

November 2015

Towards a Semantic Knowledge Management Framework for Laminated Composites

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TOWARDS A SEMANTIC KNOWLEDGE MANAGEMENT FRAMEWORK FOR LAMINATED COMPOSITES

A Thesis Presented

by

VIVEK PREMKUMAR

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

September 2015

Department of Mechanical and Industrial Engineering

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FOR LAMINATED COMPOSITES**

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ACKNOWLEDGEMENTS

I would like to thank my advisors Dr. Ian Grosse, Dr. Sundar Krishnamurty, and Dr. Jack Wileden. Without their guidance and support, I would not be pursuing my master's degree.

I have received ample guidance from my fellow researchers in the Center for e-Design. Dr. Douglas Eddy has provided guidance as an expert in the field of engineering knowledge management and ontologies. I would like to acknowledge him for his guidance in getting me started on my first research project in graduate school. Hami Dinh has provided programming expertise to aid in the creation of the framework discussed in this thesis. I would also like to thank my fellow lab mates Jeff McPherson, Alex Liotta, and Dr. Tony McCaffrey, for their help and support during my research.

I would also like to thank my family and friends for their tremendous support. Without this support, I would not have been able to achieve my academic goals.

This research was made possible with funding from the NSF to the Center for e-Design Grant Nos. 0332508 and 0838747, and through industry members of the NSF Center for e-Design, especially Vistagy, Inc. (now part of SIEMENS PLM Software).

ABSTRACT

TOWARDS A SEMANTIC KNOWLEDGE MANAGEMENT FRAMEWORK FOR LAMINATED COMPOSITES

SEPTEMBER 2015

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The engineering of laminated composite structures is a complex task for design engineers and manufacturers, requiring significant management of manufacturing process and materials information. Ontologies are becoming increasingly commonplace for semantically representing knowledge in a formal manner that facilitates sharing of rich information between people and applications. Moreover, ontologies can support first-order logic and reasoning by rule engines that enhance automation. To support the engineering of laminated composite structures, this work developed a novel Semantic LAMinated Composites Knowledge management System (**SLACKS**) that is based on a suite of ontologies for laminated composites materials and design for manufacturing (DFM) and their integration into a previously developed engineering design framework. By leveraging information from CAD/FEA tools and materials data from online public databases, **SLACKS** uniquely enables software tools and people to interoperate, to improve communication and automate reasoning during the design process. With **SLACKS**, this research shows the power of integrating relevant domains of the product lifecycle, such as design, analysis, manufacturing and materials selection through the engineering case study of a wind turbine blade. The integration reveals a usable product lifecycle knowledge tool that can facilitate efficient knowledge creation, retrieval and reuse, from design inception to manufacturing of the product.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to laminated composites

Decreasing the weight of a material used in a product has a great impact on the performance of the system in many engineering applications. This has led engineers to research and seek materials that have high strengths with low densities. Composite materials are one such type of materials that are developed to meet these requirements. Composite materials are defined as materials made with at least two distinct materials with distinctly different physical or chemical properties at the macroscopic or microscopic levels. Due to the vast possibilities this definition entails, the naming and classification of composite materials can often be non-informative and require domain specific knowledge in order to understand what is being presented.

Composite materials generally consist of two or more materials: a reinforcing agent (fiber material) and a compatible resin binder (matrix material), to obtain specific characteristics and properties. Polymer matrix composites, also called ‘advanced composites,’ consist of a polymer resin matrix that encapsulates high-strength, high-modulus fibers that are usually continuous. The matrix will guarantee a load transfer in between the fibers as well as external loadings into the fibers. This results in unique properties such as high stiffness and tensile strengths in the fiber direction depending on the fiber-volume fractions and type of fibers. However, composite materials have poor strengths in compression and transverse to the fiber directions. Moreover, shearing is a problem when compared to isotropic materials such as structural steel [1].

The focus of this research is on laminated composites. Approaches to the analysis of composite materials can be macro-scale, meso-scale or micro-scale. Macro-scale modeling would consider the analysis on the entire structure as a whole, while the micro-scale model would identify individual fibers and analyze at a microscopic level. In this research, we look at laminated composites which is the class of composite materials whose structures consist of layers (or plies or laminas) of composite materials bonded together with different orientations to form a stacking sequence as shown in Figure 1. Analyzing stresses, strains, and failure criteria of the composite laminate requires the modeling of these single layers a composite design is built up by. This type of modeling represents the meso-scale approach.

