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MODERN PROCESS OF COMPOSITE STRUCTURES MANUFACTURING BASED ON CAD DEFINITION OF THE COMPOSITE

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Abstract

The article describes benefits for composite structures manufactured with the computer aid. The evolution of manufacturing process is presented, highlighting the specifics of anisotropic and laminar properties of composites. The paper shows steps of the process, including: design, preliminary computer analysis, virtual layup modelling, materials preparation. It comprehensively describes the state-of-the-art modern process featuring all technological equipment that facilitates the efficient and certifiable manufacturing. Important parameters of fabric for the producibility are presented. The article presents flat patterns creation, presumption of potential problems at work, as well as important parameters for the producibility check. Functions that make manufacturing department's (M&P) life easier are brought closer. Different software is named in the article, one is chosen as an example in the article and guided through.

Keywords: composites, producibility, flat pattern, CATIA CPD, layup, laminates.

1. THE AIM OF THE PAPER

The purpose of the publication is to bring closer the problem how a dedicated CAD system is able to help in work with composites, present solutions available on the market, present subsequent steps and justify the choice of one system. Apart from the main objectives the work is supposed to highlight the vocabulary used in professional composites design and manufacturing (the software available on the market is mostly in English).

The aim is to present difficulties to encounter an engineer during design process and composite elements manufacturing. In order to understand an essence of the whole process the article will present steps from the idea to the physical object, not neglecting an evolution of CAD software.

2. INTRODUCTION AND TECHNOLOGY OVERVIEW

Before composites dedicated CAD software introduction composite structures were manufactured with the use of model building-like methods. There are a few requirements describing the quality of a product:

1. Surface profile.

2. Boundary trim.
3. Fiber orientation tolerance.
4. No crimps/wrinkles.

In order to achieve a product within assumed tolerances, without CAD support, the process started from handmade master model. The master model was a base for manufacturing a mould, cross-sections and cutting patterns. Once the mould was ready and plies were cut, it was a challenge to position them accurately. Accuracy of 0.25 mm on certain edges is necessary to avoid placing brackets on surfaces that are not flat or to make sure not to drill at the edge of ply.

Producibility was tested only after having the production equipment ready. A real life trial gave an answer if the material would adjust to the mould curvature. A trial demands big workload, that is why the design headed towards simple shapes with simple curvatures (ruled surfaces: a profile swept along moving straight line).

The issue of fiber orientation is worth explaining. Laying material without crimps is not a success itself, because the composite should remain fibers parallelism along the main loads directions. Specific tows of warp or weft shall not deviate from the main load direction. In practice, some deviations are allowed (about 10°) but they are a source of extra safety coefficients, which increase the mass. Arrival of CAD 2D software enabled to digitize flat shapes. Flat geometry was easier to draw but still a problem of 3D geometry transfer into a flat pattern was not solved.

Eventually, a 3D software, where surfaces were modelled and passed to CNC machines managed to optimize construction with respect to the producibility. Cooperation between 3D modelling and FEM analysis forecasting the layup gives preliminary information if assumed ply count and orientations is good enough to withstand the loads. Figure 1 presents a positive result of a producibility simulation of 45° orientation material. Figure 2 shows a more complex shape where fibers were not laid in a parallel direction.

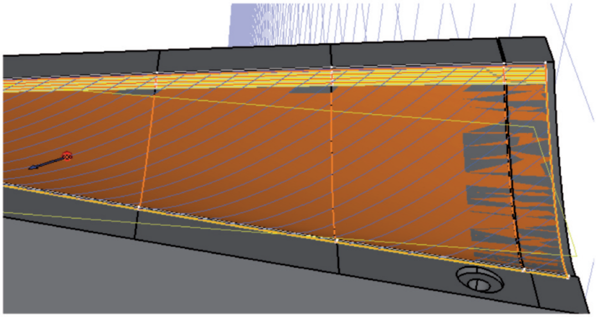


Fig. 1. Producibility simulation for 45° ply [Krauze, 2016]

