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AN ANALYSIS OF RECENT STANDARDS ON COMPOSITE PRODUCT MODELS TO ENABLE DIGITAL TRANSFORMATION OF COMPOSITE PRODUCT MANUFACTURING

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ABSTRACT

ASME and ISO are issuing new editions of their standards that deal with definitions and models for composite products. The new edition of ASME Y14.37 deals with standardized product definition for composite parts. The Edition 2 of ISO 10303-242 contains standardized data models for three-dimensional representations of composite products. This paper analyzes several salient features of these two standards with a focus on their potential impact on the digital transformation of composite product manufacturing. It also provides a mathematical and information theoretic exposition of *ply table* as an important representation for modeling some of the complex composite products and their manufacturing processes.

1. INTRODUCTION

Products made from composite materials can be found everywhere, from recreational sports (e.g., tennis racket) to advanced transportation (e.g., aircraft structure). Composite materials, which are hybrids of different materials, fill some crucial holes in the material-property space that are left open by conventional monolithic materials. When stiff, strong, tough, and light materials are needed, the designers often turn to a hybrid of materials, and to novel manufacturing processes to combine these materials to achieve their design objectives [1].

There are many ways to combine two or more materials to create a composite product. Among such products are *fibrous composites*, which consist of reinforcement fibers embedded in a plastic matrix such that the fibers do not separate from the matrix when the composite product is loaded. The fibers may be made up of materials such as glass, carbon, or aramid (e.g., Kevlar). The matrix may consist of thermosetting resins such as polyester or epoxy; sometimes thermoplastic resins may be used as the matrix. The fibers may be continuous strands or chopped up into smaller pieces before they are embedded in the matrix resin. The composite product may also contain *sandwich cores* that are lighter. This paper deals with composite products that are made from fiber-reinforced plastics (FRP) and may have sandwich cores.

Recent interest in energy efficient products and renewable energy production has accelerated the use of composite products [2]. FRP is used to reduce the weight of planes and cars, thereby contributing to fuel efficiency. Large turbine blades for windmills are made almost exclusively from FRP. Renewable energy sources (such as wind, waves, and solar) are notoriously intermittent and require energy storage. Flywheels and compressed air tanks are made using FRP, and these composite products provide the mechanical and pneumatic means, respectively, for storing such intermittently harvested energy. All these applications are made possible by the light weight, high strength, and resistant to corrosion offered by FRP.

As FRP products are gaining popularity, their manufacturing processes are attracting greater attention. The FRP design and manufacturing have remained in the hands of highly skilled engineers for several decades. During this period, several innovative design and manufacturing practices developed by these engineers have led to the introduction of numerous successful products to the market. However, many of these practices have remained *ad hoc*, and a lack of their systematization and standardization has hindered the integration of engineering information systems used in the composite product design and manufacturing processes. This problem has now become even more acute as the manufacturing industry is going through a digital transformation, a phenomenon that is variously called smart manufacturing [3], cyber-manufacturing [4], and Industrie 4.0 [5, 6].

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Standards development organizations such as ASME and ISO (International Organization for Standardization) have responded to urgent calls to enable this digital transformation and have been actively producing standards to serve the composites manufacturing industry. Two such standards have been revised for industrial use recently. One is a new edition of the ASME Y14.37 standard that deals with standardized product definition for composite parts [7]. The other is Edition 2 of the ISO 10303-242 standard that contains standardized data models for three-dimensional representations of composite products [8].

This paper analyzes several salient features of these two standards with a focus on how they may enable the digital transformation of composite product manufacturing. A major technical contribution of this paper is the mathematical and information theoretic exposition of what is called a *ply table* as an important representation for modeling some of the composite products and their manufacturing processes.

The rest of the paper is organized as follows. Section 2 provides a brief introduction to information models needed for design and manufacturing of composite products. Section 3 introduces the new edition of the ASME Y14.35-2019 standard on product definition for composite parts. Section 4 provides a brief analysis of the ISO 10303-242:2019 (also known as STEP AP 242) standard that includes composite products. Some of the future directions for research and standardization are discussed in Section 5. The paper concludes with a summary in Section 6.

2. COMPOSITE PRODUCT INFORMATION MODELS

This paper focuses on thin-walled FRP products. The design and manufacturing are very closely tied to each other for such products. In this sense, FRP products are very similar to semiconductor chips; both are led by innovations in manufacturing processes and both are built as layers involving multiple materials, with one important difference. In the case of FRP, plies and laminates can be laid up on curved surfaces and sandwich cores to produce complex three-dimensional structures. This crucial difference from semiconductor chips, which are built predominantly of planar layers, introduces some important geometrical challenges in the information modeling of composite product structures.

Figure 1 illustrates a general, high-level classification of manufacturing processes employed to produce FRP products [9, 10]. It is not intended to be the final word in the classification of FRP manufacturing processes because new technologies are being introduced at a rapid pace, thus constantly changing the manufacturing landscape. However, the classification of Fig. 1 is sufficiently general and inclusive to guide the information modeling technology and related standardization processes.

As indicated in Fig. 1, industry employs both thermosetting and thermoplastic composites. Thermosetting plastics are more popular, but they are not recyclable because of irreversible polymerization of the resins used in the manufacturing process. There is an increasing interest in replacing thermosetting plastics with thermoplastics that are recyclable and hence eco-friendlier.

