

New Standards Based Data Exchange “Bridge” For Design (CAD), Analysis (CAE) And Manufacturing (CAM) Of Composite Structures

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ABSTRACT

ISO/STEP Standards are providing international product data exchange models and versioning procedures for the purpose of capturing and sharing more complete enterprise-wide design, analysis and manufacturing data. In particular, the STEP AP209 Standard (presently at Draft International Standard (DIS) status) is focused on the product design and analysis (simulation) disciplines, and provides for data exchanges that include:

- design geometry, with its associated configuration management (CM) data
- idealized geometry, with its associated detailed finite element models and analysis results (FEM/FEA), including associated analysis version control data and critical associations back to the parent design geometry and CM data
- composite material design and analysis details such as ply and zone shape geometry, ply laminate table stacking sequences, zone laminate percentage ply tables, composite analysis material models, and ply layer analysis results (i.e., “material structure-inside-a-structure” detailed definitions)

The benefits of AP209 over current practices are improved quality of the data exchange, automation (speed), and cost sharing via ISO Standard’s collaborations between partners and suppliers.

LMTAS has selected AP209 as a preferred approach for the integration of CAD, CAM and CAE software tools (in particular MSC/PATRAN&NASTRAN, CDT/FiberSIM, and Dassault Systemes CATIA) to meet its composite structural design and analysis process requirements. LMTAS has defined a pilot production implementation scenario, which will be used to demonstrate the robustness and completeness of this multi-discipline dynamic data exchange process, using AP209. This paper documents the role MSC/PATRAN will play in this industrial scenario demonstration, using new product features which have been added to MSC/PATRAN to meet this next generation CAD/CAM/CAE composite structures integrated process.

Introduction

Production processes for composite laminated structural components require comprehensive definitions of complex composite architecture details. These “material structure-inside-a-structure” detailed definitions must not only conform to a component’s design requirements and constraints including such factors as geometric, weight, cost, and performance, but the definitions must also conform to a unique set of manufacturing requirements and constraints associated with composite material fabrication processes. Incorporating composite materials into a component’s design introduces unique production process issues that must be considered:

- Composite architectures can be defined that appear to satisfy all design requirements and constraints, but when fabricated the component exhibits unacceptable processing distortions and/or weak interstitial ply-to-ply load paths which result in degraded structural performance.
- Several complex composite architectures may be required to completely define a component’s design details. This can lead to extensive and complex geometric and material data definition requirements for composite constituents such as ply shape, ply thickness, ply fiber orientations, laminate ply stacking sequences. Imprecise definition of composite constituents can easily lead to data miscommunication between the design and manufacturing disciplines resulting in an incorrectly fabricated part.
- Composite architectures can be defined that in fact can not be fabricated as designed due too severely distorted fiber orientations distorted by factors such as fabric scissoring and wrinkling caused by draping the fabric over a component’s specific curved surface shapes.

Robust best-practices composite component production processes must account for the coupled requirements and constraints of design (CAD), analytical simulation (CAE) and manufacturing (CAM) disciplines, which means these processes must have a multi-discipline standardized data exchange mechanism. Such a mechanism exists today within the STEP AP209 Standard. AP209’s data model (schema) can capture a composite component’s unique composite material details in a manner that is completely, unambiguously and accurately understood by the varying user viewpoints of each of the above disciplines. A major benefit to the designer/analyst is the ability to share and re-use product data between their views.

The required level of composite architecture detail to be captured and exchanged is dependent on the discipline, as well as the specific task within the discipline. The following typical use-case scenario examples are provided to illustrate this point, and to provide a basis for the remaining topics presented in this paper:

- “Designer” may require a laminate’s in-depth thickness definition in a panel’s attachment region (zone) to define appropriate fastener details (i.e., length, thread length, etc.). For this, the designer would merely need to access a laminate stacking sequence table associated with that zone, and then, by

summing up the individual ply (lamina) thicknesses defined in the table, a total laminate thickness could be evaluated.

- “Analyst” may require an entire composite panel’s varying in-depth laminate definition in order to evaluate smeared composite material properties for a finite element analysis simulation. For this, the analyst would need a component’s shape definition and topology of all zones having varying laminate definitions, and each zone’s associated thickness laminate table (table also contains each ply’s fiber orientation definition). Then, using Lamination Theory, smeared composite material properties for each zone’s laminate definition could be evaluated and applied to the finite element model elements associated with (i.e., lying within) each zone’s edge shape definition.
- “Fabricator” may require actual geometric shape, stacking sequence and orientations for all plies associated with the laminated panel simulated by the analyst above using a laminate zone representation. Using “plies-derived-from-zones” and “optimized stacking sequence” composite software tools, individual ply shapes can be defined, which can then be cut to shape, oriented and stacked in accordance with the analyst’s required laminate composite definition.

What these use-case scenario examples are meant to illustrate is the critical need to capture composite architecture details in a variety of ways (laminate tables (zone and ply), “idealized” zone shape, “design” ply shape, etc.), in order to support the overall production process requirements for composite structural component design and fabrication.

Using a LMTAS defined composite structure pilot production implementation scenario, the remaining sections of this paper present a next generation integrated CAD/CAE/CAM composite structures design process, built around STEP AP209’s Standard and MSC/PATRAN’s new composites simulation software toolkit.

LMTAS Pilot Composite Structures Production Scenario

The planned LMTAS demonstration scenario is illustrated in Figure 1, with those software interfaces still to be developed noted by dashed lines (CATIA has commercial STEP AP203 part shape translators (which uses the same geometry as AP209), and CDT has based its FiberSIM internal data structure, in some part, on AP209, so a CATIA/FiberSIM AP209 CAD/CAM interface for this demonstration, although pending, should be forthcoming).

