Recent Advances in Sharing Standardized Composite Structure Design and Manufacturing Information

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Abstract

Composite structures have been developed and used in the aerospace, automobile, sports, and marine industries since the early 1940s. Compared to conventional metallic structures, newer high-performance composite structures provide benefits such as decreased weight and reduced energy consumption. An international standards subcommittee on industrial automation systems and integration has developed and implemented a standard, ISO 10303-209, for sharing the manufacturing information for these complex composite structures. This standard is considered essential for improving the design, analysis, and manufacturing productivity of composite structures, and for enabling the long-term data retention necessary to support the composite structures throughout the lifetime of the products that use them. This paper describes recent advances that led to the development of ISO 10303-209 data models for composite structural shape and composition. The paper also reports the status of ongoing implementation efforts, including efforts to use this standard to support long-term data retention. The varied usage scenarios have motivated several areas for future improvement such as full three-dimensional representation and the efficient, cost-effective visualization of composite structural parts. Issues and their proposed solutions, along with their anticipated impacts on the design, analysis, manufacturing, and long-term support of composite structures are also discussed.

Keywords: *composite structures; data exchange; ISO 10303; AP209; long-term data retention; Standard for the Exchange of Product data; STEP*

1 Introduction

Sharing design and manufacturing information for composite structures has historically been a complex and software-tool dependent process. An open standards approach to sharing this information is now considered essential for enabling the interoperability of engineering systems for design and manufacturing of composite structures, thus minimizing the cost and increasing productivity.

ISO 10303, most commonly known as the Standard for Exchange of Product model data (STEP), is an international standard designed to exchange digital information of engineered products, enabling an ever-widening range of engineering software systems to interoperate [1-7]. Each software system has its own proprietary format for writing and storing data, making it nearly impossible for organizations using different systems to communicate product model data without translation. STEP, developed through the International Organization for Standardization (ISO) by a global consortium of technical experts from industry, governments, and academia, provides a robust neutral file format that has the potential to save approximately $1 billion (in 2001 dollars) per year by reducing interoperability problems in the automobile, aerospace, and shipbuilding industries alone [8]. This paper is concerned with the recent advances in STEP standard capabilities for representing composite structural shapes, internal structure, and materials.

Open standard ISO 10303-209, *Composite and metallic structural analysis and related design* (AP209) [9], is now considered essential for improving the design, analysis and manufacturing productivity of composite structures. The long-term retention of data needed to support a large number of increasingly complex composite structures throughout the lifetime of products that use them benefits from the use of an open standard. A brief manufacturing history of composite structures, the use of Computer Aided Design (CAD) for designing composite structures, and the content of the AP209 data models for composite structural shape and composition are presented in Section 2. Ongoing implementation efforts, including efforts to use this standard to support long-term retention, are discussed in Section 3. New usage scenarios have motivated further development of standard data models to support capabilities such as full 3D representation and the efficient, cost-effective visualization of composite structural parts. We discuss these issues and their proposed solutions in Section 4, along with their impact on the design, analysis, manufacturing, and long-term support of composite structures. Concluding remarks are made in Section 5.

2 Structural Design and Manufacturing using Composites

This paper is primarily concerned with layered composite structures where the layers, or plies, are some type of fiber in a matrix. These layers are generated using unidirectional tape or fiber tows (multiple strands of narrow tape), or bidirectional material such as fabric. The stacking of these plies, their geometric bounds, their material composition, and the orientation of the fibers in the plies are the primary constituents of a composite structure. There are many ways to specify these constituents. A standard approach for organizing, naming, and representing this information is the enabler that the STEP composites data model provides.

2.1 A Brief History of Composite Structures and their Manufacture

One of the earliest composite structures is commonly known as plywood. Plywood is composed of several layers of thin wood typically peeled from a log. Some of the layers may be a softer wood of lower strength that are used to space out the higher strength plies to make a flat sheet stronger and lighter. Sometimes, thin sheets of plywood are separated by a honeycomb core made of wood or fiber. This provides a very lightweight, stiff structure since the stronger face sheets (the top and bottom of the sandwich) are in the most efficient place structurally [10]. Many household and commercial doors are made in this manner.

The aerospace industry is continually searching for more efficient, lightweight structures. Some of the earliest aerospace composite structures were made of fiberglass fabrics with phenolic or polyester resins for a matrix. As time went on, higher strength epoxy resins were developed. Fiberglass is now commonly being replaced by much lighter, higher strength and stiffer carbon fibers [11, 12]. In the 1980s, five percent of aircraft components were composed of carbon fiber composites. In Boeing's new 787 Dreamliner, composites account for 50 percent of the plane's weight [12].

Many other fibers such as boron and silicon carbide have been used in niche applications such as the General Dynamics F-111 tail or radomes (structural domes that protects radar antenna). A very different composite manufacturing technique is based on carbon fiber-reinforced carbon (carbon-carbon), where the carbon fibers are set in a carbon matrix that is cured at extremely high temperatures. This process yields structures that can withstand extreme environments such as those found in a rocket exhaust nozzle.

The complexity and variety of composite structures and materials have resulted in the development of many different fabrication techniques. Hand layup of fabric and tows over inner or outer surface molds was the earliest manufacturing technique used, and it is still quite common today because it typically requires less capital investment and generates high laydown rates for products such as aircraft and boats. Matched molds with both inner and outer surfaces are also used. Chopper guns, where fibers are fed into a gun and combined with resin and sprayed onto a mold, are another mechanism to manufacture composite structures. Though convenient and relatively inexpensive, the short, random fibers compromise the strength of the resulting composite structure. Some examples of these structures are inexpensive sport automotive exterior panels and fairground rides [13-14].