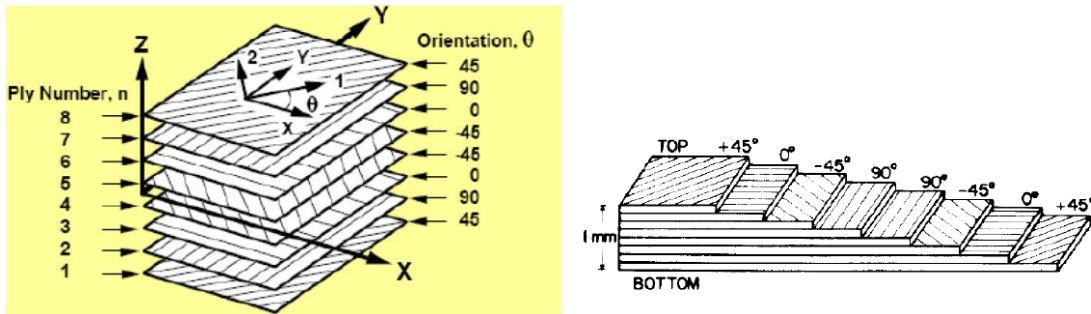


Figure 1: Two separate illustrations of a composite laminate with a stacking sequence [2]

1.1.1 Fiber material

Fibrous plies are the main components in laminated composite materials that add strength and stiffness to the material. These physical characteristics are governed by four main properties of the ply: the basic mechanical properties of the fiber itself, the surface interaction between the fiber and resin, the amount of fiber in the composite (fiber volume fraction), and the orientation of the fibers in the composite. As a general

qualitative rule, the stiffness and strength of a laminate will increase with increasing fiber volume fractions. Once the fiber volume fraction reaches 60-70%, tensile stiffness will increase, but the laminate's strength will reach a maximum and then begin to decrease. This happens due to an insufficient amount of resin to adhere the fibers properly [3].

Plies are manufactured in various fiber reinforcements and weave styles with different orientations. Composite laminate fiber reinforcements fall in the following categories: uni-axial, bi-axial, tri-axial, and multi-axial. Thus, uni-axial composites have fibers in one primary direction, bi-axial in two, and multi-axial in more than two directions. Within each category of plies, with the exception of uni-axial, various forms of plies can be created. These forms are called weave styles. The mechanical properties of the various plies are related to the number of crimps present in the weave per unit length. Crimps refer to the number of times a strand cycles between the top and bottom surface of the material [4]. For example, bi-axial plies can have the following weave styles: plain, twill, satin, basket, and leno. Figure 2 below depicts each of the weave styles. Plain weaving refers to a style in which fibers are weaved under and over each other. This style has good porosity, is symmetric, and has good stability. This material has a high density of crimps and thus has lower relative mechanical properties. Twill and Satin weave styles are similar to the plain weave orientation in that they are weaved in an under-over fashion. They differ in the number of fibers they skip before making the transition. Twill fabrics are of the form in which the distance between transitions is two fibers; while satin have more than two fibers usually four, five or eight. As can be seen from Figure 2, these styles have less crimp and thus higher mechanical properties. The basket weaving style is similar to the plain weaving style except two or more fibers are

coupled together along the weave directions. The symmetrical properties as shown in the figure are not necessary for basket weaved fibers. For instance, it is possible to have this type of weaving with eight coupled fibers in one direction and four in the other. Leno weaves have two or more parallel and interlocked warp fibers. The warp fibers are locked by spiraling them around each other. The common woven fabrics are Glass, Carbon, and Aramid. Other types of reinforcements include mat, knitted, stitched and braided forms [4].

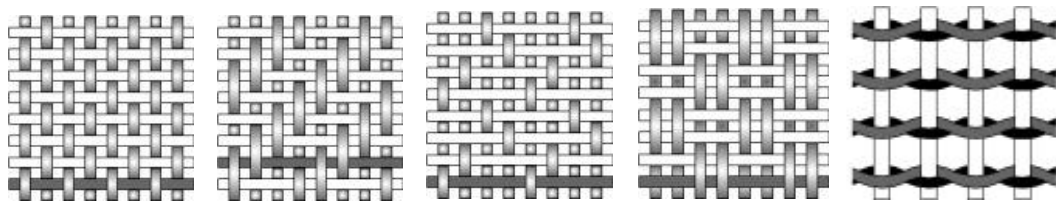


Figure 2: Weave styles (Left to Right) – Plain, Twill, Satin, Basket, Leno respectively [4]

1.1.2 Matrix Material

Resins are the common matrix material that serve as the binder in composite laminates. Their main functions include spreading loads between each of the individual fibers or plies and also protecting fibers from damage caused by abrasion and impact. To serve this goal, resins must contain the following properties - good mechanical properties, good adhesive properties, good toughness properties, and good resistance to environmental degradation [4]. Shrinkage of the matrix material after curing is an important engineering consideration during the manufacturing of laminated composites. Resins can be thermoset, thermoplastic, metal or ceramic. The three main types of resins used commonly in laminated composite materials include polyester, vinyl ester, and epoxy resins.