Both short and continuous fibers are used in composite products, as indicated in Fig. 1. While short fibers are cheaper and easier to handle, industry prefers continuous fibers when high performance in strength and stiffness are needed (for example, in aerospace applications). This is the primary reason for the importance given to continuous fibers in the ASME and ISO standards that are addressed in Sections 3 and 4.

All composites manufacturing processes described in Fig. 1 depend on a curing process, which involves application of temperature and pressure, on a finite stack (of layers of resins and fibers) to obtain the final product. Some resins do not require additional temperature or pressure than the ambient conditions for curing. Curing is a chemical process that enables polymers in the matrix resins to cross-link, which produces a harder and more homogeneous matrix within which the fibers (both short and continuous) are firmly embedded. The curing process will introduce changes, both noticeable and invisible, in the product. Therefore, it is important to distinguish between the 'cured' and 'uncured' states of a composite structure. As described in Sections 3 and 4, standards pay greater attention to the uncured state of the composite structure for reasons that will be explained during this paper.

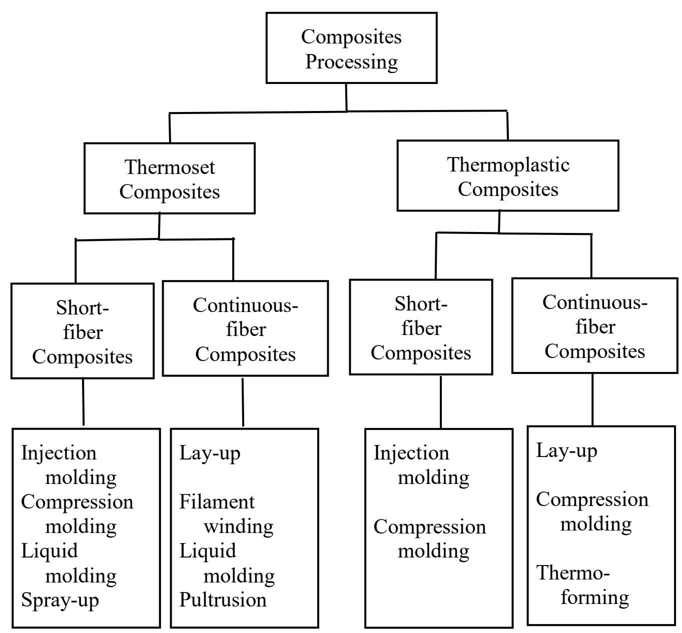


FIGURE 1: Classification of FRP manufacturing processes [9].

With these preliminaries, it is now possible to identify the following set of elements and entities that are common to all FRP products, and therefore candidates for standardization.

- *Tools and molds*: All composite processes identified in Fig. 1 start with tool surfaces (e.g., for spray-up and lay-up) and molds. Similar to casting and injection molding, the shape and accuracy of an FRP product depends critically on these tool and mold surfaces and the solids bounded by these surfaces. The standards must provide means to represent these three-dimensional surfaces and solids. Luckily, standards for such geometric representations are already available because they are needed for conventional products that are routinely manufactured every day [11, 12].

- *Fibers*: Fibers are quite correctly called the 'reinforcements' in composite products. Fibers are the load-bearing members and are the major contributors to the strength and stiffness. Fibers have a circular cross-section and can be made up of materials such as carbon, glass, or aramid (e.g., Kevlar). A typical composite product may contain thousands – often millions – of fibers even when the fibers are continuous; short fibers make the count even larger. This poses a serious problem in geometrical modeling of these important elements in FRP products.

  Luckily, continuous fibers are placed in a mathematical pattern within each ply and these plies are arranged (in an uncured state) geometrically to form laminates, which may be arranged further in a well-defined manner to form the composite product. Even when short fibers are used, they are usually placed randomly within a ply and this randomness provides a modeling abstraction for standardization. In any case, the hierarchical description of plies, laminates, and the uncured state of the final product provides a mathematical means to conquer the size complexity of millions of fibers. This then enables an information theoretic abstraction for standardization, as described in Section 3 and 4.

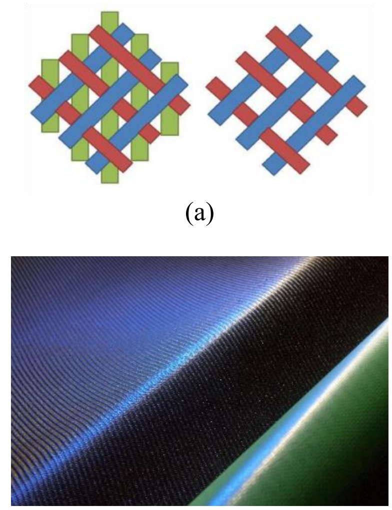
- *Resins*: Resins provide the medium, often called the matrix, within which the fibers are embedded. The resins transfer loads among the fibers and they provide much needed protection to the fibers from ambient environment (e.g., resistance to corrosion). They are also responsible for the ductility and toughness of the composite product.

  Thermosetting resins include epoxy and polyester. When subjected to temperature and pressure (sometimes even under the ambient conditions), polymers in these thermosetting resins form cross-links and result in a harder substance. This chemical process is irreversible, and this renders these resins non-recyclable. Thermoplastic resins do not suffer from this drawback, but such resins are being developed only recently for large-scale industrial use.

