

LAMINATE DESIGN METHODS FOR CLOSED VOLUME STRUCTURES

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Keywords: Laminate Design, Design Methods, Closed Volume, Aerofoil.

Abstract

The definition of composite laminates that accurately fill closed volumes such as aerofoils, while abiding to numerous laminate stacking rules, is a complex task that depends on robust methods to efficiently create a requirement compliant laminate definition.

This paper presents an overview of the methods developed to create ply shapes that, once laminated, accurately reflect the closed volume of an aerofoil geometry. Key considerations covered are: The re-stacking of the laminate within the confines of a closed volume, the compliance with laminate design rules, accounting for different material weights, material input form, the architectural requirements of the aerofoil to withstand the required structural duty and manufacturing considerations. Also covered is the checking of the laminate using 'core samples', ply-sections and 'exploded surfaces' during and after the design process. Validation of the design methods against manufactured parts is explained by analysing geometric conformance and the laminate quality is assessed from cut-ups.

1. Introduction

Typically composite structures are shell, or panel type structures. With these the composite laminate can be adjusted to fulfil the mechanical requirements by adding sufficient plies of composite material in various orientations until the mechanical properties are met. However closed volume geometries of composite construction can be more difficult to define. Aerofoil structures cannot simply be thickened indefinitely, as other requirements such as aerodynamic performance will be compromised to the point that the product is no longer a feasible design.

Design methods are required to generate ply shapes that, once formed into a laminate, accurately reflect the desired moulded geometry. The resulting laminate needs to be able to achieve the structural requirements of the component. This can be problematic across all areas of the component, but becomes especially challenging in areas of high taper, which are normally associated with rapid changes in the local stress field. Ply shape geometry is controlled by the geometry of the closed volume. It should be recognised that the ply shapes are fixed by the volume that needs to be filled; it is the ply stacking sequence which can be altered. With many aerofoils the external shape will result in ply drops coalescing in areas of high taper, thus reducing damage tolerance. Therefore ply drops need to be carefully managed through the laminate stacking sequence to minimise the proximity of adjacent ply drops and to control plies of the same orientation grouping together [1][2].

The design methods described have been used on the specimen geometry described in [3].

2. Laminate Definition

The laminate designer requires a number of inputs to be able to start the definition process, these are normally:

- Typical material information
 - Cured ply thickness
 - Available material orientations
 - Orientation percentages
- Typical laminate rules
 - No ply drops on the outer surfaces of the component
 - No angle change between adjacent plies greater than x deg
 - No ply grouping greater than y plies
 - No ply drops to be adjacent to each other
- Moulded geometry definition
- Any Manufacturing Edge Of Part (MEOP) boundaries
- Any Engineering Edge Of Part (EEOP) boundaries

The material form is important to the laminate designer, as an accurate Cured Ply Thickness (CPT) value is required. This varies with the areal weight for the chosen material and the manufacturing method. For instance, an Automated Tape Laid laminated product of the same areal weight as the broad goods form, normally has a different CPT. The CPT also varies with surface topology. The accuracy of the CPT values used in the definition process has a direct influence on the accuracy of the 'fill' of the closed volume.

2.1 Zone based design

To accurately fill a closed volume of aerofoil type geometry with different material types, and laminate rules to obey, it is important that a structured approach to the definition is executed. Using regions within the closed volume to define sub laminates (zone based design), enables the control of the definition.

Zone based ply definition has typically been used to define panel type structures with different thickness areas, core structures, and an un-constrained volume [4]. The method described here is an example of how zones can be used with the constraining features of a closed volume.

The component is split into zones. Zones are different regions of the component bounded by surfaces and are used to control the shape, size, and number of plies in certain regions of the part. They enable the designer to control where ply-drops form, so that ply-drops occur in more benign areas of the components thus maximising the damage tolerance of a laminate in functionally critical areas. Zoning also allows different material groups to be defined in different areas of the component, such as woven plies in surface regions. In addition, zoning enables the definition to be carried out by multiple designers at the same time, to compress the time taken to define the laminate.