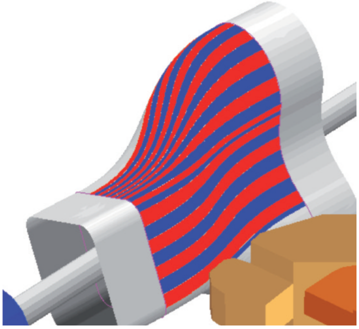


Fig. 2. Producibility simulation for 0° ply, angular deviations due to complex shape [1]

Figures 1 and 2 illustrate layup simulation. There is an experimentally proven limit for deviation from the nominal fiber orientation. The value above it, will be a reason to modify the surface shape or use other materials [2]. Bad producibility simulation results are anticipation of the following layup imperfections: deviation from the main direction, deformation, crimping and bridging. An important fact is that different weave types and fiber types have different ability to adjust to the mould shape. The more loose weave type (e.g. 5 harness) the better shape conformability (providing comparable areal weights of reinforcement).

A variety of composites design dedicated software is available on the market. Basically, they consist of 3D modelling tools and a solver that analyze ply producibility and flatten its geometry. The latter part is called as CAE (Computer Aided Engineering), however, both work within one software package. The choice of software often depends on the client and the aim is to be compatible. That involves mating not only software provider but also its version. Aviation industry has adapted two solutions (others are available but two main ones are mentioned here):

1. Fibersim (Siemens).
2. CATIA CPD (*Composites Design*) (Dassault Systemes).

Fibersim is most frequently chosen to co-work with NX software, which is also a product of wide Siemens family. Nevertheless, it works finely as an auxiliary program for French flagship CAD – CATIA. Design process of composite structures using CAD consist of the following steps:

1. Part shape, thickness and trim definition,
2. Ply table creation,
3. Plies definition including boundary, material, orientation and origin,
4. Producibility analysis,
5. Flat patterns creation.

Another function of the described software is the composite element mass calculation. Summing up plies surfaces and subtracting cutouts the program returns the final part mass. Such an analysis supports mass optimization, makes configurations comparison easier (if they differ in layup scheme).

Subsequent important usage of the tool is reliable data exchange with stress department and technical documentation creation. Flat documentation for the manufacturing department requires a list of plies (*plybook, plytable*), that is the key feature to produce the part. Plybook as a table specifies material type and the main direction (where the warp should go).

Table 1, which is part of flat documentation for a composite rotor blade, shows values generated with the use of CAD program along with parameters indicating the ply main direction.

Table 1. Sample ply table for a technical documentation of composite element [Krauze, 2016]

Ply number	Part number	Material	Mass, kg	Orientation, °	Surface, m^2
1	IL.32.32.332.11.90	COPPERMESH 2CU-100FA	0.025	OPT	0.231
2	IL.32.32.332.11.90	MTM46/CF0304A	0.079	45	0.231
3	IL.32.32.332.11.90	MTM46/CF0304A	0.079	0	0.231
4	IL.32.32.332.11.90	MTM46/CF0304A	0.079	45	0.231
5	IL.32.32.332.11.90	MTM46/CF0304A	0.028	45	0.09

Situation is comfortable until plies (prepreg sheets) cover the whole area of a mould (excluding inner holes and cutouts). A more complicated element than the described in the previous sentence, where full body plies are mixed with small local plies require precise cutting and positioning on a mould. In this point integration of the design software with CNC cutter occurs. The example is ZUND's G3, available in Europe as well as in the USA [3]. Plies are cut accordingly to flat patterns created from 3D geometry. Theoretical accuracy of the cut is ± 0.02 mm. In order to hold the precision the layup is supported by a laser projection system [4]. Average accuracy level of laser projectors available on the market is ±0.2 mm. The input shape (flat pattern) is also a subject to accuracy scatter, which is seen by comparing flat patterns obtained with the use of different algorithms (propagation type). Moreover, within one software different solvers (flattening engines) are available. It is highly advised to call for a test license before purchase and check flat patterns result. Human factor is also an important component in a tolerance chain. Taking into account all elements the tolerance of ply edge position reaches 6 mm.