  From an information modeling perspective, resins can be viewed as homogeneous and isotropic materials. But resins are never used in isolation in FRP products. Reinforcement fibers are embedded in these resins and these fibers provide the desired non-homogeneity and anisotropy. This leads to geometric modeling challenges that will be addressed below.

- *Plies*: A ply is usually an arrangement of reinforcement fibers in a resin matrix. More formally, a ply is 'one discrete piece of manufactured material (e.g., fabric, tape, adhesive film)' [7], thus generalizing the ply definition to include adhesive films as well. This formal definition elucidates the critical fact that a ply is an important *discrete* module in an FRP product, and therefore it is a basic entity in modularizing the design and manufacturing of composite products. Thus, plies play a dominant role in the uncured state of an FRP product.

  A ply can include short or continuous fibers. Dry continuous fibers can be spun, braided, woven, or stitched using any number of textile processes to produce a 'preform.' Figure 2(a) shows some preform patterns, with thousands of fibers in each strip. These preforms can then be injected with wet resins during the manufacturing process. Alternatively, such textile or plain fibers can be impregnated with resins to produce a 'prepreg' that can be subjected to curing in a later manufacturing process. Figure 2(b) shows a prepreg fabric that can be used as a ply, after it is trimmed as needed.



(a)

(b)

FIGURE 2: Examples of (a) Preform and (b) Prepreg in creating plies [13, 14].

  The plies will be stacked up in layers, starting from a tooling surface. As mentioned earlier, each ply can contain thousands – sometimes millions – of fibers. A pragmatic approach, which is probably the only sensible approach, adopted by industry is to model each ply in it uncured state as a combination of four sets of information: (1) The volume occupied by the ply as a homogeneous and isotropic three-dimensional solid, (2) The sequence in which the ply is laid up during manufacturing, (3) Arrangement of fibers within the ply and relative to the ply (or tool surface) before it in the sequence, with particular attention to fiber orientation, and (4) Information about the fiber material, resin material, and geometrical pattern of fibers used in the ply preparation.

- *Laminates*: A laminate results from the stack up of two or more plies in an uncured state, as illustrated using a simple example in Fig. 3. When cured, the resins in the plies link up by polymerization to form the composite product as shown in Fig. 4. The interfaces between plies have disappeared in Fig. 4, leaving only the fibers that are now embedded in one cured conglomerate of resin matrix.

The ply sequence in a laminate and the fiber orientations in the plies in a laminate are two of the most important pieces of information in engineering practice. This can be mathematically formalized by postulating the following invariance properties under nominal (or ideal) curing operations.

1. Preservation of three-dimensional arrangement (i.e., the order and sequence in three-dimensions) of fibers. This can be viewed as the invariance of the combinatorial topology of the fibers in a laminate before curing (e.g., in uncured state as in Fig. 3) and after curing operation (e.g., in cured state as in Fig. 4).

2. Preservation of orientation of fibers. This can be viewed as the invariance of angles between fibers before curing (e.g., in uncured state as in Fig. 3) and after curing operation (e.g., in cured state as in Fig. 4) that may result in uniform scaling due to volumetric shrinkage.

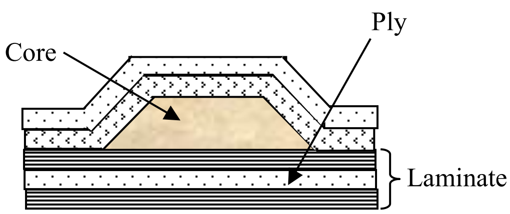


FIGURE 3: Illustration of uncured plies, laminates, and core.

Under actual (as opposed to nominal or ideal) lay-up and curing operations, the invariance of combinatorial topology may still be preserved; but, some small changes in the relative orientation of fibers should be expected. The distances between fibers in adjacent plies may, however, undergo larger changes during curing.

- *Sandwich cores*: A core is a lightweight component sandwiched between laminates and bonded to the laminates. A primary role of such a core is to increase the section modulus of thin-walled structures without increasing their weight considerably [1]. Figure 3 illustrates a cross-sectional view that includes plies, laminates, and a core.

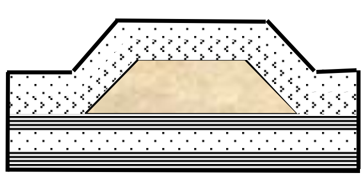


FIGURE 4: Illustration of composite product in cured state.

The design philosophy that underpins the development of composite products follows the classical causal links of processing, structure, property, and performance as shown in Fig. 5 [15]. In analyzing the performance of a composite product, engineers start with the manufacturing processes adopted for that product. Some of these processes are captured in the information modeling of plies, laminates, and cores as described thus far. But these provide a model for only the uncured state (e.g., as in Fig. 3) of the composite structure. From this, a model for the cured state of the composite (e.g., as in Fig. 4) is obtained by applying a combination of computational techniques and empirical rules derived from experiments (for example, to account for shrinkage).

The structure thus obtained is then subjected to computational analysis (e.g., finite element analysis) to predict its properties and performance under various service conditions. A typical composite product design is an iterative process, involving a cycle implied in Fig. 5 that shows a causal progression in one direction and a synthesis progression (starting with the performance goal) in the other direction.