There are also several examples of Computer Aided Manufacturing (CAM) of composite structures. Tape-laying machines allow the controlled application of fibers on a mold. This approach is widely used, but places limits on the amount of curvature that can be achieved in the surface of the structure. Automated fiber placement machines are a variant of the tape-laying machines that deposit multiple narrow tapes in a single pass. These machines are capable of building more highly contoured parts, but usually at the cost of lower laydown rates. Yet another variation is winding fiber tows or filaments around a tool, typically to generate roughly cylindrical structures such as golf clubs or ship masts. Weaving and braiding of fiber tows is a newer technique that is capable of creating complex, three-dimensional fiber pre-forms. These types of structures are commonly used to bond together items of a composite assembly such as aircraft floors and walls [13-14].

2.2 Computer Aided Design of Composite Structures

Early application of CAD to composite structures simply mimicked the conventions of manual 2-dimensional drawings. In these early systems, ply boundaries were typically represented in three projected views (plan, elevation, and side view). Occasionally a separate, often company specific, mathematical surface loft was used as a basis (or tooling) surface.

Once the 3-dimensional surface-based CAD applications were adopted, the industry moved to the current practice of using curve ply boundaries on a basis surface for composite structural representations. This is similar to the so-called ‘2½D’ geometric modeling, often found in the electronics industry, except for the fact that the base surface is curved instead of being flat. Initially larger companies developed internal applications customized to automate and standardize this practice within these companies. As time went on, CAD for composite structures became commercially available in software products such as Dassault Systemes’ CATIA Composites Workbench [15] and Siemens PLM’s (formerly Vistagy) Fibersim [16].

A typical CAD system for composite structures starts with creating a basis (tool) surface, which can be divided into one or many parts consisting of a series of plies (whose boundaries do not necessarily coincide) stacked into a laminate; or many zones consisting of plies (whose boundaries do coincide) defining that area of laminate of constant thickness within a part. Within each part or zone a laminate can be defined, either interactively or by importing from a pre-defined file. Each laminate can contain stacked plies and each ply contains fibers aligned in a particular direction. The laminates can also be stacked on top of each other. The CAD systems provide a rich set of graphical user interfaces to define geometric details about the fiber thickness, orientation, ply shape, and laminates that constitute the composite structure [17].

As discussed in section 4 of this paper, industry is now attempting to move forward with explicit three-dimensional solid representations of composite structures. Currently, this approach is not found to be practical due to the computational load of creating 3D models with the desired amount of detail, and because CAD authoring capabilities are not mature enough to adequately automate the creation of such solid models. These issues will be discussed further in Section 4 on future directions.

2.3 Evolution of a Standardized Data Model for Composite Structural Shape and Composition

The primary driver for using open standards to share information between composite structural design and composite manufacturing is that the open standards enable the data exchange and interoperability necessary for subcontracting manufacturing. Since CAD modules for composite structural design are quite expensive, savings may be realized by sharing the composite structural data in a neutral standardized format that can be read in lower-end

CAD systems, or in inexpensive low-cost visualization tools. Re-manufacture of composite parts at a later date, after the originating CAD software and associated composite structural design module is no longer a supported product, is another compelling business case for using open standards. As noted in Section 2.1, there are numerous techniques for creating composite structural parts. Which of these approaches are standardized, and how this was done is the subject of this section.

The first STEP standard for composite shape and structure was the 2001 Edition of AP209, ISO 10303-209:2001. In this Edition 1, composite structure definitions were integrated with both design and analysis (mostly finite element analysis) disciplines as shown in Figure 1.

The 2001 Edition of AP209 covers:

- Finite element data: This includes models, analysis definitions and load cases, and results. A model can be specified in as much detail as required - if necessary down to the level of element shape functions, discretization points and integration rules. Static and natural frequency analyses are within the initial scope.
- Configuration management data: A version of the finite element model is linked to a version of the product. This ensures that the correct finite element data may be associated with the correct version of a product within a Product Data Management (PDM) system.
- Product geometry: Both the design geometry and the idealized geometry created for analysis can be recorded. Nodes, finite elements, their edges, faces and volumes can be explicitly associated with aspects of the product geometry.
- It is possible to specify element properties, loadings or boundary conditions on a curve, edge, surface, or volume of the geometric model.
- Composite structures: The lay-up of a composite part can be specified in detail. Shape, stacking sequence, and property information can be supplied about individual plies and their fiber orientations.

The initial funding for the development of STEP composites implementations in AP209 was through the U.S. Air Force Research Laboratory Product Data Exchange using STEP (PDES) Application Protocol Suite for

Composites (PAS-C) program [18]. The primary goal of the PAS-C program was to provide a standard for the digital sharing, delivery and archiving of design, analysis, and manufacture of composite structures. The requirements for these capabilities were gathered from a survey of major airframe, automotive, and marine manufacturers. As the maintainers of U.S. military aircraft, the Air Logistics Centers were also a significant source of requirements. Extensive input to and reviews of the requirements were also carried out by technical experts within the ISO subcommittee developing AP209, and with engineering analysis organizations such as National Agency for Finite Element Methods and Standards (NAFEMS) [19].