3. PRACTICAL ASPECTS

In order to verify efficiency of CATIA V5R23 with CPD module the design process of composite rotor blade has been performed. The paper presents general steps to be followed during the process. For the purpose of this exercise the simplest manual ply creation method was chosen. Complete plies definition including ply boundaries modeling, ply drops zones design, orientation assignment, etc. are done by hand of the designer. The designer draws the boundaries in CATIA Generative Shape Design, common tool for 3D geometrical modeling, which are input for ply definition in CPD. The more complex and advanced methods (Zone and Grid method) were not used, they feature importing layup from ply table, automatic drop-off and solid body creation to be used as space allocation model in DMU (digital mockup). Manual method is proper to present the essence of composite design, requires bigger workloads however is to be used with complicated, non-repetitive and unconventional layups. Economy of scale stands for using Zone and Grid method, as they are presumed to be used in large scale production.

3.1. Preparation

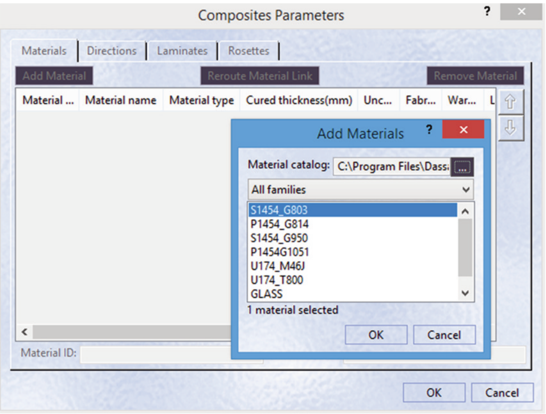
Composite part CAD definition begins when the following input is complete:

1. Tool surface.
2. Rosette.
3. Ply boundaries.
4. Ply table.
5. Material database.

3.2. Material database preparation

In order to make a full use from composites potential it is advised to set together different prepreg types in one part. It relates to the reinforcement types, as the resin system should be the same. Important properties to be acquired before design process (figure 4):

1. Raw material thickness (before cure cycle).
2. Cured material thickness.
3. Roll width.
4. Warning angle.
5. Areal weight.
6. Limit angle.
7. Material density.
8. Poisson's ratio.
9. Young's Modulus.



Material catalog: C:\Program Files\Dass

All families

S1454_G803
P1454_G814
S1454_G950
P1454G1051
U174_M46J
U174_T800
GLASS

1 material selected

Fig. 3. Material selection window [Krauze, 2016]

3.3. Tool surface

Catia CPD requires continuous base surface called a tool surface, which is an exact representation of a mould (tool) shape. This is a basic input for the laminate definition and shall not be modified during creation of a CAD model. In case of a sandwich structure two base surfaces are to be modelled. Apart from the tool surface also an overcore surface should be defined. Producibility simulation is expected to show how the material would behave during layup on the particular surface. In case of sandwich panels manufacturing Tool Surface represents clean mould tool shape and is used for undercore plies simulation. Overcore surface represents a shape in the middle stage of part layup just after core placement. As it may be concluded, overcore surface is more challenging for material placement, owing to the fact it consists of curves, ramps and pandowns. In that case a single panel is supposed to acquire two levels, called LAMINATES is presented in figure 5.

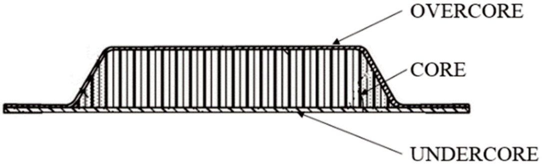


Fig. 4. Tool surfaces [Krauze, 2016]

3.4. Two main boundaries to be frozen

For the correct definition of composite part it is required to define and remain without any changes the boundaries:

1. EOP (Edge of Part): boundary of the cured part after final trim.
2. EOL (Edge of Layup): typically 25 mm beyond the EOP, surplus material is also taken into account for the producibility analysis.

3.5. Rosette definition

The essence of fiber reinforced composites is anisotropy. That is why definition of the main direction (zero direction) and orientation of plies in relation to the main direction is the key factor. Rosette is the compass to show the directions. It is an axis system, common for all plies within a part. For example, X axis can be parallel to 0° direction (main load direction), Z axis parallel to composite thickness increase. Y axis is resulting from X and Z and the general rule of a thumb.

