size:** This variable defines the relative mesh size (mesh width/mesh thickness). It should always be set to a number bigger than 1.0, indicating that the mesh width is always bigger than the maximum layer thickness. For a very thick cross-section, *e.g.*, a cross-section with more than 200 layers, if this value is too small, a large finite element mesh will be generated and may be beyond the memory handling capability of current VABS. Obviously, keeping this variable as small as possible while still satisfying the memory requirement for the VABS run will provide accurate results. Typical values for this variable range from 3.0 to 8.0.

4.2 PreVABS verification and some modeling results

Recently, the functionalities and accuracy of PreVABS have been tested, evaluated, and verified by comparing modeling results generated by PreVABS and VABSIII with those obtained using other methods and computer tools through a systematic analysis of several benchmark examples, including a circular aluminum tube, a highly heterogeneous section, a multilayer composite pipe, an isotropic blade-like section, and a realistic composite wind turbine blade. Interesting reader may refer to reference⁷ for more details. Up to now,

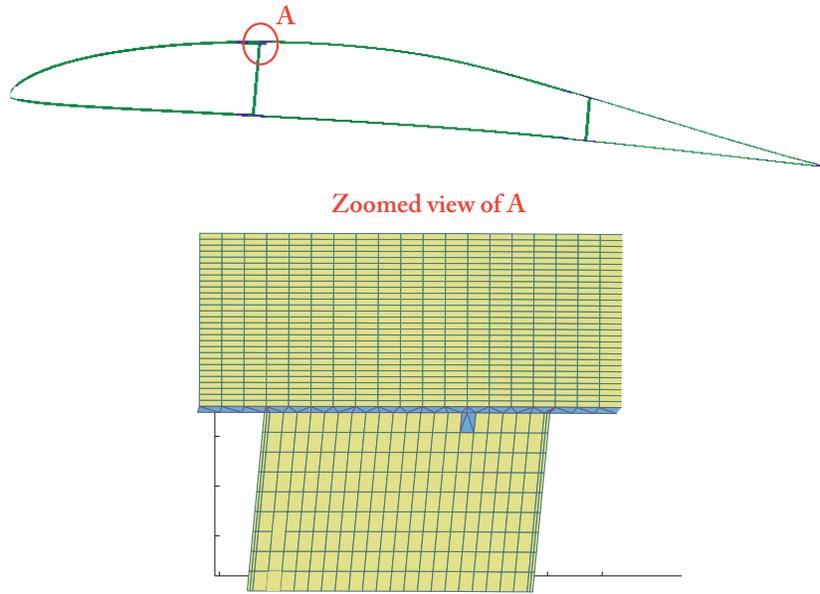


Figure 6: PreVABS modeling of an aircraft wing cross-section.

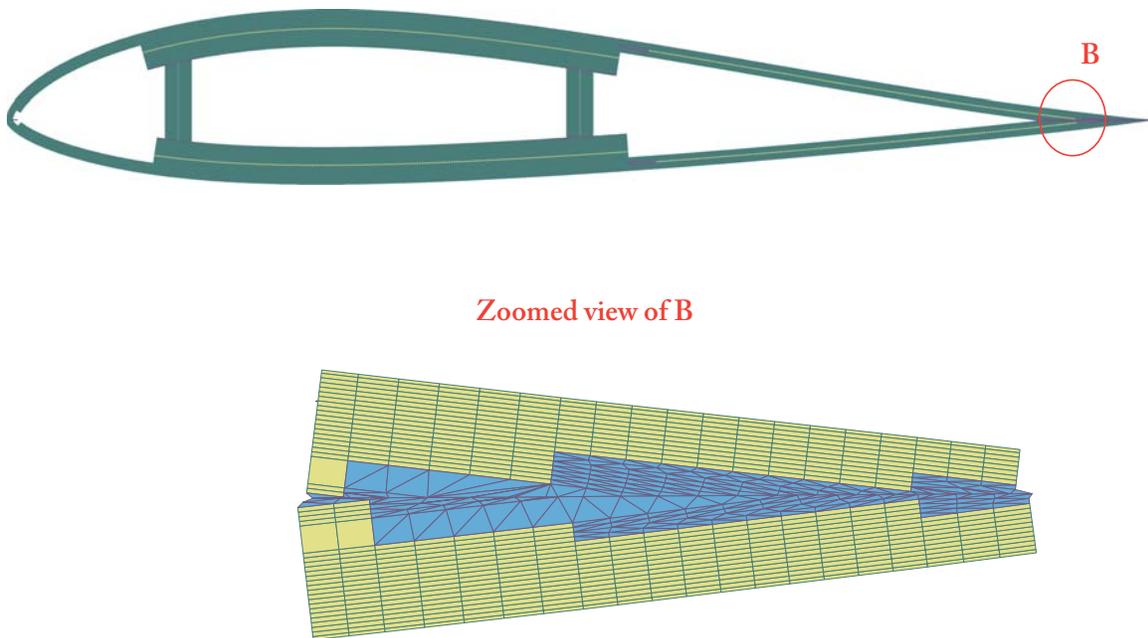


Figure 7: PreVABS modeling of a stall controlled wind turbine blade cross-section.

PreVABS has been successfully used by several aerospace companies for effective and high-fidelity analysis of various composite helicopter rotor blades and aircraft wing structures. Figures 6 and 7 provide some results for the cross-section modeling of an aircraft wing and a stall controlled wind turbine blade.

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