Common commercial practice uses two distinct methods to represent the laminate stacks of composite structures. Both are based upon layers of curve-bounded geometric surfaces representing plies stacked upon a basis or tooling surface providing a 2½D shape representation. The thickness of the ply surfaces is implicit; i.e., specified by metadata related to these curve-bounded surfaces. Later in this paper we will discuss a new fully-3D approach where the thickness of the ply shapes are explicitly defined by solid shape representations (either tessellated or more precise B-rep solids) and the issues associated with 3D representations and plans to address those issues.

Figure 2 presents an EXPRESS-G [20] diagram of the STEP AP209 composites data model. On the left side, top of the diagram the highest-level class of laminate_table is shown. There are two main subclasses of laminate_table connected by a heavy relationship line: part_laminate_table and zone_structural_makeup.

- The part_laminate_table subclass is made of one or many sequences of plies that all lay upon one layer of the composite laminate representing the structural part. The external boundaries of these plies may, and usually will, vary considerably resulting in different thicknesses over the surface of the part. These part_laminate_tables may be simple stacks of plies, or complex assemblies of many laminate_tables typically used to represent bonded assemblies.
- The zone_structural_makeup subclass is of constant thickness over the shape of the zone. The shape may be a point, or a curve-bounded surface. There are options for the zones to be specified by percentages of thickness for each of the plies, specific thickness of plies, or a smeared representation that averages all the plies in a laminate to provide properties for a total thickness. The smeared representation is typically used only for first order structural analyses.

Over the past decade, the data model and document publication architecture used for STEP were revised to follow a modular approach [21]. Once this was done, there was demand for a generalized, modular composites capability that could be used in other STEP data exchange specifications. Since the STEP composites data model initially standardized in AP209 in 2001 was modularized, the STEP composites data model has been incorporated in new, modular editions of other STEP specifications, such as ISO 10303-203, *Configuration controlled 3D design of mechanical parts and assemblies* [22]. The modular capabilities for STEP composites are currently being incorporated in an emerging standard ISO 10303-242, *Managed Model-Based 3D Engineering* as well as a second edition of AP209.

The modularization of STEP specifications has supported a continuing evolution in STEP composites capabilities. During the modularization process an opportunity arose to add new types of composite constituents to the AP209 composites capabilities. These new constituents include braided and woven manufacturing processes, reflecting composites fabrication technology developed since the first edition of AP209 was published.

3 ISO 10303 Composites Implementation and Testing

Several implementation trials have been completed successfully during and after the development of AP209. All of the tests exchanged composite structures using AP209 files between two CAD systems. This section presents an overview of these efforts.

The first implementation was undertaken during the development of the AP209 standard under the PAS-C program. The initial testing of AP209 composites was conducted during the validation phase of the PAS-C program. Here design shapes of plies were created in CAD and passed via prototype AP209 translators to CAE (Computer Aided Engineering) tools for analysis and feedback. Several hybrid composite structures including the F-16 aircraft's horizontal tail and the C-17 aircraft's proposed composite tail were then used as a baseline for demonstrating an integrated design-analysis cycle. Figure 3 shows a nested set of plies in a panel on a complex, contoured lay-up surface that was the first successful test problem to concentrate on both laminate table metadata and the geometrical ply shapes. The outermost boundary of the part in Figure 3 represents the edges of the basis or lay-up surface. The next two curves towards the center of the laminate are the outer boundaries of the composite part. The closely spaced polygons near the center of the part denote a set of ply drop-offs that result in the center of the part being only as thick as the first two outer boundary plies.

Shortly after the PAS-C program, the US Army Tank Command (TACOM) [23] provided a test case with an emphasis on CAE tools and composites. For the TACOM demonstration and evaluation, the test case was a prototype Composite Armored Vehicle (CAV). CAD geometry for plies was passed to purpose-built software that took laminate table and material properties as input and combined them with a derived Finite Element Analysis (FEA) mesh of the body and nose of the CAV. The software automatically generated the material response matrices for each of the finite elements of the model. The FEA model was then analyzed and passed back to a software tool, as AP209 data, for post-processing of results (Figure 4).

Currently, two large-scale AP209 composites implementations and testing are underway. The first is undertaken under the auspices of PDES Inc., an international industry, academic, and government consortium formed to speed the development and deployment of standards that enable enterprise integration [24]. Several PDES, Inc. pilot demonstrations were performed to advance the maturity of AP209 composites implementations. In support of these efforts a recommended implementation practices guide for AP209 was developed [25]. Among these efforts, the following two are noteworthy:

- *MSC.PATRAN Translator*. The major commercial implementation of AP209 composites, shape, and FEA, developed and tested in PDES Inc., was for the MSC.PATRAN FEA pre/post-processing tool [26-28]. The composites capabilities within MSC.PATRAN included not only the ability to translate into and out of AP209 format, but also to create and edit laminate tables within PATRAN itself using the AP209 composites schema as the basis for its internal representation. These laminate tables could be associated with FEA meshes within PATRAN and used to automate the creation of thickness and material response matrices. The FEA mesh and associated thickness and material information was then shared with an internal General Dynamics Electric Boat (GD/EB) implementation.
- *GD/EB Internal Translator and work with Altair Hypermesh*. A small implementation was undertaken to share laminate table and FEA information between the above-mentioned GD/EB internal AP209

implementation and the Altair Hypermesh FEA pre/post-processor tool. Several simple finite element models with composite properties were successfully shared.