The brief exposition of composite product information model presented in this section forms the basis for analyzing two recent standards. Section 3 focuses on the recent revision of the ASME Y14.37 standard, followed by Section 4 that addresses Edition 2 of the ISO 10303-242 standard.

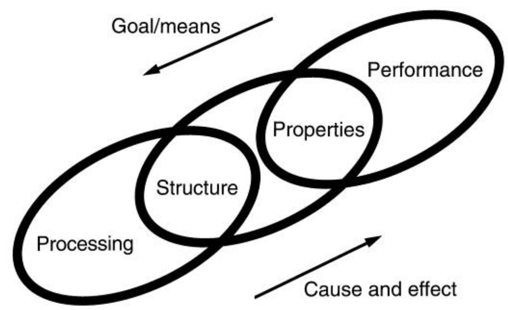


FIGURE 5: The causal links of processing, structure, properties, and performance [15].

3. ASME Y14.37-2019 STANDARD

ASME issued its first standard on composite parts in 2012, when it was called ‘Composite Part Drawings’ [16]. It reflected the practice at that time to focus on two-dimensional drawings as the primary means of defining engineering products. While revising this standard, the title was changed to ‘Product Definition for Composite Parts’ to acknowledge the increasing industrial use of three-dimensional models and machine-readable representations of products and manufacturing processes [7]. This new edition also started harmonizing its definitions with other standards, such as the ISO STEP standards [8], which deal with three-dimensional data models to represent products that include FRP products.

There are other ASME standards that deal with dimensioning and tolerancing drawings and three-dimensional models [11, 17]. These can be used for composite products as well, but these standards are not sufficient due to the complexity of FRP structures. To address this deficiency, ASME Y14.37-2019 deals with those composites definitions that are not covered by the other ASME Y14 standards.

Broadly speaking, the types of information standardized by ASME Y14.37-2019 fall under two categories. The first category is the geometric information, either as two-dimensional drawings (projected views and cross-sections) or three-dimensional models, which are already covered by the above-mentioned ASME standards [11, 17]. The second category relies heavily upon *ply tables*, which are unique to composite products. The ply tables also refer to the geometric information mentioned in the first category to define the geometry of plies, cores etc. Thus, the ply tables and the geometric information complement each other for composite products.

Since ply tables play such an important role for FRP products, the rest of this section is devoted to them. A typical ply table, in its simplest form, is shown in Table 1. Such a ply table is accompanied by a three-dimensional model, or a two-dimensional presentation such as the one shown in Fig. 6. The ply table alone will not capture the composite product model; it is the combination of the ply table and the accompanying geometric model (or drawing) that conveys a more complete information.

TABLE 1: A simple ply table.

-101 ASSEMBLY			
PLY LEVEL	PLY/ITEM	ORIENTATION	MATERIAL
1	P1	0°	10745
2	P2	90°	10721
3	P3	0°	10745
4	-103 CORE		
5	P4	45°	10679
6	P5	90°	10721

The rows and columns of Table 1, and the accompanying Fig. 6, require some explanation. Each ply in Fig. 6 is graphically presented as a curve (with straight line segments, in this case) without any thickness attribute. In three-dimensions, a ply will be presented as a surface without thickness. The first row in Table 1 identifies an assembly of plies as -101, which is shown in Fig. 6, and this assembly is also called a laminate. The first column specifies the ordered sequence in which the plies and the core are arranged in the laminate (which is identified as the assembly -101). The plies and core are then identified as named items in the second column and are thus labeled in the geometrical presentation of Fig. 6. The core is identified and labeled as -103 in Table 1 and in Fig. 6, respectively.

As described in Section 2, the ply level in the first column of Table 1 provides a representation of the combinatorial topology of the fibers in the laminate, and this topology remains invariant under the curing operation. The ply level also provides the sequence in which the plies (and the core) should be stacked to form the laminate. Thus, it also serves as an important part of the FRP manufacturing process specification.

The third column in Table 1 specifies the orientation of the fibers in each ply with respect to a reference system, which may be fixed on a tool surface. This is a representation of another invariant geometric relationship (i.e., angles between fibers) that is preserved under the nominal (or ideal) curing operation with uniform volumetric shrinkage, as discussed in Section 2. The fourth column identifies the material associated with each ply. Such material identification can refer to a much richer definition of each ply, which is not covered in the ASME standard. The ply thickness (in uncured state) may also be defined under the material category; the thickness of the FRP product after curing – also known as 'consolidated thickness' – may differ from the sum of the ply thicknesses due to volumetric shrinkage.

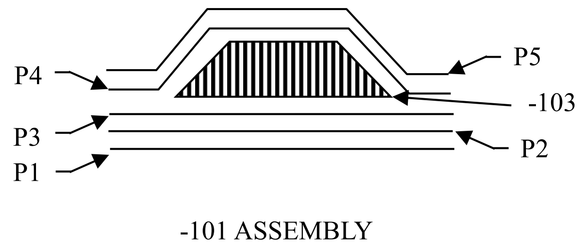


FIGURE 6: Geometrical companion to the ply table in Table 1.