1.1.3 Other Design Considerations

In addition to the above mentioned constituents of laminated composites, two important design considerations in most cases include core material and coatings. The purpose of a core between layers is to increase a laminate's stiffness by thickening it to form a sandwich structure as shown in Figure 3. Since this is its major function, core material is of low weight so as to not add additional stresses on the final product [4]. Foam, balsa wood, and honeycomb are popular examples of core materials used in marine and wind energy industries. The term coatings refer to finishes applied to composite materials that protect the final product from environmental damage and increase the durability and resistance of the outer surface. Gel coats are specialized polyester resins formulated to provide a cosmetic outer surface on a composite product [4].

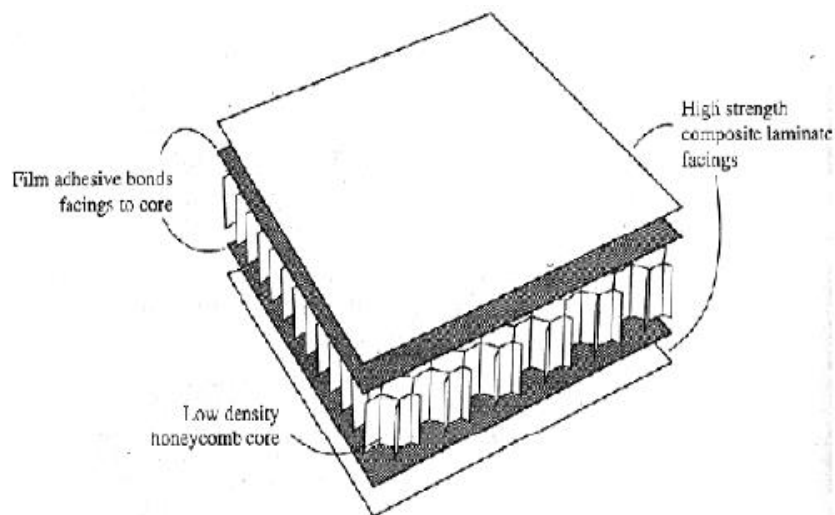


Figure 3: Example of a sandwich structure with core material [2]

1.1.4 Manufacturing of laminated composites

The two main categories of composite laminate material manufacturing are open and closed molding. Open molding processes involve the creation of composite materials with open exposure to the atmosphere during fabrication [5]. Open molding is often more cost effective than closed molding techniques, yet requires increased labor and can have negative effects on the health of workers due to their close interaction to the resins [4]. It can be inferred that closed molding techniques do not allow for such open exposure to the atmosphere and thus the potential for negative health effects are greatly diminished. Open molding techniques include hand lay-up, spray lay-up, and filament winding whereas closed molding manufacturing include prepreg molding and resin transfer molding [5].

1.1.4.1 Hand Lay-up

Hand lay-up refers to the production technique in which fiber and resin layers are applied by workers to a mold sequentially to produce the final product. The advantages of this technique include the fact that it is the simplest method to implement, there is minimum investment in equipment, and with skilled workers, consistent quality and production rates can be obtained [5]. To minimize dry spots, rollers are often used to spread resin and remove air [4]. This void reduction process is not very efficient and thus composites made using this process need a higher proportion of resin, and thus have lower material mechanical properties. Figure 4 shows the manufacturing process used in hand lay-up.

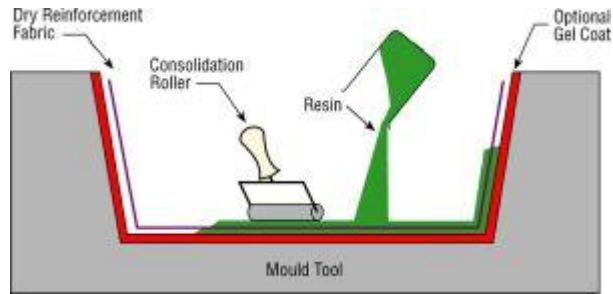


Figure 4: Hand lay-up process [4]

1.1.4.2 Spray Lay-up

The spray lay-up manufacturing process involves combining chopped fiber (roving) with resin that combines while being sprayed onto a mold. This process is one of the least expensive composite material manufacturing processes. But the low cost comes with consequences for reduced mechanical properties of the material. The decreases in attainable mechanical properties come from a variety of sources including the small size of the chopped fibers, the necessity to use low viscosity resin, and the fact that laminates made using this process have high proportions of resin compared to volume [4]. Figure 5 below depicts a typical set up for the spray lay-up process.