The second large-scale testing of AP209 is a joint effort between two major standards consortia. The PDES, Inc. and ProSTEP [29] consortia have a joint testing forum for maturing ISO 10303 STEP translators in commercial computer-aided tools, called the CAx Implementers Forum (CAx-IF) [30]. In the CAx-IF, the software tool vendors sign non-disclosure intellectual property agreements that allow them to work together. This forum has proven to be ideal to mature the STEP composites capabilities in commercial implementations of AP209. At the time of publication, the authors know of one major commercial CAD vendor who has implemented AP209 composites directly. Several other CAD vendors are providing AP209 capability indirectly by embedding third-party translators into their products. The CAx-IF testing has already greatly widened the availability of AP209 composites commercial implementations. The first round of part testing has been completed using a simple part illustrated in Figure 5. Currently a series of more complex parts are being tested that have more complex shapes and ply laminate tables.

4 Future Directions

Composite structure design is an area with much potential for continued innovation. The immediate future work that we envision will take place on two fronts. The commercial implementations of the STEP composites capabilities need to be expanded to cover all the capabilities in the current STEP specification; this is essentially a software development effort. Additionally, the STEP composites specification must evolve to meet new requirements and new manufacturing technologies; this will involve considerable research and development effort.

Addressing the expansion of commercial implementations first, we note that there are still several implementation areas that need to be addressed by commercial software vendors. These needs include complex bonded assemblies, cost effective visualization, and long-term data retention. Current design practice has increased the complexity of bonded composite assemblies to include embedded electronic and other systems. Figure 6 shows a core-stiffened part with embedded fluid transfer (the pipe visible in the upper left of the part), embedded electronics (illustrated by the raised pattern on the inside of the part), and optical circuits (the thin wires leading to silver cylinders on the lower left of the part). Figure 7 shows an end view of the same part. Here we see that there are aspects such as a bonded on metal U-channel at the edge of the part, and a blade stiffener bonded on one of the exterior flanges using a Pi-preform.

Though the AP209 data model currently supports these kinds of complex assemblies, current vendor implementations have yet to address these capabilities. A further complicating factor is that in order to properly implement this type of complex composite part, the CAD shape representations must also be associated with a product structure to record all the appropriate metadata. Current STEP translators only record a portion of this information, further complicating the implementation of this capability. In addition, the current CAD and CAE tools implement composite materials in quite different fashions. Some of the CAE tools have very simple ply representations and many simply define the resulting material response matrices. Some trial implementations of AP209 composite data models in MSC.PATRAN and Altair Hypermesh have shown promise that eventually a unified CAD-CAE approach may be available and would be preferable.

We now address the second part of the future work, which involves considerable research and development concerning the extension of AP209 composites capabilities. As discussed above, the current practice in defining composite shape representations in industry is reflected in the current STEP composites data model: a 2½D approach where plies in a laminate table have their shape represented by a series of curve trimmed surfaces upon a basis or tooling surface. Without the associated metadata for each ply it is very difficult to understand this type of implicit shape representation.

Recent work in industry [31] is promoting an approach where each ply is represented by a solid or volumetric shape representation assembled properly with respect to other plies in the laminate table. Metadata such as material and ply orientation is still associated with each ply in the laminate table. The major scenarios for this type of explicit representation of composite parts are in the bidding, manufacture, and field support of composite parts. Some of the benefits of full 3D explicit ply representation include the removal of intellectual property, making it easier to comprehend design intent while minimizing misinterpretation risk in subcontracting; and the ability to use low cost visualization tools throughout the entire value chain. However, two major research challenges remain:

- *Challenges in Model Creation*. There are several issues with the full 3D explicit-ply-representation approach. Industry has been experimenting with this approach for many years, and it became apparent quickly that the size of the resulting models became unwieldy and impractical. Rapid advances in computing are beginning to address these issues. In addition, the plies in composite structures are very thin (typically 0.14 mm to 0.30 mm) compared to their boundary dimensions. This type of geometry presents several challenges in numerical stability and visualization. And once again, new technology such as 64-bit hardware, Graphic Processing Units (GPU), and inexpensive memory are starting to diminish the potential impact of the unique thin structural configurations. The process of creating these models, particularly the geometry of ply transitions where one larger ply is layered and overlapped over smaller ones, is quite difficult and time consuming. Current efforts are concentrating on industrial and academic research, and encouraging the CAD vendor community to develop and adopt such new capabilities to make this type of modeling practical.
- *Challenges with visualization*. The main issues with visualizing 3D composite shape representation include dealing with the geometry of thin volumes. The complexity and resulting model size of large composite assemblies also presents challenges. Typical composite part laminates have many thin plies stacked upon each other. When tessellated for visualization the numerical stability of the tessellation often results in triangles from adjacent plies protruding through triangles of a ply directly above or below. This produces a visually incorrect image that often is quite confusing. Some approaches being tested include better tessellation algorithms, smaller triangles, an aligning the triangles from ply face to ply face. The large-size issues of 3D composite shape representations in visualization tools are also a challenge. Composite parts are becoming larger and more complex, resulting in tessellations that challenge even the most robust computers and algorithms. Efforts to cull interior triangles from the tessellation of the composite parts and to implement distributed scene generation to allow the use of smaller low-end visualization software and hardware tools are a few of the approaches being pursued to alleviate these problems.

These challenges are being addressed in a Long Term Archiving And Retrieval (LOTAR) consortium, which is comprised of many of the aerospace companies worldwide [32, 33]. One of its main goals is to specify the set of standards and practices that will provide a digital archive that will last many decades. Goals of the LOTAR project include:

- Developing a standards series for archiving and retrieval of product data of referred and needed methods, process modules, and data models;
- Providing methods, process modules, and data models to enable long-term archiving and retrieval of CAD and PDM data along with electrical and composite design data;
- Developing recommendations for practical introduction of long-term archiving of relevant data at industry;
- Enabling the development of commercial off-the-shelf software (COTS) based on user requirements generated in cooperation with CAx-IF and jointly funded pilot projects.