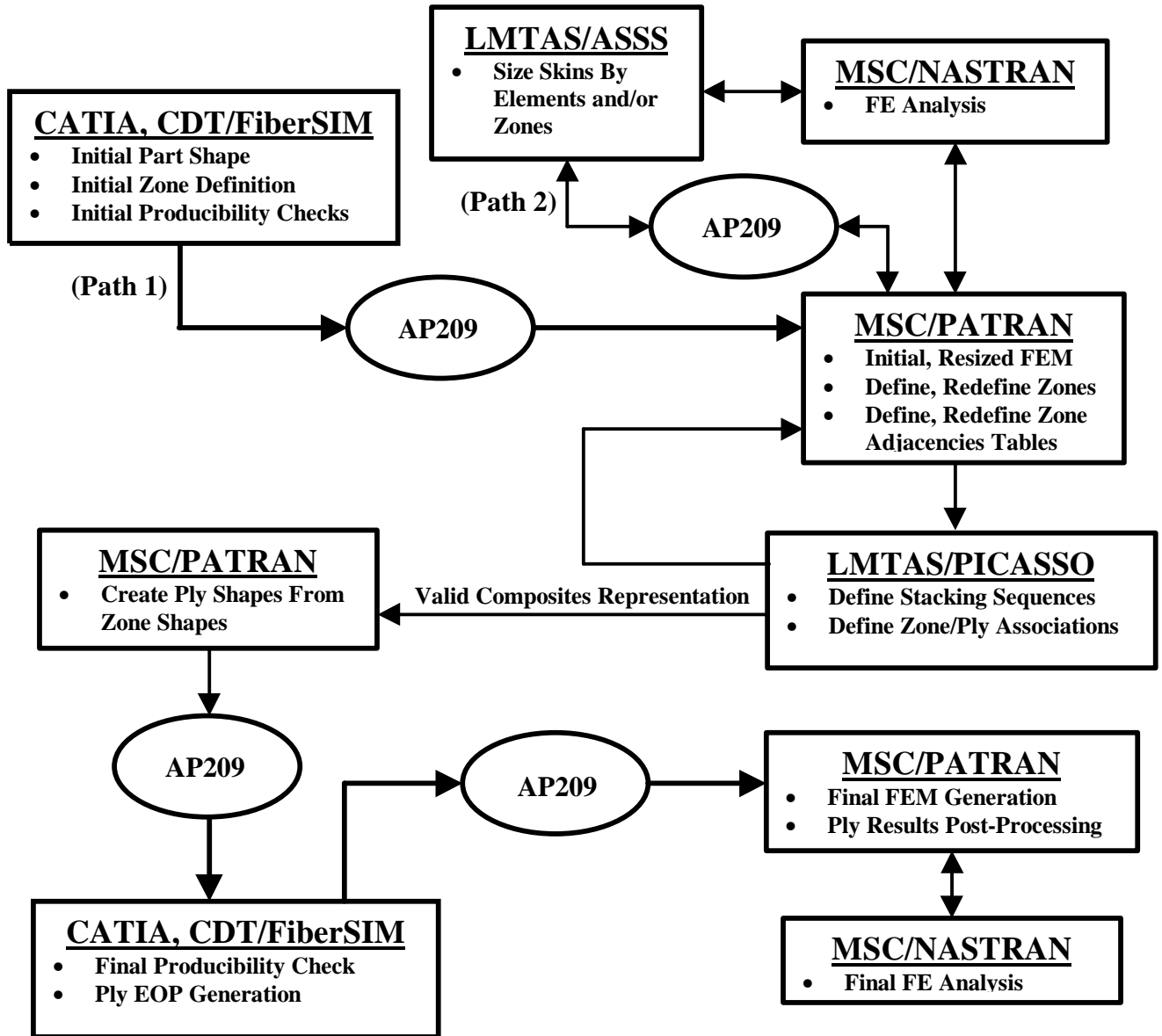


Figure 1. LMTAS Composite Structures Pilot Production Implementation Scenario

The LMTAS production process will start in CATIA with the creation of the initial part and zone shapes, at which time an initial producibility check is done using FiberSIM, which works directly within the CAD environment (predominate industry scenarios start with ply definitions directly). The shape and zone information will be transferred to MSC/PATRAN via STEP AP209. MSC/PATRAN has been extended to retain the requisite composite structure and shape information based on the AP209 ARM schema. Figure 2 illustrates the composites' data objects and relationships required for the LMTAS process to be automated between the commercial and LMTAS proprietary software tools illustrated in Figure 1. A more detailed presentation of these data

requirements, as they are defined within the AP209 ARM schema, is presented in the next section.

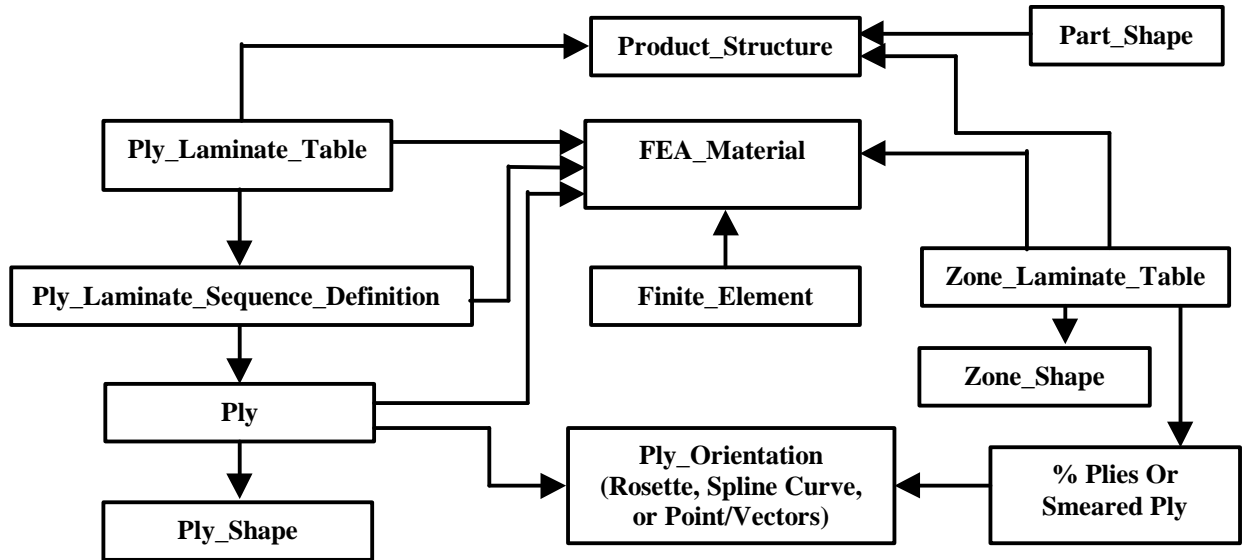


Figure 2. Composites Information Required To Support Figure 1 Scenario

With the part shape and composite zone information imported into MSC/PATRAN, a finite element model will be created and the analysis performed in MSC/NASTRAN. Then a LMTAS sequential sizing procedure that is tightly coupled with MSC/NASTRAN and proprietary LMTAS detail analysis tools will be used to optimize the composite design.