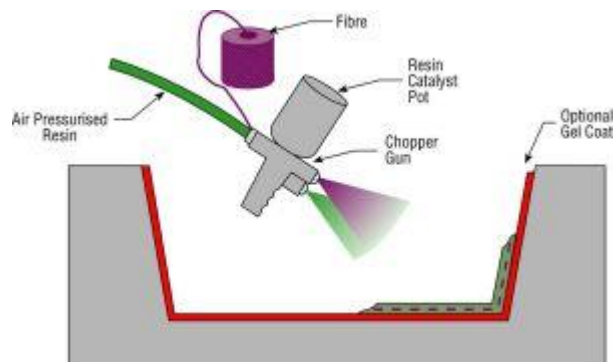


Figure 5: Spray lay-up process [4]

1.1.4.3 Filament Winding

Filament winding is an automated manufacturing process in which a male mold (mandrel) is rotated and wraps fibrous material around the mold. A predetermined geometric pattern is used that provides optimal material characteristics [5]. Once the winding process has finished the material is cured and the mold is removed. Advantages of this technique include its automated process, the ability to achieve a high strength-to-weight ratio, and the ability to create composites with uniformity and precise fiber orientations. Only materials with cavities can be created because a male mold is used in the process [5]. Figure 6 depicts a typical filament winding machine used in the manufacturing process.

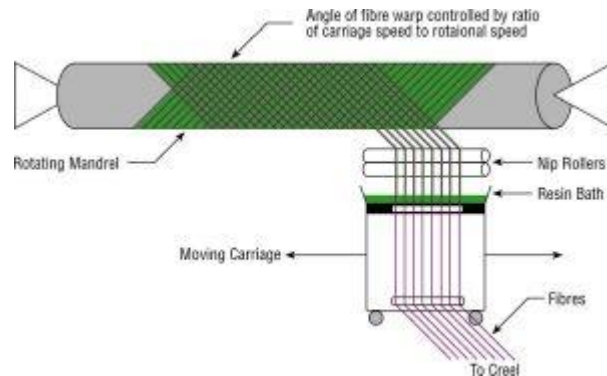


Figure 6: Filament winding process [4]

1.1.4.4 Vacuum Bagging

Vacuum bagging, a closed mold manufacturing process, is a process performed after the hand lay-up operation. The vacuum bagging process involves sealing a plastic film over the laminate and sucking the air out. This process removes much more air from the hand lay-up process and thus decreases dry spots that cause lowered mechanical

properties. The main disadvantages of this process include higher costs and a higher worker skill level needed. Figure 7 depicts a typical setup for the vacuum bagging process. As seen from the figure, an absorption fabric is sometimes added to the vacuum. This mops up any excess resin used in the hand lay-up process. The decrease in excess resin allows for laminates with higher fiber volume fractions and thus increases mechanical properties [5].

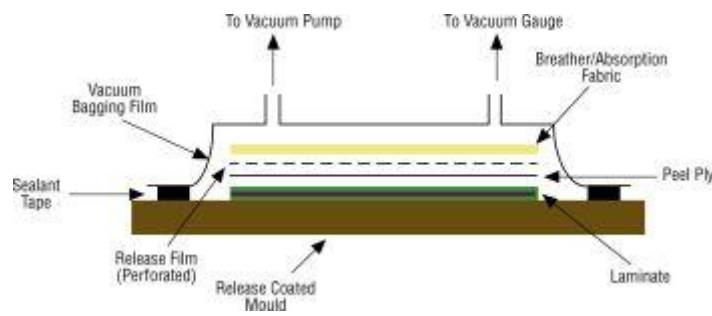


Figure 7: Vacuum bagging process [4]

1.1.4.5 Resin Infusion

There are many different types of Resin infusion techniques but they all share certain commonalities. One common resin infusion method is the Resin Transfer Molding (RTM) process which involves holding dry fibers in their desired orientation and applying resin through use of a differential pressure that completely wets the fiber. The main advantages of using RTM include the ability to attain a high fiber volume content, very low void or dry regions, a double-sided mold that allows for exact geometry on both faces, increased worker safety due to the molding enclosure, and reduced labor. The main disadvantage is the high cost of the tooling and the weight of the tooling which is needed to not break under the pressure load [4]. Figure 8 illustrates a typical RTM process.