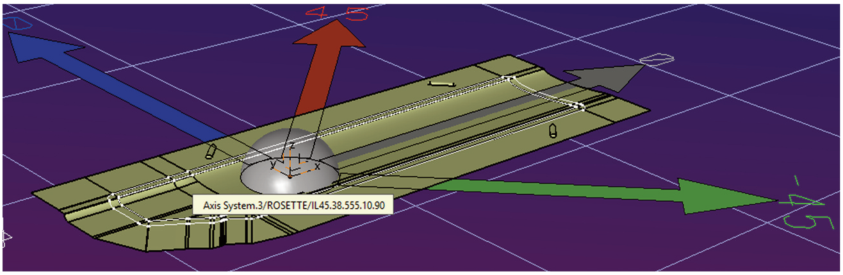


Fig. 5. Right handed rosette on the rotor blade mould tool surface [Krauze, 2016]

3.6. Ply boundaries drawing

Not all plies consist of one piece of material. Big elements require dividing plies, owing to few reasons:

1. Single ply dimension larger than material roll width.
2. Operator's limited arms range.
3. Materials utilization (nesting optimization).

In order to maintain load transfer capability, plies should be overlap spliced. Complicated ply levels gathering more than 2 plies in a corner or at an edge ('tiles') are advised to avoid overlapping more than 2 layers. It is very essential to keep follow golden rules in composites design:

1. Uniform overlaps distribution.
2. Keeping a minimal overlap length.
3. Avoid placing overlaps under brackets.
4. Splicing only where necessary.

3.7. Geometry (3.1 – 3.6 transfer to the composite module)

Complete ply definition consist of the following parameters:

1. Materials: from list defined in 3.2 appropriate material must be chosen.
2. Material orientation: a good practice is attaching to the boundary the line defining materials orientation. Usually parallel to warp direction.
3. Origin point: good practice continuation is attaching to the ply boundary a point, that indicates the material layup initial position.

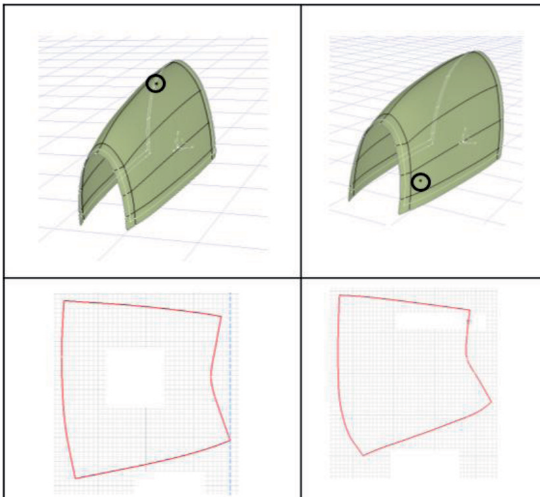


Fig. 6. Flat patterns differences depending on a location of the Origin Point [Krauze, 2016]

Figure 6 clearly presents which origin point should be chosen. A general rule can be deducted from that example. Black circle indicates a location of the origin point, for which the flat pattern has been developed. Answer for the question – which one should be chosen – is obvious: the one which gives more symmetrical and rectangular-like shape. Moreover, the manufacturing practice shows, that material should be laid from top to the bottom (going downslope). In more complicated cases the software and solver will develop various acceptable shapes and the designer should chose the one most suitable. Nevertheless, the Origin Point location affects fiber orientation deviation. The further from Origin Point, the greater deviation. It may be concluded that placing the Origin Point in geometrical center minimizes the maximal fiber deviation.

4. Rosette: the main directions of the composite. Depending on the choice, program will orientate the warp parallel to X axis of the chosen rosette. Rosettes are constructed on the tool surface (for flat elements) or positioned on a generic revolution axis of the element. In the latter case, the rosette is called a ‘translational’ one.
5. The main surface (laminate): ply boundaries still in the design module should be constructed or projected on the tool surface. Point 1.2 introduces a term ‘tool surface’ (mould surface), being one of main surfaces. For sandwich structures also a top core surface is introduced (‘overcore surface’). Certain surface (tool or overcore) along with rosette create a ‘laminate’, thus a typical sandwich bondment would contain 2 laminates (see figure 5).