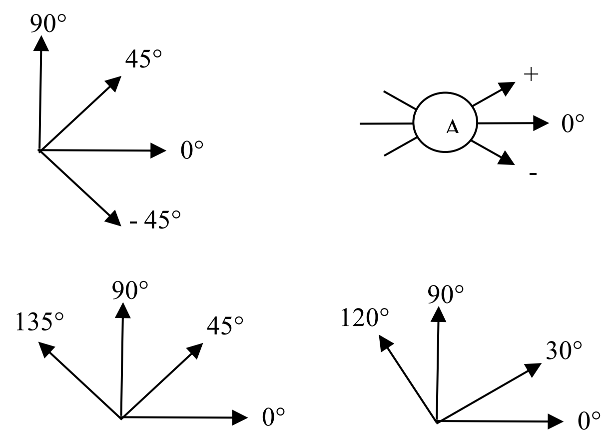


FIGURE 7: Examples of ply orientation symbols.

To support the orientation specification in column 3 of Table 1 for complex three-dimensional products, a more elaborate definition may be necessary. This is accomplished using an object called a *rosette* and an orientation symbol associated with that rosette. Figure 7 shows some examples of orientation symbols, which look like the needles on a two-dimensional magnetic compass used to get a local bearing on direction while standing on an undulating terrain – these symbols serve a similar purpose to orient fibers in a ply on a curved surface.

Once a ply orientation symbol is chosen from Fig. 7 and is associated with a rosette, it defines a two-dimensional coordinate system – either a Cartesian or a polar coordinate system. Using the right-handed rule, a unique normal to the two-dimensional plane of the orientation symbol can be found, thus forming a fullfledged three-dimensional coordinate system. The origin of such a coordinate system associated with a rosette can be initially place at a specific point on a ply surface, and its coordinate axes can be appropriately oriented to indicate the fiber orientation in the ply at that initial point.

In some flat FRP products a single rosette per ply might suffice. But in more complex products, especially those that involve non-developable surfaces, more than one rosette per ply will be necessary. To facilitate the specification of these additional rosettes in a ply, ASME Y14.37-2019 defines five types of transformation rules, which transform the initial rosette on a ply to any or specific points on the ply surface. Figure 8 illustrates one such type (Type 2, in this case) of transformation that can be specified to guide the lay-up (also, to guide wrapping and draping of 'cloths') of the ply so that the 0° fiber orientation is along the indicated guide curve. Other transform types, including a user defined type, are among the five ply orientation transformation types defined in ASME Y14.37-2019.

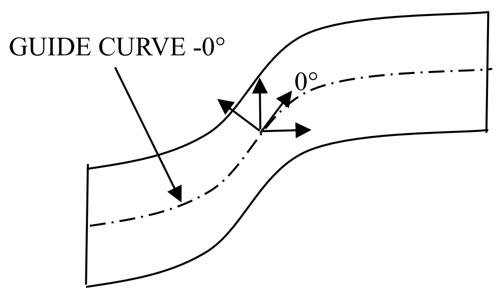


FIGURE 8: Type 2 rosette transform per ASME Y14.37-2019.

Even beyond the rosettes, some FRP products will require more complex information than those provided by the likes of Table 1 and Fig. 6. ASME Y14.37-2019 provides means to add rows and columns to the ply table beyond the simple example shown in Table 1. For example, when pultrusion is used to produce FRP products, the ply table is expanded to cover other information types such as roving, ply count, ply yield, and percentage weight.

The brief analysis of the ASME Y14.37-2019 standard presented in this section captures only the important features to illustrate the progress that has been made thus far. It has focused on ply tables and their geometric companions. More detailed information can be found in the ASME standard document [7].

4. ISO 10303-242:2019 STANDARD

ISO 10303, commonly known as STEP (Standard for Exchange of Product model data), is a family of international standards designed to exchange digital information of engineered products, enabling an ever-widening range of engineering information systems to interoperate [18–25]. An important recent member of the STEP family is *ISO 10303-242, Application protocol: Managed model-based 3D engineering* (commonly referred to as AP 242), which has quickly emerged as a critical enabler of digitization of manufacturing [26].

The first STEP standard for representing composite shape and structure was published in 2001 as *ISO 10303-209:2001, Application protocol: Composite and metallic structural analysis and related design* (commonly referred to as AP 209). In this standard, composite structure definitions were integrated with both configuration-controlled three-dimensional design and finite element analysis disciplines [27]. In preparation for the second edition of AP 242 and the third edition of AP 209, significant changes have been made to STEP data models for three-dimensional representations of composite structures, particularly for ply orientation (rosettes) and ply tables. Recent work on rosettes has been coordinated between the ISO subcommittee on Industrial Data and the ASME subcommittee Y14.37, whose standard was described in Section 3. In keeping with these new developments, significant changes to the analysis domain are also being planned (only in AP 209 Edition 3).

The APs 242 and 209 are specified according to a STEP modular architecture [28]. Both APs include the same three-dimensional composite structure representation. In addition, AP 209 supports the causal links of processing, structure, properties, and performance depicted in Fig. 4. So, AP 209 supports a design product structure and an analysis product structure, with versioning of each and relationships between the design and analysis models. This means that there may be representations of a nominal design shape, analysis shape(s), and optimized analysis shape(s). Any healing or meshing based on the nominal geometry may be stored separately with links to the nominal geometry being modified.