A LOTAR compliant archive must have the required completeness to fully re-manufacture and certify aerospace composites. Since many aerospace vehicles are increasingly made of composite structural parts, the use of AP209 composites is being added to the LOTAR 300 series of standards. Such pressing industrial needs are driving the research and development work outlined in this section.

5 Concluding Remarks

This paper presented recent advances in the evolution and implementation of an open international standard for the sharing of composite structural part product data, ISO 10303-209. This composites structure standard has proven to be effective and capable of handling very complex composite structural parts and assemblies.

The current implicit 2½D approach in common practice in industry needs to be evolved to a full 3D approach. Several use cases for the full 3D approach have been documented through the CAx-IF and LOTAR projects [33], particularly for sharing composites design information with manufacturing, and for long term data archival and retrieval. A series of standardization, implementation, and research issues have been identified, many of which are being addressed.

Disclaimer

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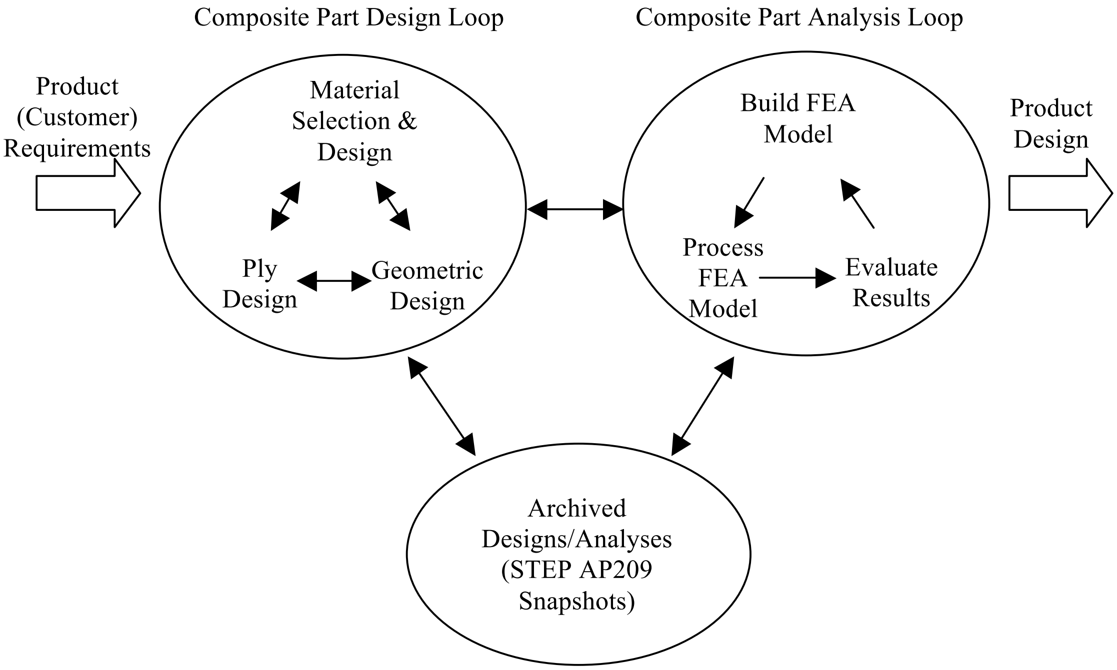


Figure 1. A depiction of the role of STEP AP209 in the design and analysis of composite structures.