Zones can be self-contained regions such as wedge pack zones, or a single zone that is interleaved between other zones such as the main structural ply zone, see FIGURE 1.

Zoning can be problematic, if too many zones are created, due the rounding errors. The use of interleaved zones reduces the number of zones required, improving laminate accuracy and reducing the time taken to define the laminate.

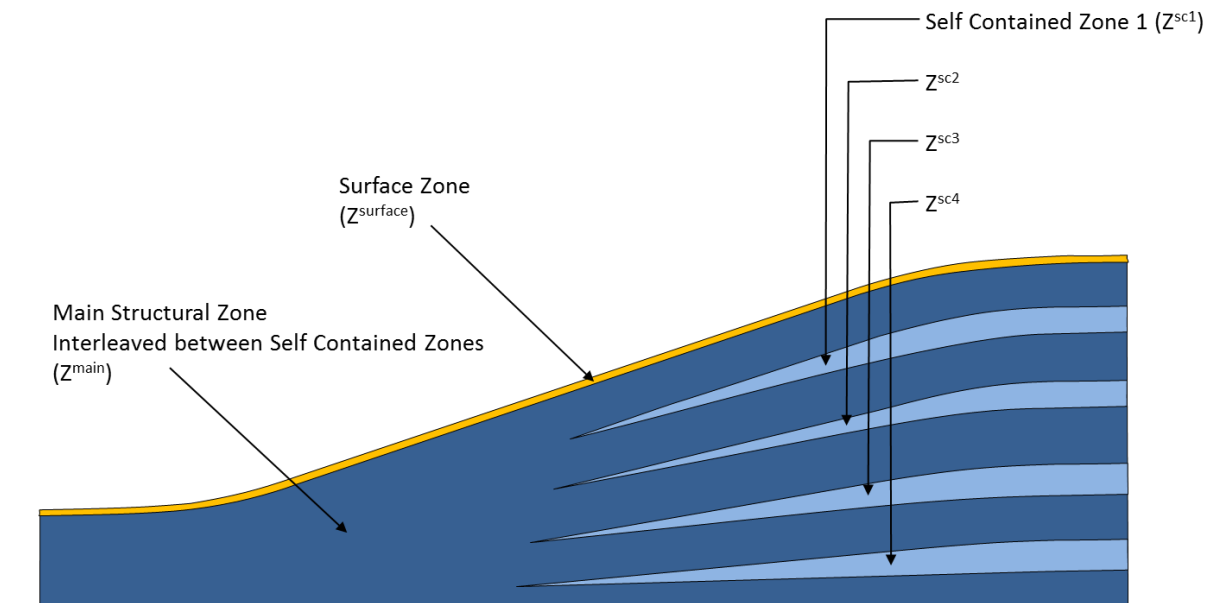


Figure 1 Plybook zone definition

2.2 Ply shape creation

A number of CAD solutions are available that help with composite definition, such as FiberSim and CATIA Composite Part Design (CPD). These software solutions offer tools that fill closed volumes automatically. However these solutions do not currently allow the filling of closed volumes with multiple CPT values, and are not compatible with zone based definition described in 2.1 without manual intervention. Therefore ply shapes need to be constructed manually using surface and wireframe based CAD techniques.

For a given self-contained zone, an extended zone outer surface $Z^{sc1}S^a$ is created, which is offset by the CPT for the chosen material. The number of offset surfaces is calculated by dividing the maximum thickness of the zone, divided by the material CPT and rounded to the nearest whole ply. The offset surfaces are intersected with the zone inner surface $Z^{sc1}S^b$. The resulting intersection curves are projected onto surface $Z^{sc1}S^a$ using a surface normal or perpendicular to surface function. This process is repeated for each of the remaining self-contained zones.