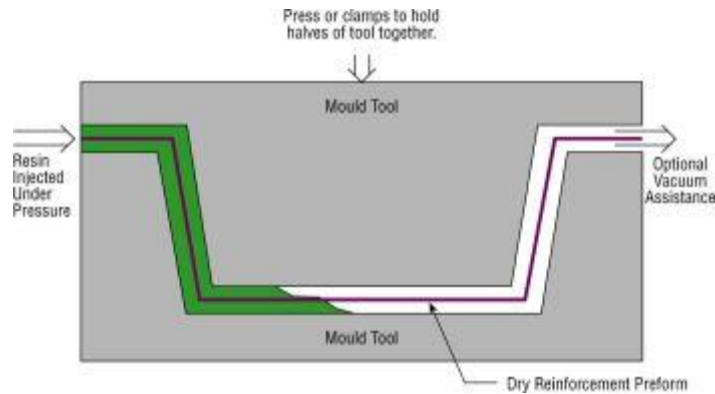


Figure 8: Resin transfer molding process [4]

1.1.4.6 Prepreg Molding

Prepreg molding or pre-impregnated molding refers to the manufacturing processes in which plies are used that have resin already imbedded in them by the manufacturer. Generally an autoclave is used to apply a desired heat and pressure to the plies to attain the desired results [4]. The main advantages to such a system include a high attainable fiber volume fraction, accurate resin to fiber ratios as specified by the manufacturer, optimal resin chemistry due to the ability to use high viscosity resins which are not possible in other techniques, and potential labor saving through automation. The disadvantages include the high costs of an autoclave and tooling equipment, core materials that can withstand high temperatures, and the need to store the material in a freezer before use to keep the resin in the desired location [4]. Reinforcements made in this fashion are usually available as ‘prepregs’. Prepreg molding is usually followed by vacuum bagging and then curing to get the final product. Figure 9 shows a typical setup for a prepreg molding process.

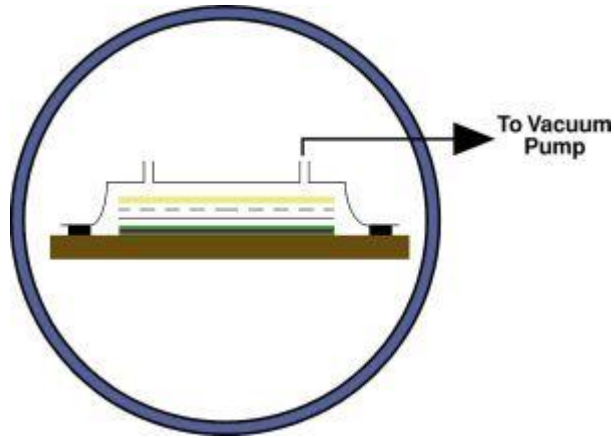


Figure 9: Prepreg molding [4]

1.1.4.7 Pultrusion

Pultrusion is a continuous manufacturing process in which fibers are pulled through a resin tank and a heated die. The die shapes the material and controls the resin content of the final product [4]. Due to the continuous nature of this process composites can be manufactured quickly and inexpensively. Additionally composites produced with such a process have very straight fibers and high fiber volume fractions leading to increased material strength [4]. However, this method cannot be used for certain applications such as wind turbine blades because the process is restricted to materials with constant cross-section. Figure 10 shows the pultrusion process.

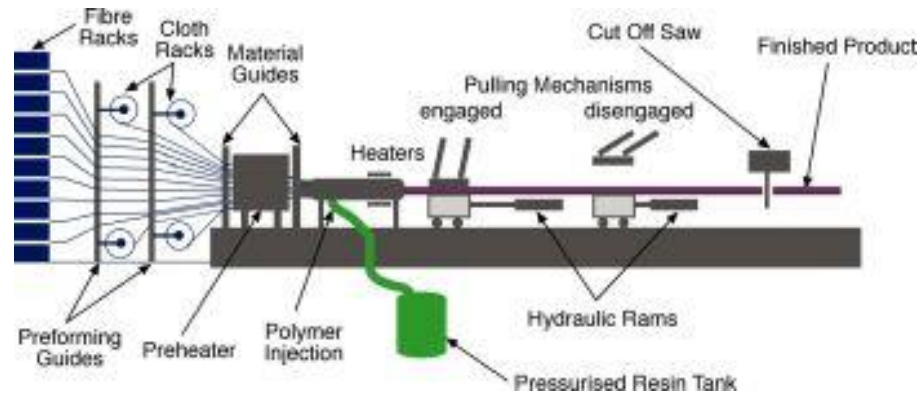


Figure 10: Pultrusion process [4]

1.2 Depth of knowledge and lack of synergy between domains of expertise

The use of laminated composites in engineered products has seen a rapid rise in recent years. As can be seen from section 1.1, the engineering of laminated composites is remarkably different from traditional design using isotropic materials. Companies dealing with projects involving laminated composites have a difficult time trying to efficiently manage the large amount of knowledge throughout the product lifecycle [6]. There is usually some loss of clarity about the information in the design-to-manufacturing process flow as the cycle advances [7]. This is especially true in the case of automobile and aerospace industries where laminated composites are heavily used. For example, consider the construction of Boeing's Dreamliner. It includes thousands of parts and involves designing laminated composite structures for which the design engineers spend days trying to evaluate the right choice of material combinations. This is because there is an abundance of materials to choose from in the design of a laminated composite part. The design engineer needs to consider many parameters during the design process of a laminated composite part which makes the process knowledge intensive. A few examples

are: fiber orientations, ply angles, choice of fabric for the plies, matrix material, number of layers in the stacking sequence, and how the final product is going to be manufactured.