3.8. Technologically driven geometry creation

Producibility analysis: the ‘producibility’ is not a composite manufacturing specific term. General definition says of general ease of manufacturing [6]. From composite industry standpoint it is to be understood as an analysis of the ply layup (will the ply wrinkle, bridge, deformat, tear or deviate from the nominal fiber orientation). This stage is a facilitation for Materials and Processes team. Plies have to be designed with respect to manufacturing limitations and operator capabilities, not every designer has a production background, thus basic analysis tools must exist to put virtual ideas through a sieve. Eventually, it allows to spare the time of experts and money on technological trials. Every market available software has one common feature: analysis result are presented as a colored mesh on the tool surface (presented in figure 7).

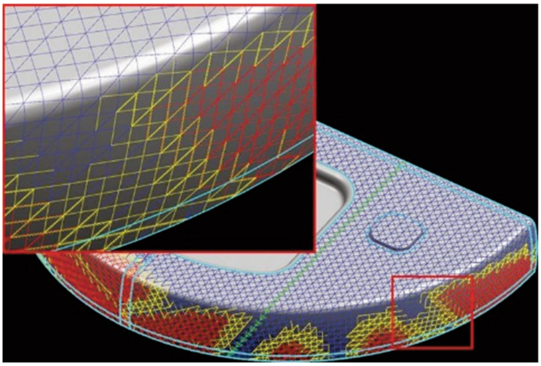


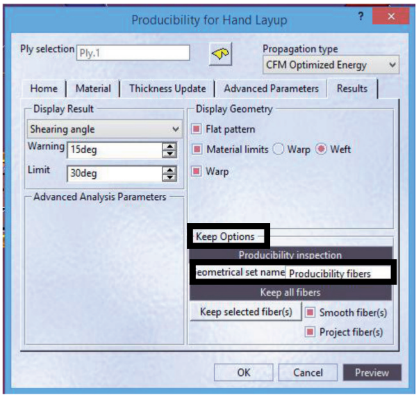
Fig. 7. Graphic representation of Producibility analysis [2]

In order to warn a user the program displays colored mesh:

1. Red: the area will cause manufacturing problems.
2. Yellow: the area is likely to cause problem, watch for fiber deviations.
3. Blue: go ahead, no problems anticipated.

Depending on the manufacturing specifications cuts are allowed to relax fabric in certain areas (darts). Accounting such a cut in a producibility analysis is quite a challenge. Programs usually create cuts in the indicated location.

Other result of the operation is a check whether a particular ply fits within a roll width. It is usually called as Weft Check. An example from CATIA CPD presented in figure 8. Weft runs along the roll width (fig. 9).



Producibility for Hand Layup

Ply selection: Ply.1

Propagation type: CFM Optimized Energy

Display Result: Shearing angle

Warning: 15deg

Limit: 30deg

Display Geometry:
☒ Flat pattern
☒ Material limits ○ Warp ● Weft
☒ Warp

Keep Options

eometrical set name: Producibility fibers

☒ Smooth fiber(s)
☒ Project fiber(s)

Fig. 8. Roll width check [Krauze, 2016]

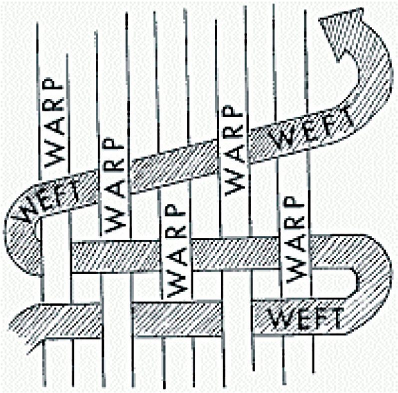


Fig. 9. Weft fibers along roll width [5]

3.9. Flat pattern creation

Having the producibility passed, the flat pattern may be created. Flat patterns are displayed on user pointed plane, then exported to selected file for flat documentation (typically .dxf). It is highly advised to visually control the flat patterns. It is possible that boundary is unacceptable. The correction action could be a change of the propagation type. If that does not help then it may call for a change of a solver. A solver is an engine that performs the flattening. It is an optional feature, and buying a better one results in better geometry. Figures 10 and 11 present the same boundary flattened with the use of the same solver but different propagation types.