For a zone that is interleaved between other zones, the process is slightly different. To create ply shapes for an interleaved ply zone, the zone extended outer surface $Z^{main}S^a$ is offset by the required CPT. The required number of offset surfaces can then be determined by the maximum thickness of the plybook divided by the CPT, minus the number of plies already defined in interleaved self contained zones. The offset surfaces are then intersected with the zone extended inner surface $Z^{main}S^b$. The intersection curves are projected perpendicularly onto the $Z^{main}S^a$ surface.

At this stage of the process it is crucial that the ply shape curves are projected on to the self-contained zones surfaces $Z^{scn}S^a$ before being projected on to the $Z^{main}S^a$. This is important to

enable interleaving of the main zone between each of the self-contained zones. An overview of the process is shown in FIGURE 2.

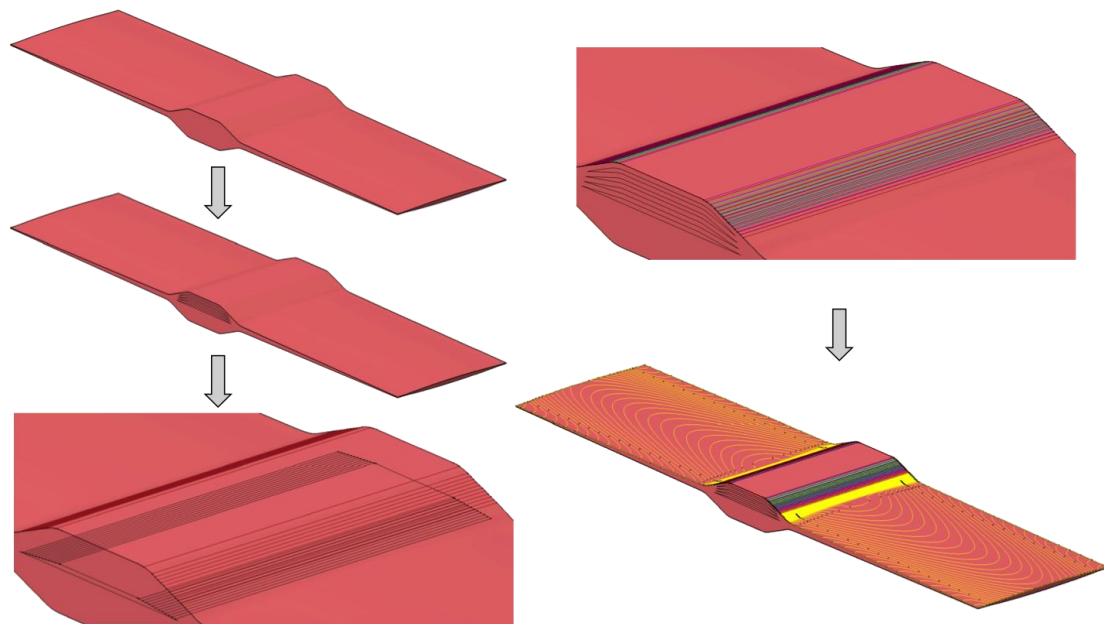


Figure 2 Plyshape creation process

2.3 Ply Definition

The ply definition process turns wireframe geometry, representing the contours of each ply, into a full CAD plybook laminate definition.

Laminate properties are defined at the start of the process. The materials, and their allowable orientations are set, the rosette system is created, the main edge of part created, a tool surface selected and the drape direction defined. Once these parameters have been created, the plies can be created automatically. The created plies will have a sequence number, a ply boundary, material, rosette and orientation attributes applied. This process creates ply shapes that are based on the tool surface boundary. The plies are trimmed in the following operation using the wireframe geometry created in section 2.2.

2.3.1 Ply Trimming

A laminate definition, with all the design information to enable analysis and manufacture, such stacking sequence, ply orientations, and volume fill, needs to have ply shapes that reflect the wireframe geometry created in 2.2.

Wireframe geometry only defines the shape of each of the plies. To be able to create a laminate, the individual plies need trimming to the wireframe geometry. Trimmed plies can be restacked, re-orientated, and checked to ensure an accurate fill of the volume has been created.