There are now two ways that zone information will be updated. The first is if zone shapes were already created either in CATIA/FiberSIM (Path 1 in Figure 1) or MSC/PATRAN, in which case they will then be updated based directly on the MSC/NASTRAN FEA results. The second case is when the zones are created a priori in PATRAN based upon the results of optimizations completed in LMTAS/ASSS (Path 2 in Figure 1). Then, within MSC/PATRAN, the following composite architecture details will be defined for subsequent input to the LMTAS/PICASSO code:

- Thickness and ply percentages translated into discrete ply type numbers required for each zone
- Zone adjacencies table

PICASSO¹ stands for Panel Integrated Computer Aided Stacking Sequence Optimizer. To understand the purpose of PICASSO, it is necessary to look at the composite aircraft design process as a whole. The process starts with an educated guess of what the plan-form of the aircraft should look like, such as illustrated in Figure 3.

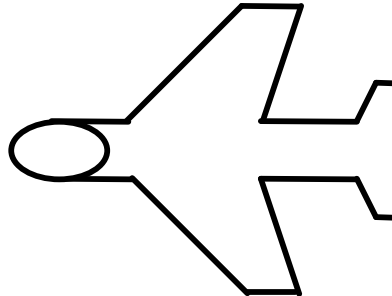
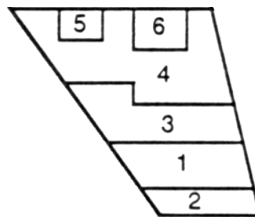


Figure 3. Aircraft Plan-form

Stress and/or aeroelastic codes are used to tailor the shape, material properties and thickness distribution of the laminates of interest. The laminates may be associated with a wing, fuselage, empennage or interior structure. Material properties are controlled by changing the proportions (or percentages) of 0°, 45°, -45°, and 90° laminas. Thickness and ply percentages can be translated to discrete ply type numbers required for each zone. Zone identifiers and ply percentages for a simple wing are shown in Figure 4. The translation of thickness and ply percentage to discrete ply type numbers is shown in Figure 5. The zone summary data in Figure 5, coupled with a zone adjacency table, represent input requirements for the PICASSO code.



<u>ZONE</u>	<u>THICKNESS</u>	<u>%0°</u>	<u>%45°</u>	<u>%-45°</u>	<u>%90°</u>
1	.176	37.5	25	25	12.5
2	.198	33.3	22.2	22.2	22.2
3	.209	36.8	26.3	26.3	10.5
4	.242	31.8	27.3	27.3	13.6
5	.286	34.6	26.9	26.9	11.5
6	.286	34.6	26.9	26.9	11.5

Figure 4. Zone Identifiers, Thicknesses, and Ply Percentages for a Wing

<u>Ply Percentages</u>	<u>Zone 1 Ply Type Numbers</u>	
%0° = 37.5%	nply0° = .088*37.5/(.0055*100) = 6	Ply thickness = .0055
%45° = 25%	nply45° = .088*25/(.0055*100) = 4	
%-45° = 25%	nply-45° = .088*25/(.0055*100) = 4	
%90° = 12.5%	nply90° = .088*12.5/(.0055*100) = 2	

<u>ZONE</u>	<u>TOTAL PLIES</u>	<u>0°</u>	<u>45°</u>	<u>-45°</u>	<u>90°</u>
1	32	12	8	8	4
2	36	12	8	8	8
3	38	14	10	10	4
4	44	14	12	12	6
5	52	18	14	14	6
6	52	18	14	14	6

Figure 5. Translation of Ply Percentages to Ply Type Numbers for Zone 1, and Ply Type Numbers for the Entire Wing

In order to build the laminate, the exact stacking sequence needs to be found. The manufacturer needs to know the order in which to lay up the plies. The order will determine the laminate's stiffness and durability. The present method is to use heuristic rules to find acceptable stacking sequences. One rule says that no more than two plies of the same type will be stacked consecutively. Another rule says that a 0° ply and 90° ply must not be stacked consecutively. Also, where two or more zones with different ply type numbers are adjacent, a rule says that the plies that the zones have in common must be continuous. This rule is necessary to prevent weakness at the boundaries of the zones. When the order of plies in each zone and the connection of continuous plies to adjacent zones are defined, the manufacturer has a definition of each ply in the laminate (its shape, stacking order, and type). The definition of plies for the wing is shown in Figure 6.