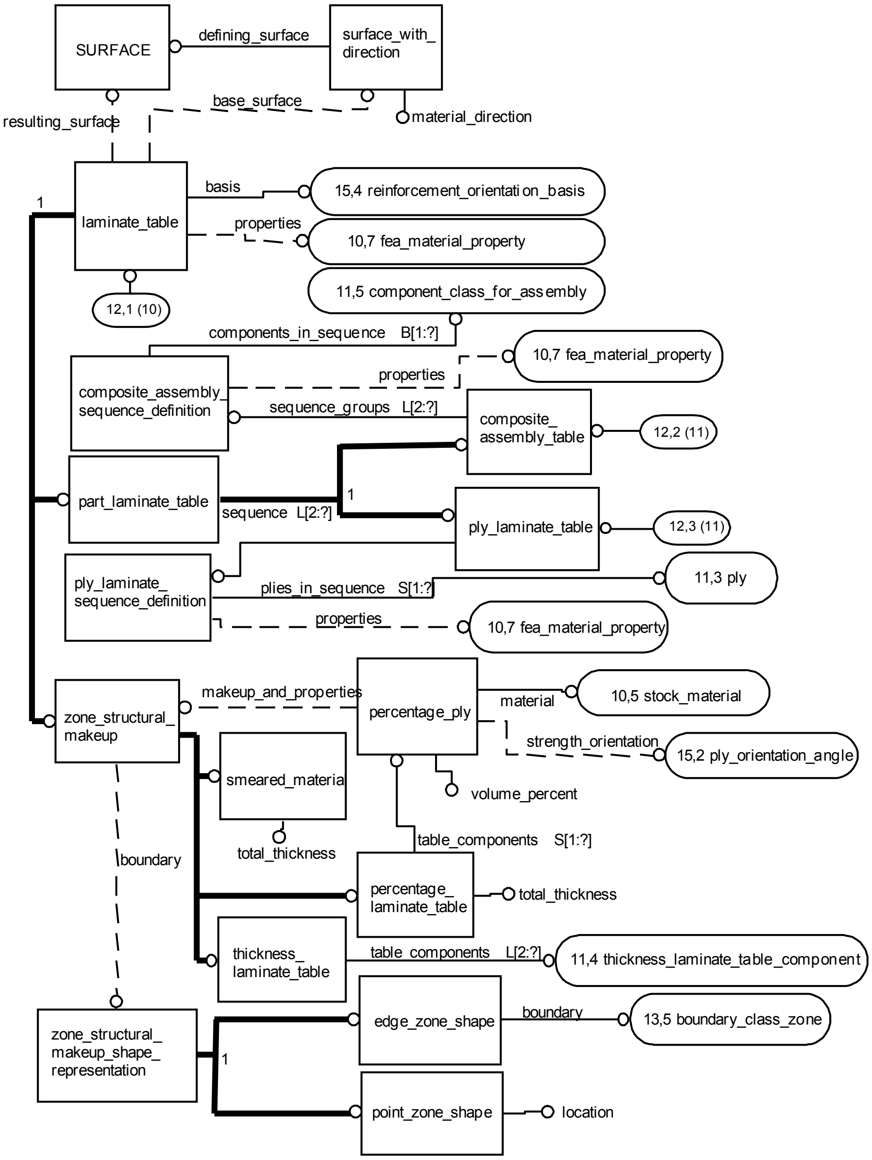


Figure 2. The core of the STEP AP209 laminate table data model