2.3.2 Ply Positioning, Re-Stacking and Re-Orientation

The plies are grouped by zone following the operation described in 2.3.1. A majority of zones are not in the correct position through the thickness of the laminate, only the outer surface

zones and the main structural interleaved zone are correctly positioned. Therefore the self-contained zones are positioned to the correct point in the laminate stack by exporting the ply table out of the software and into a spreadsheet, manipulating the ply order and then reimporting the ply table to update the laminate.

The outermost self-contained zone (Z^{sc1}) is moved to the correct position in the stack. This is repeated for the following self-contained zones, see FIGURE 3.

When all the zones are positioned correctly, local areas are restacked and re-orientated, to achieve the desired material performance and to improve the damage tolerance of the part. Each self-contained zone is restacked and re-orientated to the chosen stacking sequence. In this study the restacking and reorientation operation was done by exporting the ply table to a spreadsheet, where the ply drop pattern was applied (see FIGURE 4), and reimported into the plybook.

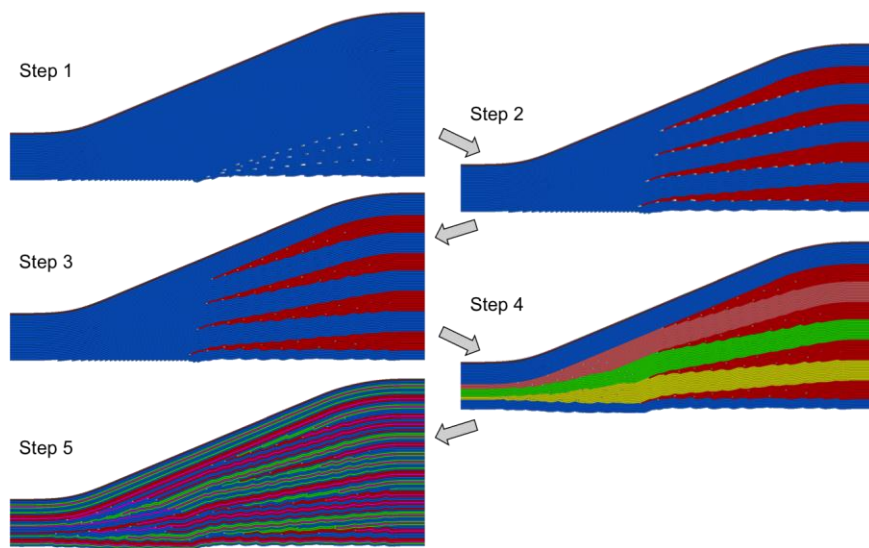


Figure 3 Restacking and re-orientation

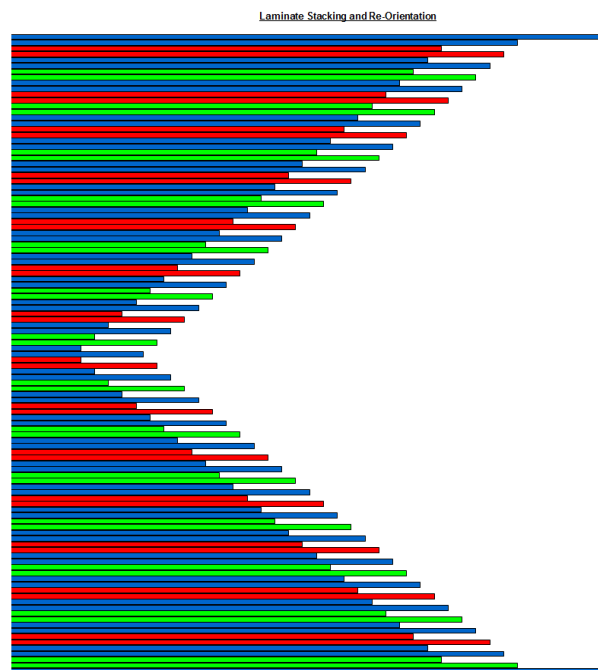


Figure 4 Laminate Stacking Sequence and Orientations – One zone only

2.3.3 Edge of Part definition

In the final stage of the definition process, material excess may be required for each ply in order to aid manufacture, however this may be different from ply to ply. The excess is only added when the ply reaches the edge of the moulded geometry definition. For each ply the appropriate preforming MEOP and EEOP is added. The preform excess defined by the preform MEOP is trimmed prior to the moulding process, to the moulding MEOP. MEOP's and EEOP's lie on the moulded surface defined in the composite parameters dialog box.

The following operations check the laminate against the targets and export the data in a format compatible with manufacturing operations.