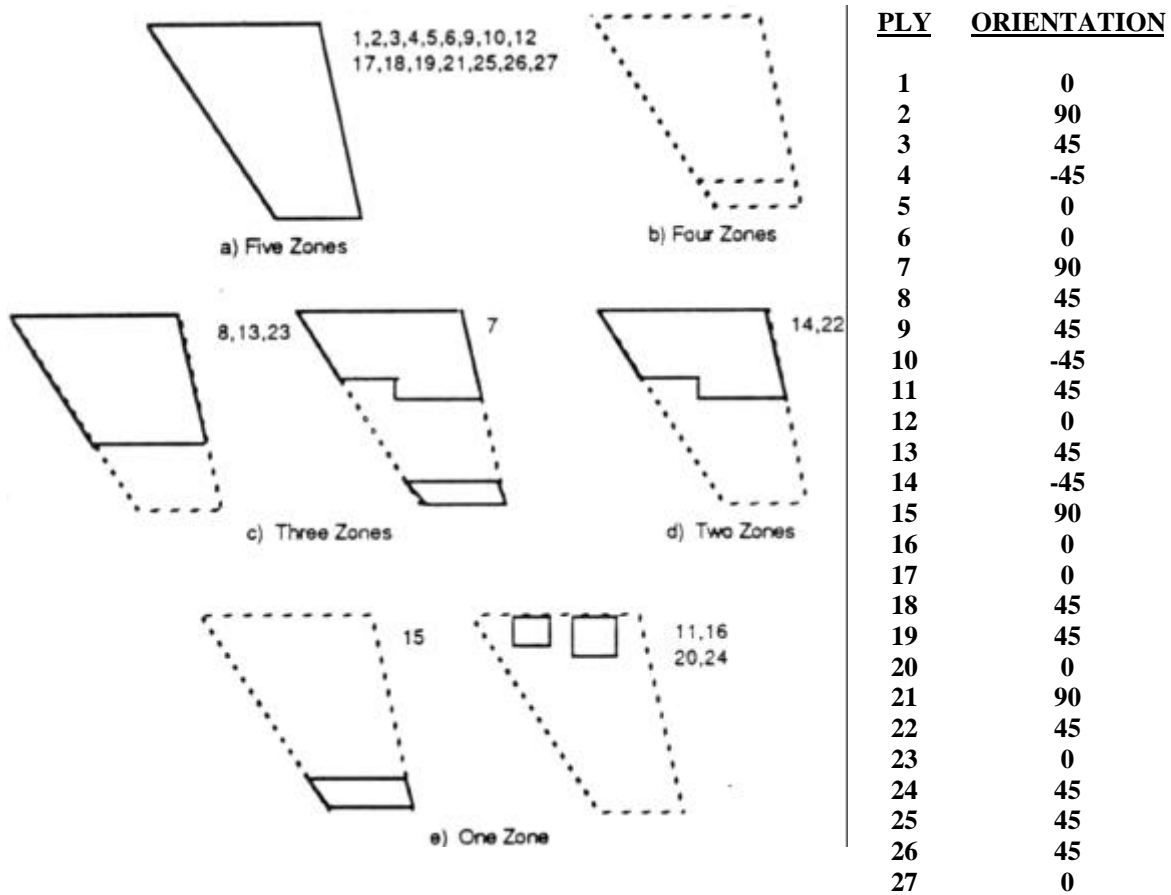


Figure 6. Geometry of Actual Plies in the Laminate, and the Stacking Sequence for Half of the Symmetric Laminate

The task of creating an exact stacking sequence from discrete ply type numbers and adjacent zones is completed in PICASSO. This software tool starts by generating a stacking sequence for a sub-laminate of the plies that cover all zones in the laminate. The sub-laminate for the example problem is shown in Figure 6a. The program then shuffles the plies that cover four zones. For the example problem, there are no plies covering four zones, so the plies covering three zones, shown in Figure 6c, are shuffled in.

Using the AP209 data structures, MSCPATRAN will then take the zone adjacency tables and the PICASSO defined stacking sequences to create the ply tables and individual ply shapes. It is this information that will then be fed back to CATIA/FiberSIM via AP209 format. FiberSIM will then be used to perform the final producibility checks. Ply Edge of Plies (EOP) will be adjusted for practicality. Once the design has been finalized the ply tables and ply shapes, if necessary, will be transferred back to MSC/PATRAN via AP209. A final FEM will be generated (or zone-based one merely updated) and a final verification analysis will be performed with MSC/NASTRAN.

Key AP209 Data Model Entities and Relationships

AP209 provides critical multi-discipline data associations between design part versions and analysis versions, as illustrated in the Figure 7 (AP209 ARM Schema data model representations). As noted in Figure 7, the single key ARM entity **analysis_design_version_relationship** is used to link the CAD and CAE worlds.