The STEP data model for composites is divided into the following five parts: (1) Part and zone laminate tables [29], (2) Composite constituent shape [30], (3) Composite constituent material aspects [31], (4) Stock material [32], and (5) Ply orientation specification [33]. Each of these parts will be explained briefly below.

Part and zone laminate tables, whose data model is shown in Fig. 9, is the core specification of the STEP composite structure. Note that what the ASME Y14.37-2019 calls a 'ply table' is referred to as a 'laminate table' in Fig. 9. A closer examination reveals entity definitions for base surface, direction for material lay-up, ply orientation, and ply sequence. Also included are information for the material properties, ply thickness, and volume percentage of fibers in the ply; these are important for the finite element analysis of the composite product.

A more detailed model for the shape and material of the ply, core, resin, and fiber is shown in Fig. 10. It defines composite constituents such as processed core, ply orientation, ply sequence, and woven and braided fiber filaments. It also refers to the stock materials from which the core, resins, and fibers are made. A separate stock material module defines the material stock of composite constituents and how they are approved and shaped; it also defines their material aspects and versions [32]. The composite constituent placement, net shapes, and boundaries are described by shape representations such as *Advanced_brep*, *Edge_based_wireframe*, *Faceted_brep*, *Shell_based_wireframe*, *Tessellated_shape*, and *Three_d_geometry_set*.

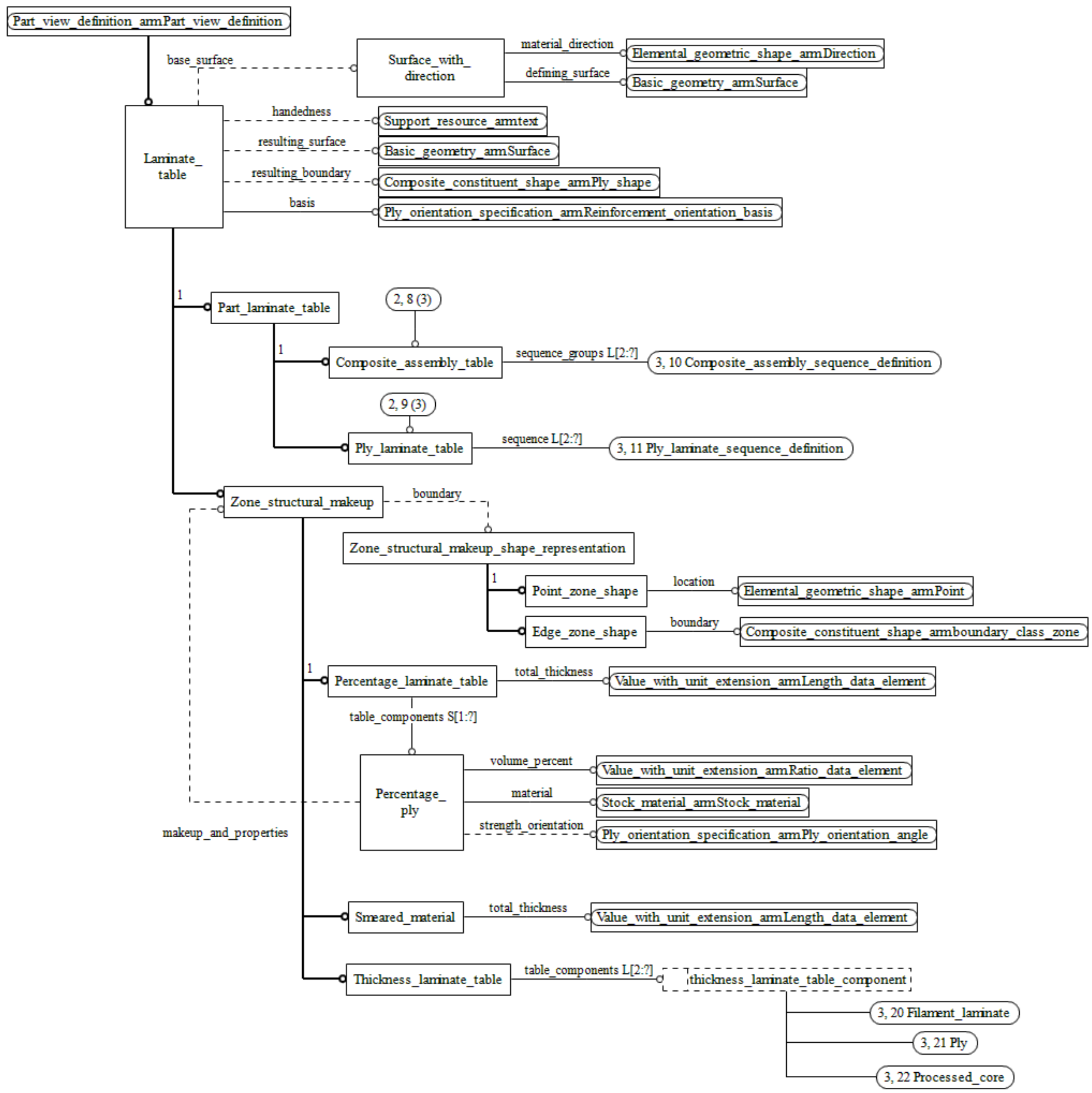


FIGURE 9: STEP data model for laminate table [29].