3. Validation

A number of techniques have been developed to check that the laminate definition is achieving the requirements and rules set out at the start of the design process. These techniques vary, depending upon which objective is being checked.

3.1 Inner Mould Line (IML)

The IML is used to check if the laminate has correctly filled the closed volume. The IML is a surface that represents the top of the laminate stack. For the laminate of an individual zone to successfully pass the IML check, the IML should be within one ply thickness of the Zone B Surface (Z^b). If the check is for a complete closed volume, the IML should be within one ply thickness of the surface opposite the main tool surface (S^b).

3.2 Core Samples

Core samples are run on the final laminate as a check of compliance against the laminate targets and rules.

A core sample is an analysis of the laminate stacking sequence at any perpendicular line through the part defined by a point on the part surface. These are used to check that the laminate is obeying the defined rules; material properties can be calculated at any location. The output is a ply table viewable in a spreadsheet. Spreadsheets can be setup to automatically detect non-compliance to the rules listed in section 2, or report statistics on the level of compliance against each rule. Non-compliance against the targets can be easily rectified in the laminate definition and the core samples re-generated.

Post processing of the core samples allows for many different ways to analyse data. Classical Laminate Theory (CLT) can be used to generate material properties for each core sample, which in turn can be used within structural analyses. Adherence to the target orientation percentages can be displayed as two ringed pie charts, to easily visualise how successful the laminate re-stacking operation has been.

Typical processed core samples results are shown in FIGURE 5. The results show a good compliance to the target orientations.