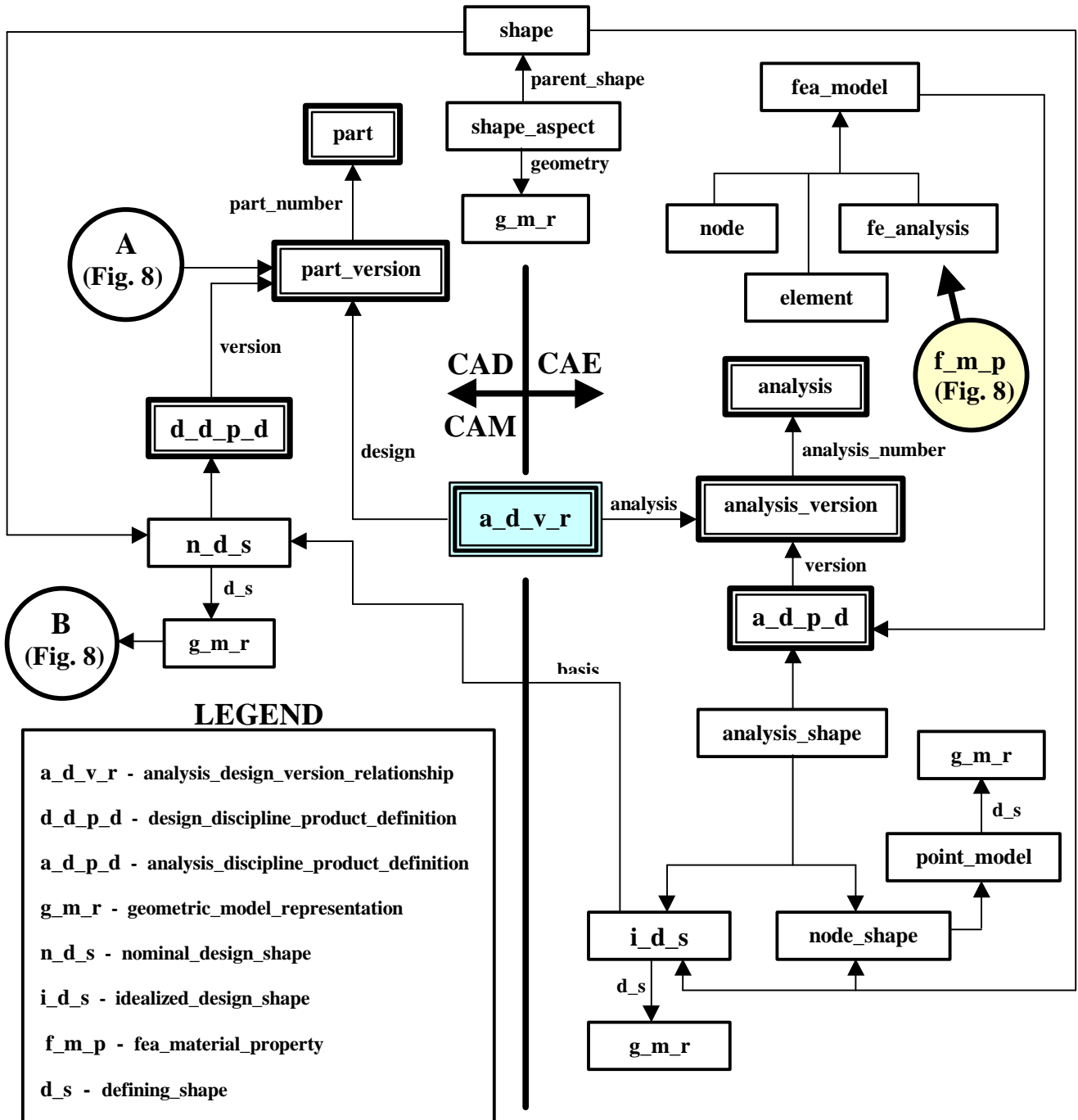


Figure 7. AP209 Data Model “Back-Bone” Linking The CAD And CAE Worlds

Configuration management between the design and analysis disciplines is assured with multiple analysis versions (each with their own **idealized_design_shape** and **fea_model**) associated with a specific part version and its **nominal_design_shape**. A significantly extended **design_discipline_product_definition** data model representation (A and B notations in Figure 7) is required to capture the complex and varying design views (plies, zones, etc.) associated with composite structural details, typical of those to be demonstrated in the LMTAS pilot production scenario. Figure 8 illustrates these extended data model requirements, many of which have been captured in a new MSC/PATRAN database implementation. These are discussed in more detail in the next section.