Ideally, design engineers will constantly interact with the analysis and manufacturing engineers to brainstorm and discuss major issues of laminated composites such as materials selection, zonal stresses, failure criteria, fiber orientations, draping, warpage, and ply-drops to name a few [8]. However, in reality, design, analysis and manufacturing engineers do not work together constantly. Instead, they often tend to recede from the big picture and focus on their own domains, often leading to conflicts of interest [8]. Thus, the large amount of knowledge coupled with a serial product development process usually causes multiple design iterations, excessive design reviews, large lead times and high costs.

1.3 The need for knowledge management tools

Since the design and manufacturing of laminated composites are highly knowledge-intensive activities, efficient mechanisms for capturing, reusing, and sharing the wealth of knowledge involved are sorely needed. The first challenge is the creation of web-enabled knowledge bases that will replace existing knowledge structures to facilitate consistent exploitation of knowledge throughout its lifecycle. Creation of such knowledge models requires a solid understanding of the concepts of the attendant domain along with the interrelationships and concept attributes [9]. Also, the problem of the increasingly heterogeneous and distributed nature of current engineering environments and the lack of synergy needs to be addressed [10]. Hence, the second challenge is to bridge the gap between legacy systems and to integrate the various product lifecycle domains. This can

be done, for example, by leveraging output information from Computer Aided Design (CAD) or Finite Element Analysis (FEA) software typically used in organizations that design with laminated composites.

Another critical aspect is that the scientific data and knowledge such as laminated composite materials testing data generated in organizations and institutes are available on the Internet as Wikis, e-Journals, and online databases [11]. These resources are often decoupled or at best loosely linked with each other, and their “representation, terminology, and formats are not standardized” [11]. Hence, the third challenge is to develop an efficient knowledge structure which unifies such existing web resources for laminated composite materials and integrates these information resources with the design, analysis and manufacturing domains for laminated composite products.

1.4 Ontologies: The path to efficient knowledge management

Ontologies have been a philosophical subject of study since the time of Aristotle around 300 B.C., according to Barry Smith [12]. However, when computer scientists discuss ontologies, they are likely not referring to this philosophical study, but rather the modern definition of ontologies. In the 1980s, the Artificial Intelligence (AI) and Information Sciences fields adopted the term “ontology” to cover their contributions and efforts in knowledge engineering and management [12]. Finally, in 1993, Gruber stated the modern definition of ontology as “explicit formal specifications of the terms in a domain and relations among them” [13]. In other words, ontologies are formal representations of terminology used in a given field, with connections showing specifically how each term relates to each other. Theoretically, the main components of

an ontology are classes, properties, and instances. A class can be thought of as a category that groups semantically relevant instances. Properties are assigned to classes that describe their instances. Instances, also called individuals, are the actual items in a class that one categorizes.

In order to illustrate an ontology, let us look at the example in Figure 11. The figure shows a simple ontological structure of an 'Assembly'. The class 'Assembly' has an instance called 'Wind_Turbine_Blade_Assembly'. Now, this assembly will have certain components associated with it. This is given by the property 'has_Component'. From the hierarchy, it is evident that the individual 'Wind_Turbine_Blade_Assembly' has the components, 'Shear_Web', 'Upper_Mold_Part', and 'Lower_Mold_Part'. The component 'Shear_Web' belongs to the class 'Sandwich_Structure', and the parent class of the class 'Sandwich_Structure' is 'Laminated_Composite_Component'. In this example, all the three components, 'Shear_Web', 'Upper_Mold_Part', and 'Lower_Mold_Part', belong to the class 'Laminated_Composite_Component'.