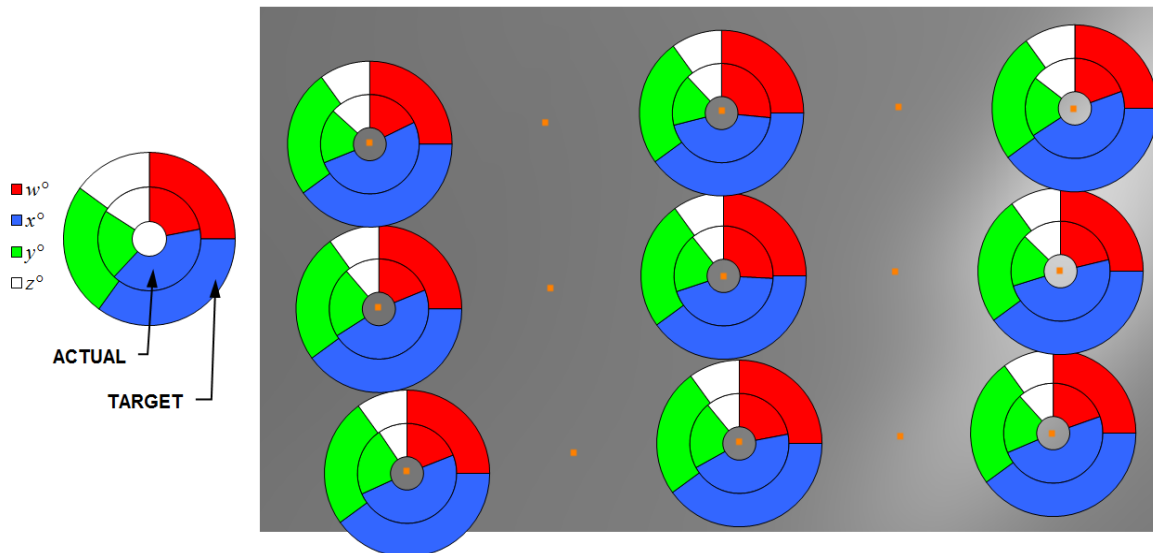


Figure 5 Core Sample Results

The core samples have been used to statistically analyse the resulting orientation percentages against the targets. In this example, the average deviation from the orientation percentage target is 2.66% with a Standard Deviation 3.35.

3.3 Ply Sections

Another useful technique is the use of ply sections. Ply sections don't produce any numerical data that can be analysed, however they do help to visualise the laminate. This can alert the definer to areas of poor fill of the closed volume, and to check the proximity of ply drops. They can also be used to help validate a laminate, by comparing the design intent to cut up parts. This can be seen in **Error! Reference source not found.**

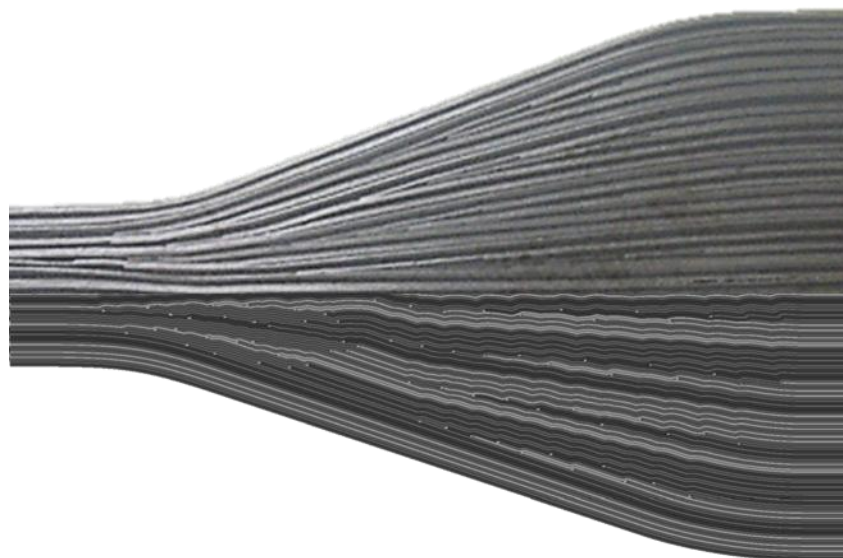


Figure 6 Actual Part (top) CAD Image (bottom)

Ply sections can be used to validate the finished laminate. In the example above, specimens suffered from under fill of the volume, and laminate wrinkling. Ply sections were used to understand differences between the definition and the as laid part. By measuring the length of plies in the CAD ply section, and then comparing it to the same dimension on the 2D flattened profile, a discrepancy was found. This was traced to incorrect algorithms be used to develop

the 2D flattened profile. Plies on subsequent laminates used a different method to develop the 2D patterns. The resulting laminate was wrinkle free, and filled the volume correctly.

3.4 Ply Surfaces

If a surface for each ply in its formed 3D position is required, a 'Ply Surface' or 'Ply Explode' can be performed. This is particularly useful for the automated methods of manufacture. They can also be used to verify if a laminate correctly fills the desired moulded definition. Each generated surface is a tessellated mesh that takes account of the plies beneath it, and therefore drapes over ply drop features.

4. Conclusion

It has been demonstrated that detailed CAD based laminate definitions can be produced for complex closed volume geometry. With the design methods described, it is possible to create laminate definitions, which obey laminate definition rules that can be analysed and be manufactured.

The laminate of the specimen described in [3] has been validated. The volume has been filled very accurately, resulting in a high quality laminate, with very low levels of fibre waviness, and good consolidation with low levels of porosity. The definition obeys the laminate requirements.

References

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