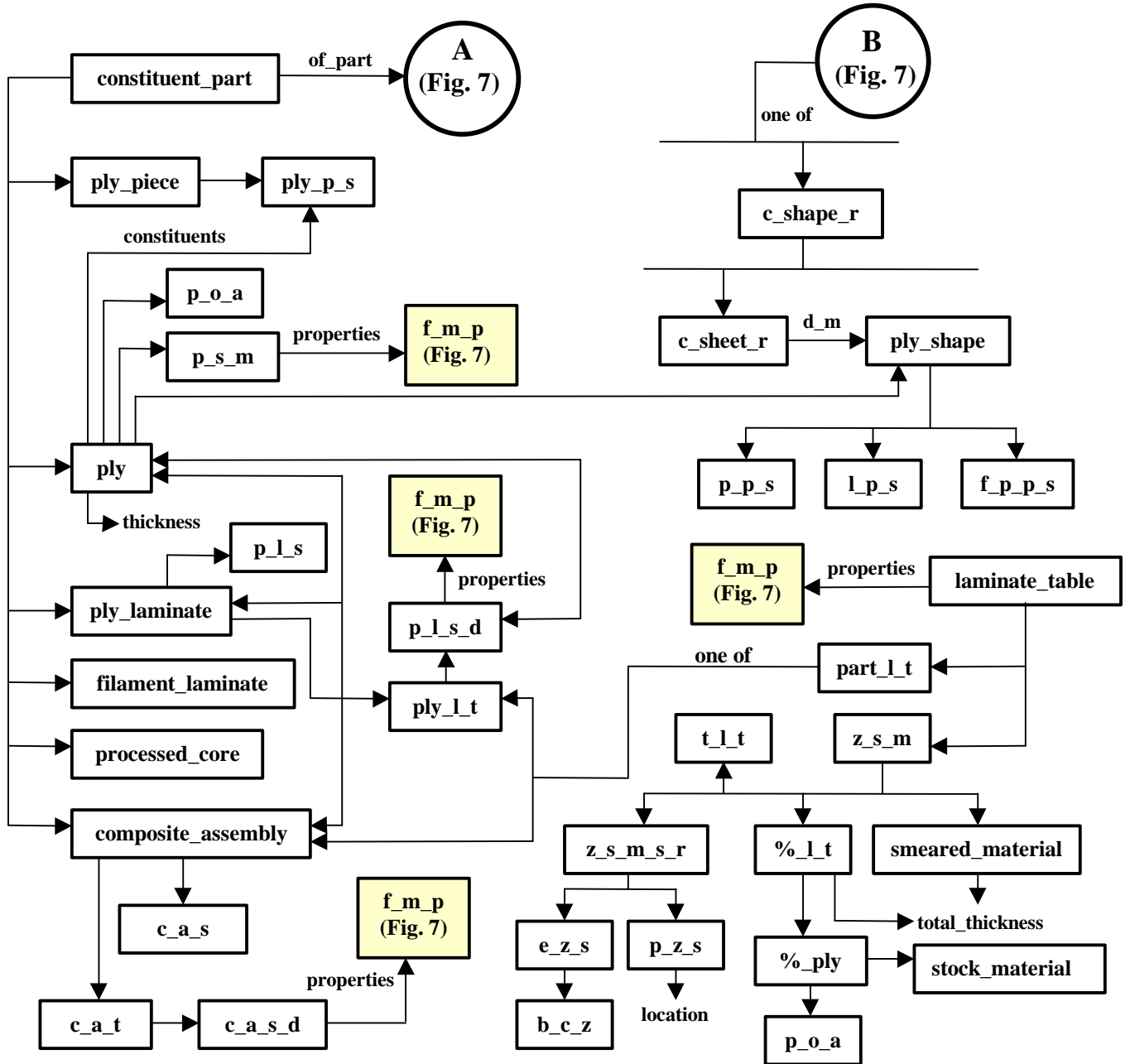


Figure 8 AP209 Composites Data Model Entities And Relationships

Figure 8 LEGEND

<p>ply_p_s - ply_piece_shape</p> <p>p_o_a - ply_orientation_angle</p> <p>p_s_m - ply_stock_material</p> <p>p_l_s - ply_laminate_shape</p> <p>ply_l_t - ply_laminate_table</p> <p>p_l_s_d - ply_laminate_sequence_definition</p> <p>p_p_s - projected_ply_shape</p> <p>l_p_s - laid_ply_shape</p> <p>f_p_p_s - flat_pattern_ply_shape</p> <p>part_l_t - part_laminate_table</p> <p>c_shape_r - composite_shape_representation</p> <p>c_sheet_r - composite_sheet_representation</p>	<p>c_a_s - composite_assembly_shape</p> <p>c_a_t - composite_assembly_table</p> <p>c_a_s_d - composite_assembly_sequence_definition</p> <p>z_s_m - zone_structural_makeup</p> <p>%_l_t - percentage_laminate_table</p> <p>t_l_t - thickness_laminate_table</p> <p>%_ply - percentage_ply</p> <p>z_s_m_s_r - zone_structural_makeup_shape_representation</p> <p>e_z_s - edge_zone_shape</p> <p>p_z_s - point_zone_shape</p> <p>d_m - defining_model</p> <p>b_c_z - boundary_curve_zones</p>
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A composite part is made of constituents that are laminated in layers to create a part. AP209 provides specialized product definitions to represent the structural makeup and properties of composite parts. Ply, processed core, and filament laminate are the basic constituents in composite parts. A ply laminate is a composite part comprised of layers of or sequences of plies. A composite assembly is also constructed in layers, except that a composite assembly may have sequences of constituents other than plies, such as core (sandwich panels) and may contain ply laminates and other composite assemblies as constituents.

A laminate table describes the structural makeup of a composite part. The laminate table may describe allocation of the physical constituents for the overall laminate (part laminate table), or for a particular zone area, or point on the part (zone structural makeup). The part laminate table is called the ply laminate table for a ply laminate part, and the composite assembly table for a composite assembly part. Examples of zone structural makeup are thickness laminate tables or percentage laminate tables (illustrated previously in Figure 4). A smeared material definition is a special case of zone structural makeup representation, where all the composite constituents across the thickness are lumped together in accordance with Lamination Theory.

Associated with each laminate table is a shape representation for the base surface of the composite part with an identified material side. A laminate table is also characterized by a reinforcement orientation basis (rosette). Entities are provided to relate the

reinforcement orientation basis to the corresponding orientation representations for each ply or composite constituent in the table.

The material properties to be used in the finite element analysis of a composite part may be specified by associating the overall properties to the laminate table. To this end, a fea_material_property relationship entity is used to relate the material property representation to the product definition for the laminate table.

AP209 Composites Support in MSC/PATRAN

Existing MSC/PATRAN AP209 import/export translators, that already supported the exchange of configuration management, geometry, FEM and FEA data, have been extended to include AP209 data model representations for composites. The MSC/PATRAN database has been extended to support the storage of the required composite data in an efficient manner. Finally, a Composites Toolkit Graphical User Interface (GUI) has been developed to support composite structure design processes, and subsequent AP209 data exchange requirements between the design (CAD), analysis (CAE) and manufacturing (CAM) disciplines.

MSC/PATRAN Database Extensions

Additional MSC/PATRAN database entities that support geometry based ply and zone information have been implemented as Client Data tables:

- laminate_table – definition of component laminate table
- reinforcement_orientation_basis – definition of orientation of a laminate table e.g., coordinate system aligned with axis of fuselage.
- ply_orientation_angle – angular orientation of a ply (angle only for now)
- ply_shape – definition of shape on surfaces for plies
 - AP209 – base surface with bounding curves
 - MSC/PATRAN – trimmed surfaces
- ply – ref. To one material id, orientation angle, thickness and ply shape id
- ply_laminate_sequence_definition – definition of a ply sequence (array)
- ply_laminate_table – definition of a ply laminate table
- part_laminate_table – definition of a part laminate table (initially only points to ply_laminate table)
- zone_shape – definition of shape on surfaces
- percentage_ply – definition of ply orientation and % by volume
- percentage_ply_table - definition of zones referencing %_ply's array
- smeared_material – ref. to PATRAN mid, total thickness, zone shape id
- select_table
- thickness_laminate_table
- processed_core
- zone
- composite_assembly

Note from Figure 8 that a laminate over a zone can be one or more of a thickness_laminate_table, percentage_laminate_table and smeared material. Percentage_laminate_table can be inferred from thickness_laminate_table, and smeared_material can be inferred from percentage_laminate_table.

With these additional database entities, the MSC/PATRAN database can store a full set of composites data in the following complementary ways:

- Properties (and referenced Laminate Materials), which is the existing MSC/PATRAN method for describing a composite model. This description is similar to the MSC/NASTRAN PCOMP data structure.
- Zones, which are fairly similar to properties except their way of defining application regions uses the CAD convention of bounding curves, and there are several different ways of describing the laminate material.
- Plies, which constitute the most detailed descriptions of the composite model. These will typically be generated only once the basic parameters of the model have been established.

MSC/PATRAN Composite Toolkit GUI

The new MSC/PATRAN composites manipulation tools allow the user to Create, Modify, Show and Delete AP209 composites information stored in the PATRAN database. These tools have a Graphical User Interface (GUI) implemented as standard MSC/PATRAN Action-Object-Method (AOM) forms which are accessed under the existing Tools menu. The initial set of tools described below is being developed to provide fundamental support for the LMTAS production scenario as shown in Figure 9. The toolkit will be extended in the future to provide support for additional customer requirements.