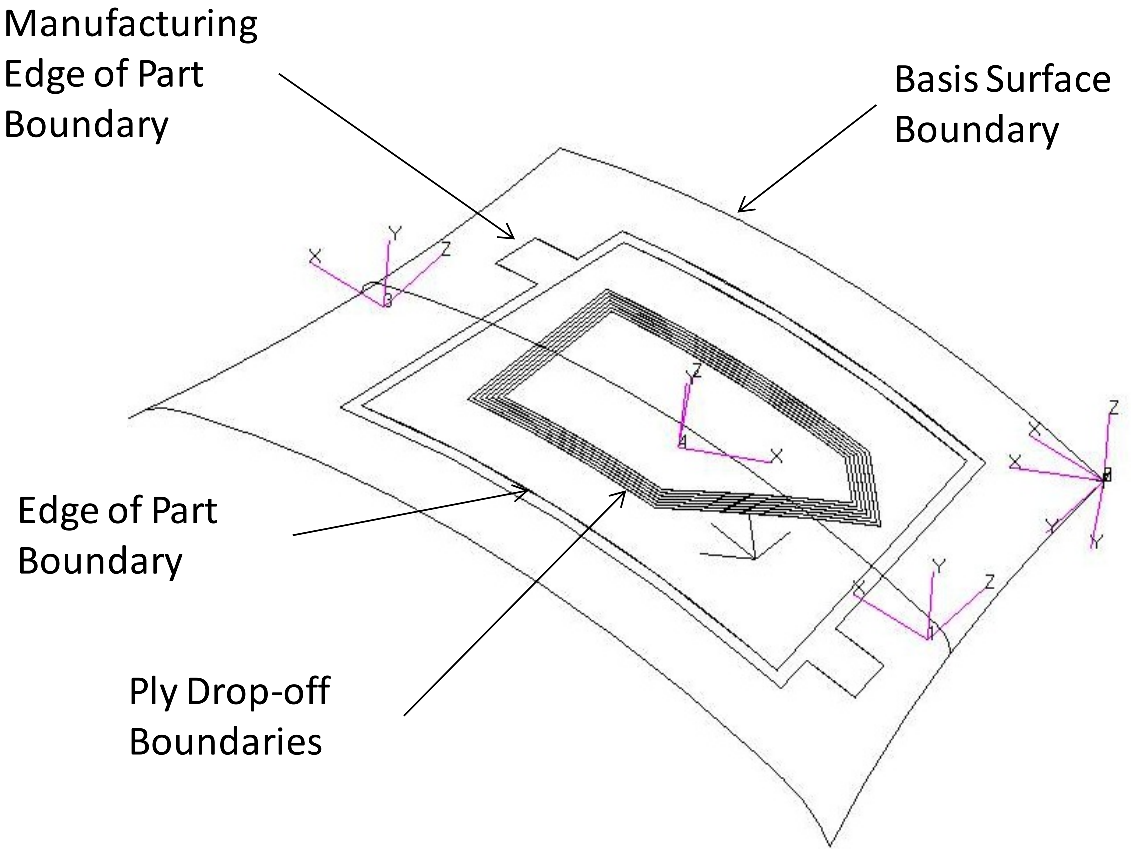
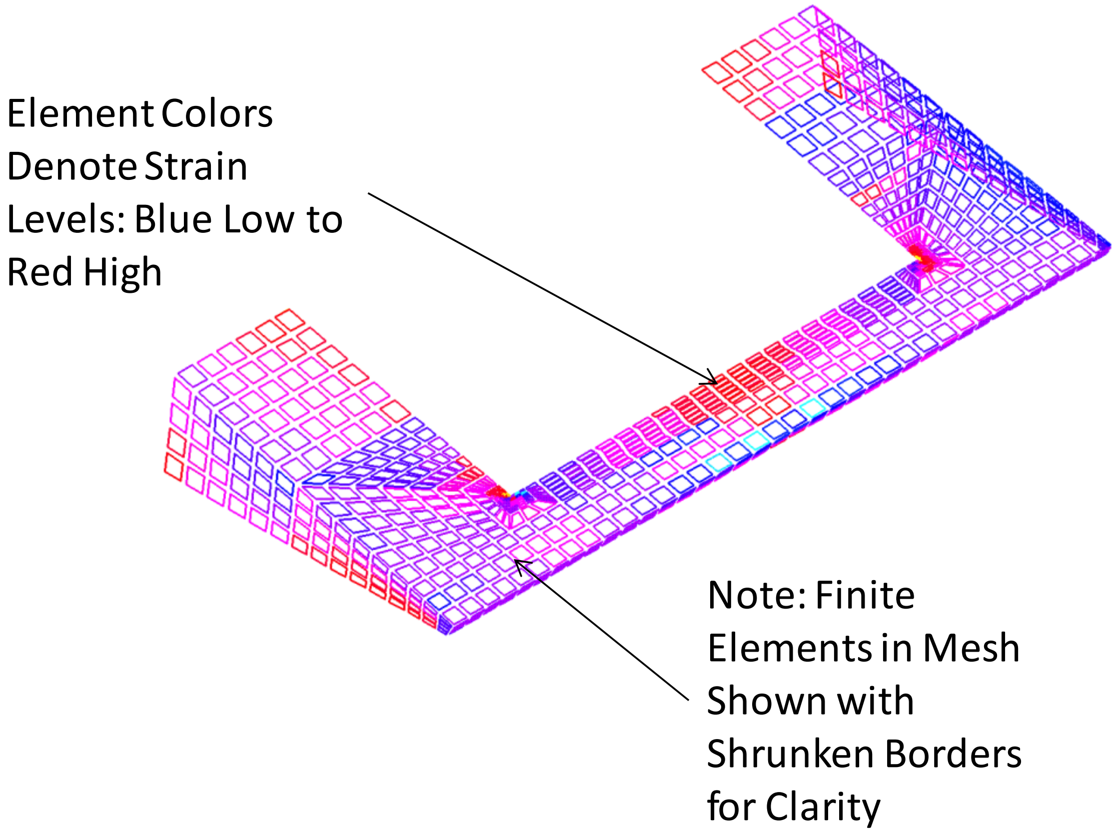