Figure 11 shows a more detailed data model for ply orientation, with emphasis on the orientation of reinforcement fibers. As described in Section 3, several types of rosettes are used for this purpose. Figure 11 defines many such fiber orientation types, including guide curve that is shown in a simple example in Fig. 8. Definition of these rosettes have been harmonized with the ASME Y14.37-2019 standard.

The new editions of AP 242 and AP 209 also make it possible to identify material specifications from internal and external document references, and properties for specific operating environments. The current best practice for composite product definition is to define the uncured (i.e., pre-autoclave) components as a typical assembly and then use a derived ('made from') solid to represent the cured part.

Such a cured solid model could then be defined as a 'make from' part that consists of the inseparable assembly of cores, fibers, and resins; it can be augmented with dimensions and tolerances, and other post-autoclave manufacturing information. This is very similar to how metallic parts are designed and manufactured. This approach has the additional benefit of separating the ply and component data that is potentially export controlled from the geometric form, fit, and function information needed for downstream applications that may involve a large supply chain.

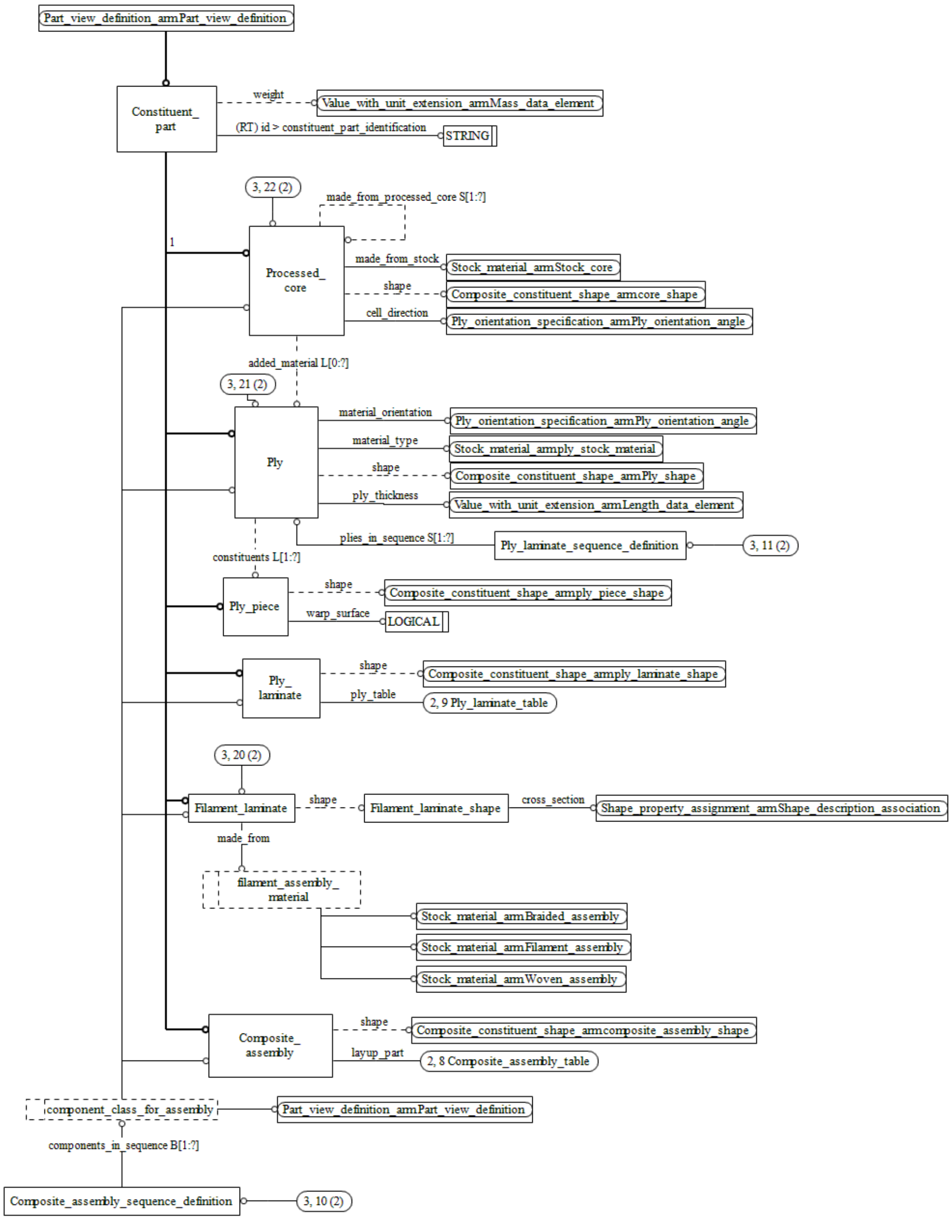


FIGURE 10: STEP data model for composite constituents [30, 31].

5. FUTURE RESEARCH AND STANDARDIZATION

The complexity and rapid technological changes in the FRP products and their production processes necessitate more research efforts and more revisions of standards. Even with the currently available standards, software vendor implementation and testing of the data models are needed to verify their compliance to the ASME and ISO standards. Such testing will involve both native models in the software vendor's proprietary system and the exchange models in the open ISO STEP formats.