CAD/CAM

CAE

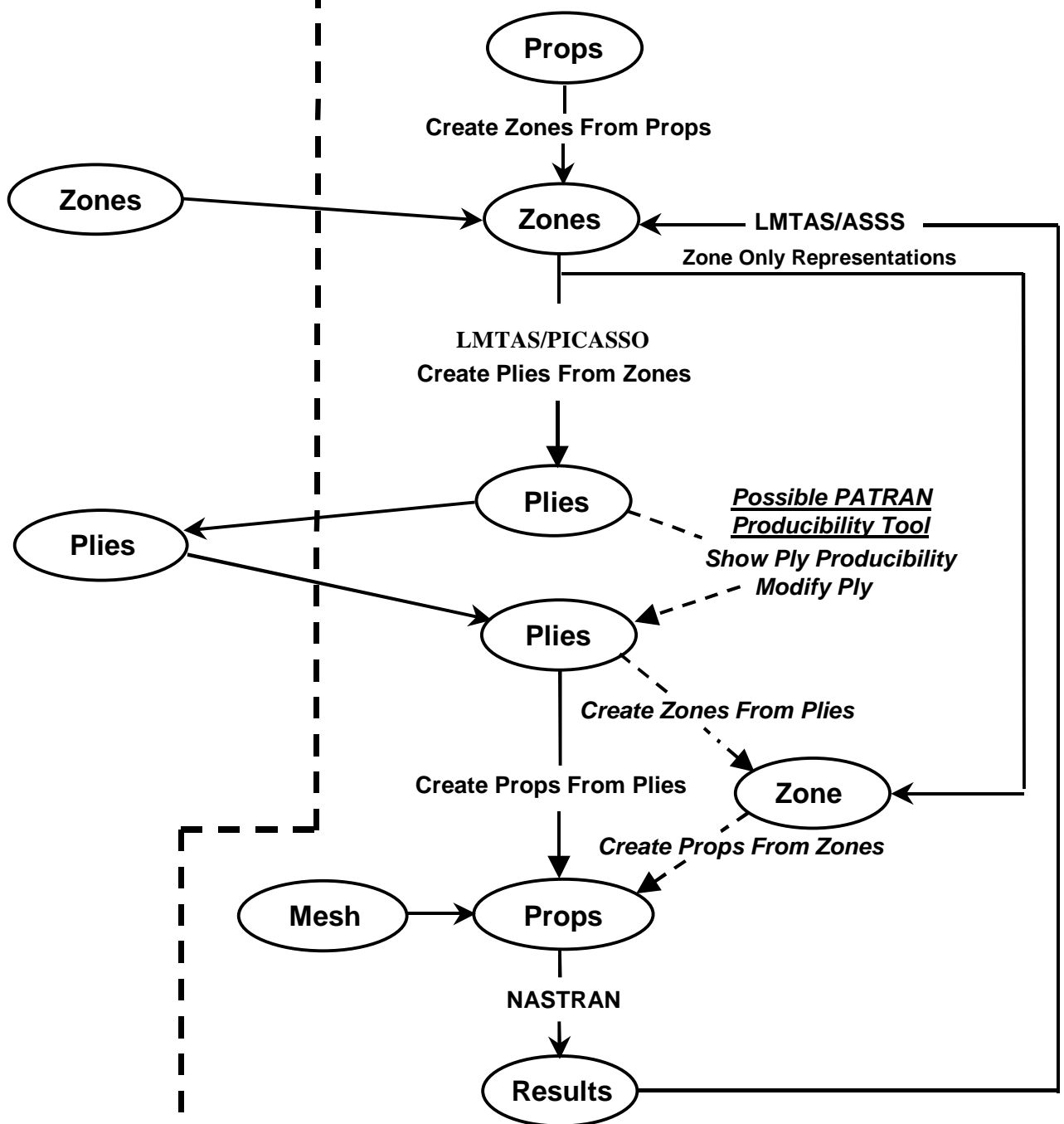


Figure 9 Data Flow Effected by Composites Tools

- **Create/Modify/Show/Delete Data**

The first set of tools simply provides a convenient mechanism to manually create, modify, show and delete the data in the database. By working seamlessly in the MSC/PATRAN environment, these tools provide a very efficient and familiar method of generating AP209 composites data.

- **Create Zones from Properties**

This tool converts standard MSC/PATRAN element property descriptions into AP209 zones. The FEM model could have been built in MSC/PATRAN, or have been generated through the import of an existing MSC/NASTRAN bulk data file. This ensures that existing models can be transferred easily to the new composites paradigm.

- **Create Plies from Zones**

This tool generates a ply description of a composite component starting from adjacent zones and the lay-up on each zone. These zones could have been defined manually within MSC/PATRAN, created using another composites tool, or imported from an AP209 file. The application region of the zones is defined using trimmed surfaces in the normal MSC/PATRAN manner. The tool uses existing MSC/PATRAN functionality for identifying surface neighbors to provide zone adjacency information for LMTAS/PICASSO. Based on LMTAS/PICASSO's output, it adds up the relevant surface edges to define ply boundary curves for each ply. These plies are then stored in the MSC/PATRAN database.

- **Create Properties from Plies**

This tool generates appropriate properties for each element directly from the plies. The general mode of operation is as follows:

1. The area covered by each ply is determined from the basis surface and boundary of each ply.
2. The warp and fill angles over the ply are generated through projection or via a producibility algorithm.
3. A piercing algorithm is used to determine whether the midpoint of each element lies on the ply (within angle and distance tolerances), and the ply angles and thicknesses are mapped onto the element.
4. Total lay-up on each element is determined after considering all plies in a `part_laminate_table`.
5. Minimum number of laminate materials and properties are generated to describe the lay-up within prescribed tolerances and saved to the MSC/PATRAN database.

Much of this functionality already existed in MSC's LAMINATE MODELER module, so this module was used as a basis for MSC/PATRAN's new Composites Tools development effort.