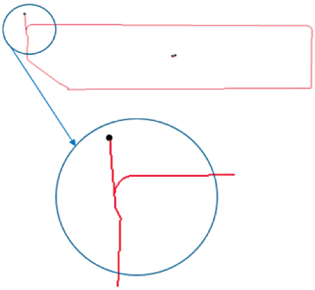


Fig. 10. Bad flat pattern, propagation type: CFM Optimized Energy [Krauze, 2016]

Fig. 11. Good flat pattern - closed contour, propagation type: Minimum Distortion [Krauze, 2016]

3.10. Flat pattern export to DXF file

In the case of technological flow of Center for Composite Technologies (CCT, Institute of Aviation, Warsaw) flat patterns are exported to .dxf file, which is an input for subsequent steps of a process. Flat patterns are precisely cut with the use of a cnc machine (vacuum table cutter), and the location on a mold is indicated with use of a laser projection system, also using geometry from CAD program.

4. RESULTS

Technological department of CCT has been using dedicated software CATIA CD3+CFM configuration to create documentation, cutting patterns, laser projections patterns and preliminarily simulate ability to manufacture a part (producibility). As well as for concave, convex as on-mandrel laid (closed in assembled external mold) details the process proved its worthiness. The example that confirmed the fact is a successful closure of the multipart mold for composite blade spar. It was a challenge to lay 35 layers (not a full body) on a mandrel in their exact position. The mandrel had suitable undercuts on offset surface to compensate variable thickness. Boundary precision and exact positioning were key factors that the element passed First Article Inspection.

Apart from the above mentioned, this is a basis for the product quality control, traceability and conformance with drawings. This is a huge ease to certify for AS9100 (Aerospace Standards) and cooperate with aviation companies. As pointed by W. Wiśniowski, R&D activities without commercialization are not justified. The aim of prototyping is commercialization. Prototyping and R&D works without standards described in the article are not ready to emerge on market [7].

5. CONCLUSIONS

Benefits from computer aided composites design range from quality raise, through economy improvement to empowering business potential.

1. Surface development to DXF files and CNC cutting shortened materials preparation time of 50%, taking into consideration a profile of R&D manufacturing (short series, frequent change-overs). In the case of series production the benefit would reach 80-90%.

2. Tolerance of ply positioning consists of 10% mechanical devices component and 90% component from 3D geometry export into flat pattern and human factor (hand layup) together. Computer aided process helps to control the factor responsible for 90% of tolerances.
3. Use of computer aided design for composites is a condition to archive the process and to obtain repeatable results.
4. Use of computer aided design for composites is a tool to calculate required materials, product weight and effective communications with stress department.
5. The use of CAD definition of the composite for design and manufacturing process is a condition to be assumed as a true innovation.

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NOWOCZESNY PROCES PRODUKCJI STRUKTUR KOMPOZYTOWYCH W OPARCIU O KOMPUTEROWĄ DEFINICJĘ KOMPOZYTU

Streszczenie

Artykuł opisuje jak komputerowa definicja struktur kompozytowych w modelu CAD upraszcza proces wytwórczy oraz przyczynia się do uzyskania najwyżej jakości owych struktur. Zaprezentowana została ewolucja procesu wytwarzania struktur z uwzględnieniem anizotropowych i warstwowych właściwości kompozytu. Krok po kroku ukazany jest proces projektowania części kompozytowych włączając w to definiowanie kompozytu w modelu komputerowym, symulacje technologiczności, uzyskiwanie płaskich kształtów poszczególnych warstw i transfer wyników na produkcję. Kompleksowo opisany został stan techniki, oprogramowanie i przyrządy konieczne by w sposób nowoczesny produkować wysokiej jakości części. Odpowiednio przygotowany przez konstruktora proces jest wielkim ułatwieniem podczas wytwarzania co w jasny sposób zostało ukazane w niniejszym artykule.

Słowa kluczowe: kompozyty, technologiczność kompozytów, rozkroje warstw, CATIA CPD, laminaty.