Internal fiber arrangements and orientations of composite products are notoriously difficult to measure. In addition to destructive testing, several non-destructive testing methods are emerging to verify if the built part conforms to the design specifications. More research is needed for such measurements.

The new editions of ASME and ISO standards cover several composite manufacturing processes, but they need to cover even more processes that are being introduced into manufacturing at a rapid pace. There is an opportunity for both standards to be able to represent both a design (net) ply shape, and a manufacturing ply shape that included excess material added for activities such as hold-down pads for trimming and drilling. This calls for more research efforts in information modeling and engineering analysis tools.

6. SUMMARY AND CONCLUDING REMARKS

This paper presented a brief analysis of recent ASME and ISO standards on composite products. More details can be found in the standards documents themselves [7, 8]. By restricting the

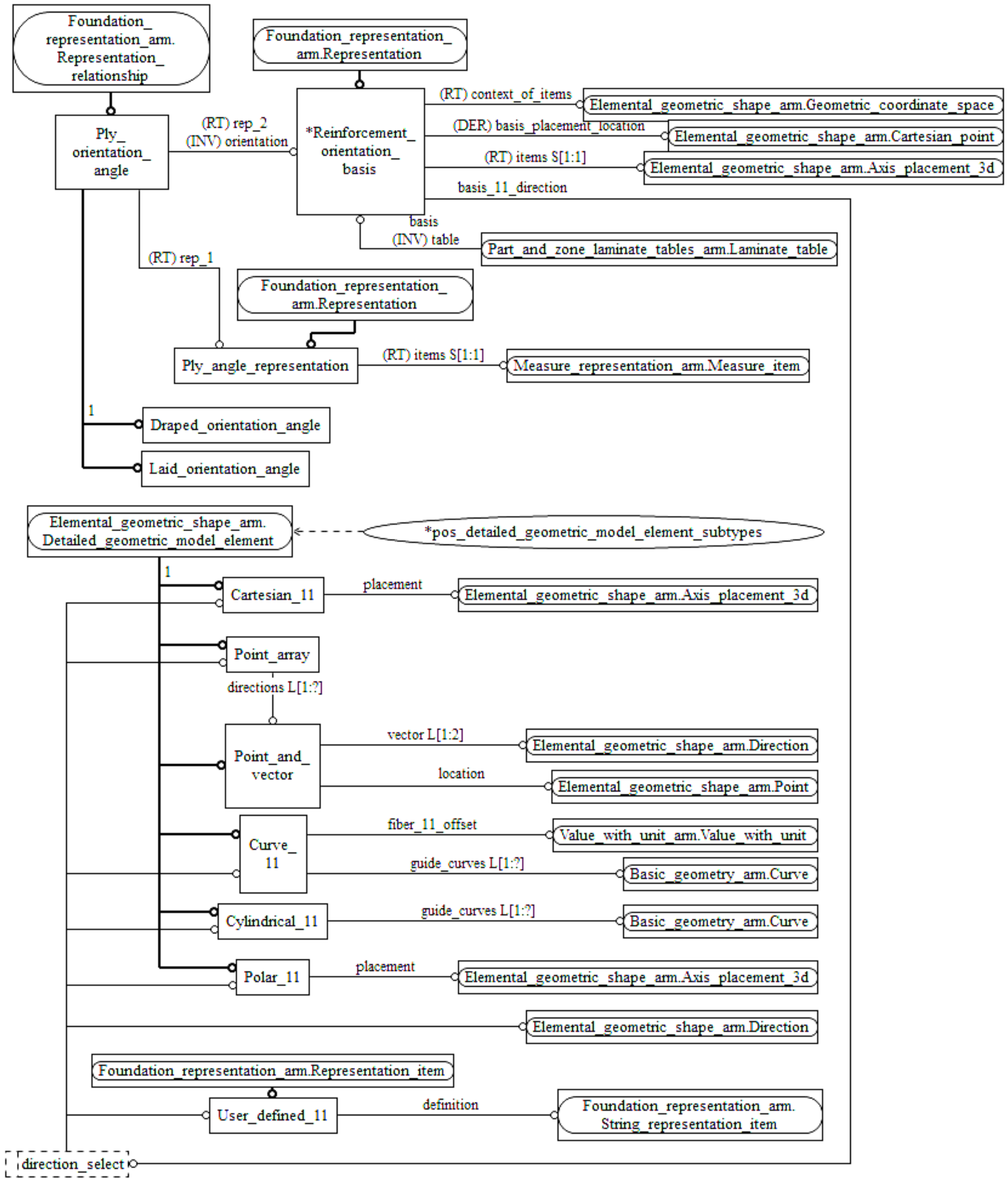


FIGURE 11: STEP data model for ply orientation [33].

analysis to a few salient features of these standards, the paper was able to focus on the concept of ply table, which together with its geometric companion, provides an important abstraction for information modeling.

While the ply table may represent only the uncured composite product, it provides a convenient representation for two of the important invariants under the curing process: combinatorial topology of the fibers and the angles between the fibers. Identification of these invariants in ply table is a major technical contribution of this paper. The ply table also provides vital information for sequencing for lay-up of plies, which is important for the composite manufacturing process.

The new editions of ASME and ISO standards are moving in the right direction towards enabling a digital transformation of composite product manufacturing. However, as described in Section 5, more research, measurements, and standardization are needed.

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