Figure 3. PAS-C initial ply test problem



Element Colors Denote Strain Levels: Blue Low to Red High

Note: Finite Elements in Mesh Shown with Shrunken Borders for Clarity

Figure 4. The TACOM composite armored vehicle’s nose finite element model showing stress results

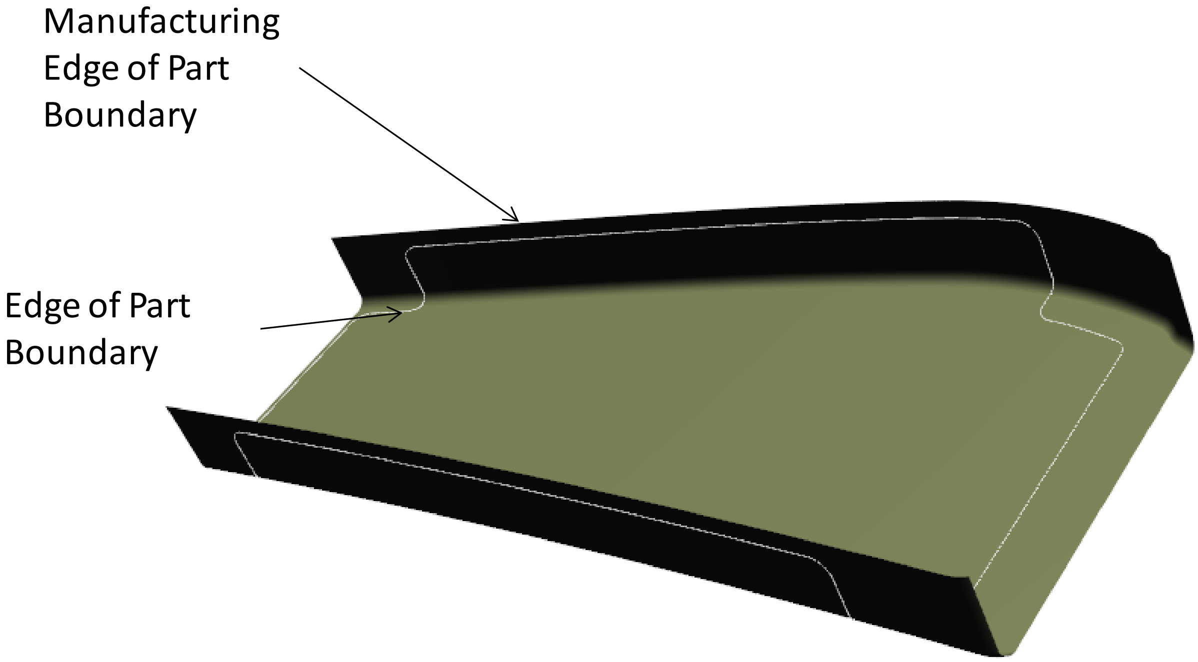


Figure 5. A simple wing rib for initial CAx-IF testing

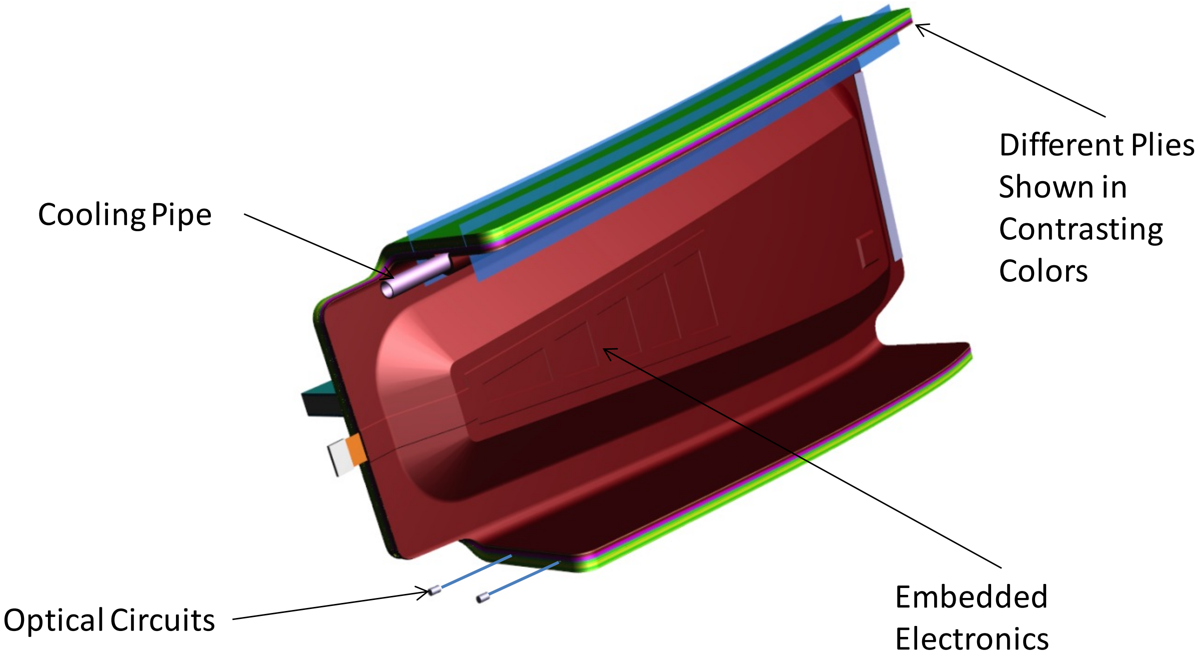


Figure 6. A complex bonded assembly inside view

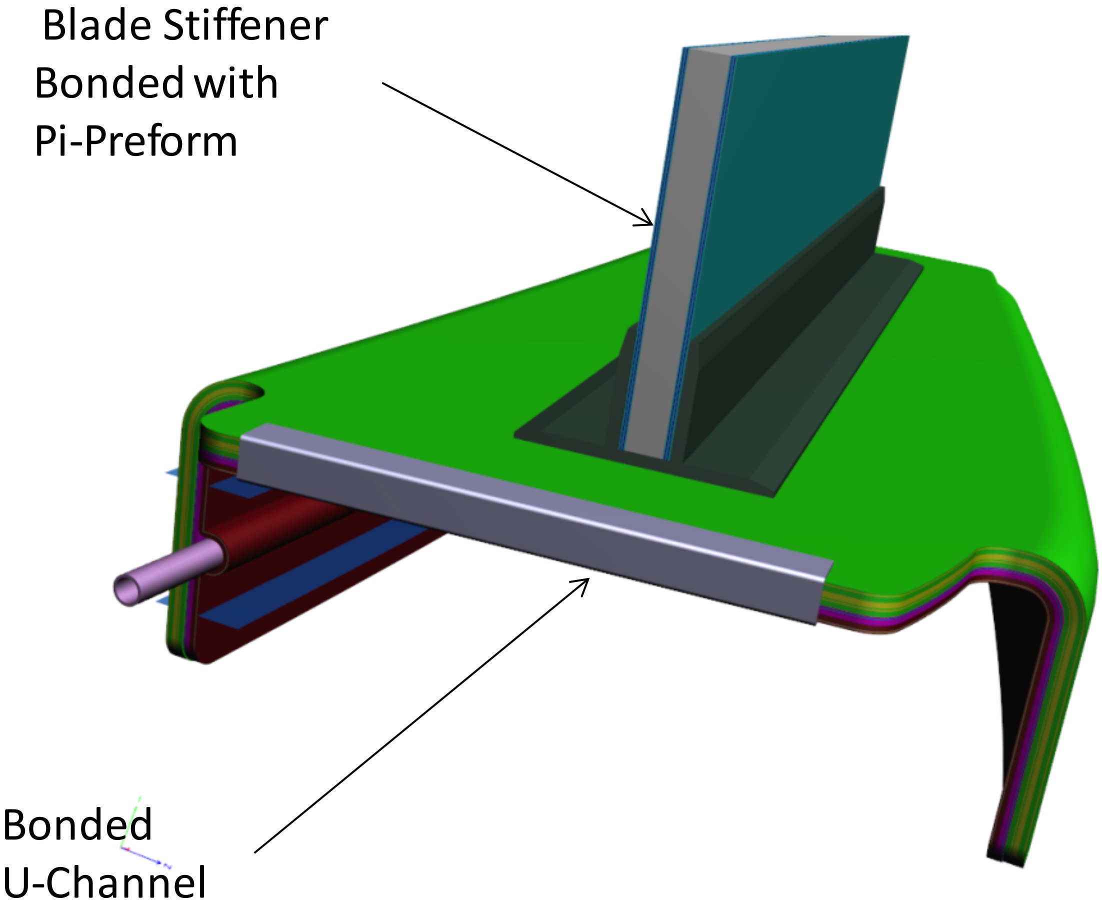


Figure 7. A complex bonded assembly end view