There are special property types that can be described in an ontology. Two of the most common property types that can be assigned to individuals are object properties and datatype properties. Object properties describe relationships between two or more instances in the ontology. A good example is the 'has_Component' property illustrated in Figure 11. Object properties can be generally functional, inverse, symmetric, or transitive. The 'has_Component' is a functional property. The inverse of this property would be 'is_part_of', indicating the parent assembly of the respective component. A symmetric property indicates the same relationship both ways for two instances. For example, consider that the 'Upper_Mold_Part' has a property, 'bonds_with', with

‘Lower_Mold_Part’ as the target instance. Then, the same is true for the ‘Lower_Mold_Part’. This means ‘bonds_with’ is a symmetric property and has the same effect both ways on the two instances. Now, if an instance ‘A’ is related to an instance ‘B’ by a property, and instance ‘B’ is related to an instance ‘C’ by the same property, then instance ‘A’ is also related to instance ‘C’ by the same property, if the property is transitive. Datatype properties associates a property on an instance in the form of common datatypes such as integer, float or string.

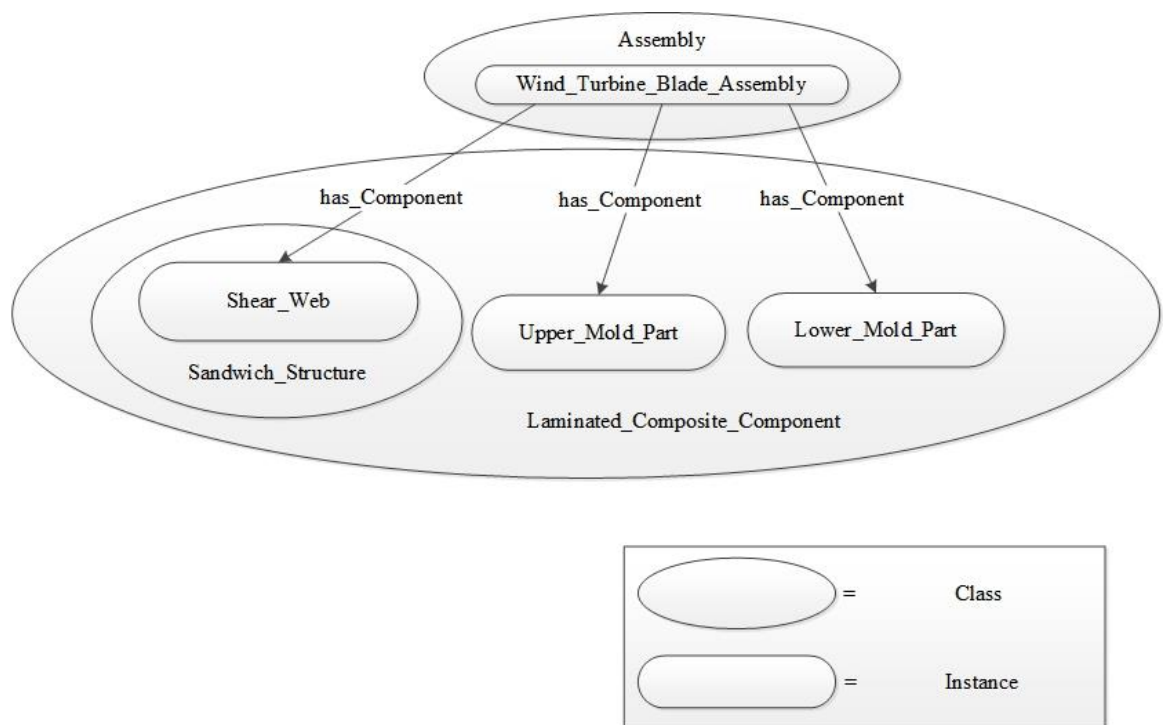


Figure 11: Illustration of a simple ontological structure

Ontologies are now extensively used to formalize domain knowledge with concepts, attributes, relationships and instances resulting in “reliable, verifiable and computer-interpretable knowledge mappings of a domain” [9]. Ontologies are already quite popular

in the biology domain. The National Center for Biomedical Ontology (NCBO) hosts the BioPortal which boasts a myriad of ontologies in the biology domain [14]. In engineering, ontologies can also address semantic interoperability issues between legacy systems because of their compatibility with the Semantic Web. Thus, ontologies offer the promise of efficient integration and transfer of knowledge between the various domains in the product lifecycle. Further, automated reasoning capabilities of ontologies can provide us with a semantic knowledge base that can act as an expert system for engineers to aid in certain design situations such as materials selection. Hence, we find that ontologies are potentially a powerful tool to help address all of the three challenges mentioned before [6].

Ontologies are generally compared with the abilities of relational databases. A relational database stores information in tables with rows and columns, where information stored in the same table is of the same type and therefore has the same characteristics, or column headers, that define it [15]. This database type is widely used in practice today in Database Management Systems (DBMSs) such as Oracle and MySQL. While ontologies can also serve the same purpose, relational databases fall short to ontologies in terms of sharing and semantic relatedness. The answers to queries from ontologies may include implicitly derived facts due to the ontology axioms, whereas relational databases can only just 'check' against the available data. While ontologies and the terms within them are defined by Universal Resource Identifiers (URIs), relational databases are relatively less universal [15]. These differences make ontologies a much more powerful tool.