- **Show Ply Producibility**

This tool will allow the user to determine the producibility of a ply early on in the development scenario. Initially, this tool will use the MSC/PATRAN LAMINATE MODELER's present functionality to simulate the drape of fabric over a surface. Later, it will be possible to add other third-party producibility modules (e.g. CDT/FiberSIM) in the same user-interface to allow for the simulation of other manufacturing processes. This tool will also generate data defining the varying fiber directions over a surface if this is relevant (e.g. if the surface has double curvature).

- **Create Zones from Plies**

This tool is the inverse of the "create plies zones tool". The basic operation of the tool is as follows (illustrated in Figure 10):

1. Identify all unique ply edges.
2. Define intersections between unique edges and split at intersection point.
3. Hence define new zone boundaries.
4. Determine number of plies etc. within each zone.
5. Store zones to MSC/PATRAN database.

If the ply fiber angles vary continuously over a surface, such as in the case of sheared fabric covering a surface of compound curvature, then zones will be smaller than areas containing unique ply sequences, as the orientation will probably be varying at different rates for each ply. In this case, routines in LAMINATE MODELER will be used to identify zones based on orientation and thickness tolerances. If the trimmed surfaces defining zones are used to generate the finite element mesh, the elements will be aligned with the ply.

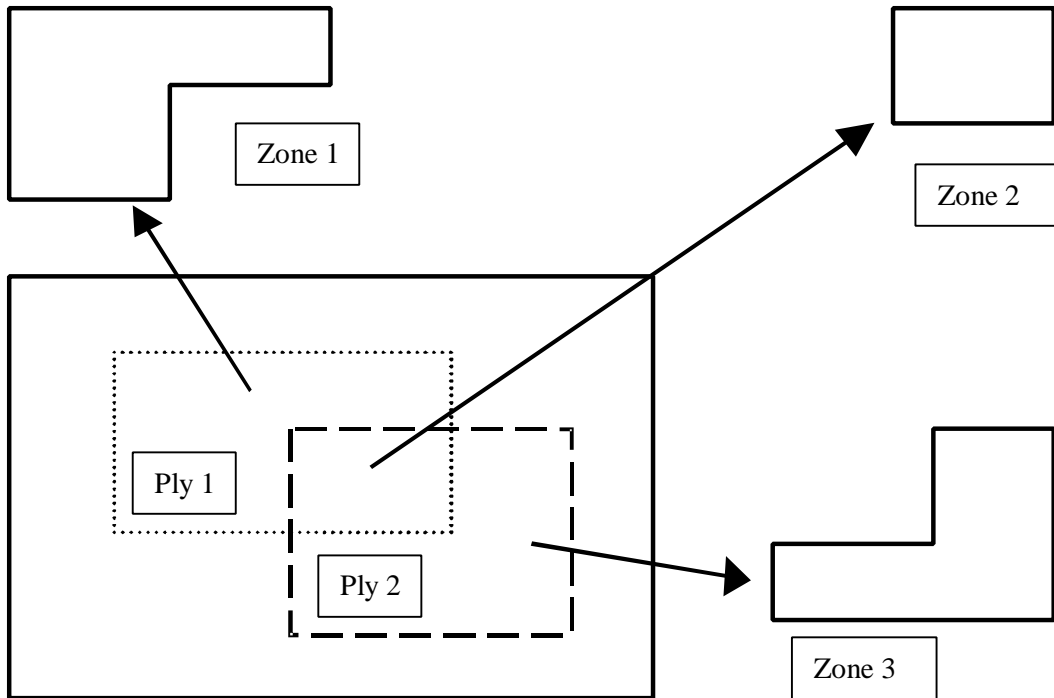


Figure 10. Aggregated Ply Shapes Converted to Zone Shapes

- **Create Properties from Zones**

This tool will generate the properties from the zone data. If the elements are associated with the trimmed surfaces defining the zones, creating properties from zones is a trivial matter of creating element properties directly. However, it may be that the mesh is not aligned with the zone boundaries. This may typically happen because the mesh is fixed at an early date in the project but ply boundaries are changed to allow inclusion of manufacturing details. In this case, a simple triangular mesh will be generated on each surface for manufacturing simulation. Then, all plies on the model will be mapped onto the analysis mesh by using a piercing algorithm. Finally, the properties in the zones will be mapped onto the mesh.

Conclusions

ISO/STEP/AP209 Standard is available today to improve current practices for the exchange and/or sharing of multi-discipline (CAD/CAM/CAE) composite structures data. This will provide significant benefits in cost savings, product quality and time to market for those companies that implement it into their current enterprise processes. LMTAS has graciously provided a representative pilot production process scenario, which through actual commercial software demonstrations will prove the benefits attainable by implementing AP209 into the composite structures design and manufacturing process.

MSC's strong corporate commitment to AP209 is demonstrated by its comprehensive import/export translators, the implementation of AP209's ARM composites data structures within its database coverage, and its new MSC/PATRAN Composites Tools functionality that takes full advantage of the substantial composites data model features of AP209 schema.

Acknowledgements

1. PDES, Inc., for AP209 development support and for its role as an industry consortium for establishing industrial requirements and acceptance.
2. Mike Henson, Lockheed Martin Tactical Aircraft Systems, for consultation.
3. NASTRAN is a registered trademark of NASA. MSC/NASTRAN is an enhanced, proprietary version developed and maintained by MacNeal Schwendler Corporation.
4. MSC/PATRAN is a registered trademark of the MacNeal Schwendler Corporation.
5. FiberSIM is a registered trademark of Composites Design Technologies Corporation.
6. CATIA is a registered trademark of Dassault Systemes.

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1. Wang, B.P., Twu, M.J., "Laminate Ply Stacking Sequence and Ply Termination Selection", 30th Structures, Structural Dynamics, and Materials Conference, pp 1200 - 1202, April 3-5, 1989

Abbreviations List

ISO, International Standards Organization

STEP, Standards for the Exchange of Product Model Data

AP, Application Protocol

ARM, Application Reference Model

FEM, Finite Element Model

FEA, Finite Element Analysis

CAD, Computer Aided Design

CAM, Computer Aided Manufacturing

CAE, Computer Aided Engineering

CDT, Composites Design Technologies

ASSS, Automated Sequential Sizing System