1.5 SLACKS: Semantic LAMinated Composites Knowledge Management System

In summary, the engineering of laminated composite products 1) involves a large volume of information and knowledge spread across the domains of design, manufacturing, and analysis, 2) there is a general lack of formal semantic information models for capturing and sharing this engineering information and knowledge, and 3) the result is a disjoint nature of work between the domain experts that hinders efficient collaboration, and a lack of reuse of information and knowledge. To resolve this situation, we developed **SLACKS** - the **S**emantic **L**AMinated **C**omposites **K**nowledge **M**anagement **S**ystem [6]. The foundation of **SLACKS** is a laminated composite materials ontology that can assist the design engineers in finding adequate and relevant information. Furthermore, the laminated composite materials ontology standardizes the domain knowledge structure to enable consolidation of scientific and engineering data from existing resources. The design of laminated composites is closely related to its manufacturing processes and techniques, as the lay-up on the mold and the curing stage describe the setting of the final design. This is one specific reason for multiple design reviews and increased production times in laminated composites manufacturing environments. Hence, better integration of design, analysis and manufacturing domains in laminated composites engineering is required. Accordingly, **SLACKS** includes complementary ontologies related to the design for manufacturing (DFM) of laminated composite products. To facilitate a holistic approach to the laminated composites design process, **SLACKS** is integrated with a previously developed suite of ontologies for facilitating engineering design, called the e-Design framework (See the works of Grosse *et al.* 2005 [16]; Witherell, Krishnamurty and Grosse 2006 [17]; Fernandes *et al.* 2007

[18]; Witherell *et al.* 2008, 2009 [19,20]; Rockwell *et al.* 2008, 2009, 2010 [21,22,23]; Rockwell 2009 [24]; Witherell 2009 [25]). The application and effectiveness of **SLACKS** is demonstrated through the design, analysis, and manufacturing of a laminated composite wind turbine blade [6].

CHAPTER 2

LITERATURE REVIEW

2.1 Evolution of Engineering Knowledge Management

The field of knowledge management and representation has been evolving continuously over the past three decades. Alavi and Leidner [26] summarize the conceptual foundations, taxonomies and research issues in the field of knowledge management systems. Of particular importance are the definitions for data, information and knowledge. In short, data are facts, information is processed data and knowledge is personalized information [26]. Therefore, one can possibly have too much information or too little knowledge. However, there exist knowledge taxonomies based on different perspectives. Examples include tacit, explicit, declarative and pragmatic types of knowledge [26]. In the case of engineering design, we tend to deal mostly with explicit knowledge.

In the engineering realm, collaboration between knowledge experts in different domains is one of the first steps towards effective knowledge management strategies [72,73,74]. In 1994, the International Organization for Standardization (ISO) came up with ISO 10303 - Standard for the Exchange of Product model data (STEP) for efficiently exchanging electronic product data between computer-based product lifecycle tools. Pratt [27] has given a brief review of STEP. Since then, there has been a strong push to effectively use structured knowledge to improve the work in the engineering domain. For instance, one of the key research efforts was the Methodology and tools Oriented to Knowledge-based engineering Applications (MOKA) project [28]. The MOKA project aimed at developing a standard methodology for the development and

maintenance of knowledge-based engineering applications for product design [28]. Szykman *et al.* [29] introduced the concept of design repositories through the National Institute of Standards and Technology (NIST) Design Repository Project that helps store a large amount of corporate engineering design knowledge and thus reduce product development times. Also, an infrastructure for efficient exchange of information to address the issue of poor interoperability between Computer-Aided Engineering (CAE) software tools was put forth by Szykman *et al.* [30]. Szykman, Sriram and Regli [31] were major movers towards establishing the importance of knowledge in representing product models along with representing design rationale. Substantial efforts on the NIST Design Repository Project later evolved into the NIST Core Product Model (CPM) which divides artifact information into categories of form, function and behavior [32]. Unified Modeling Language (UML) diagrams detail the structure of CPM [32].

2.2 The growth of ontologies

The use of ontologies in engineering and scientific knowledge management can be dated as far back as 1994 when the Plinius ontology for ceramic materials was created [33]. In 1996, an ontology for managing requirements in engineering design was proposed by Lin, Fox and Bilgic [34]. Horváth, Vergeest and Kuczogi [35] then proposed formalizing design concepts using ontologies. It was becoming evident that ontologies not only provided formal structures for concepts and vocabularies, but they also had the potential for supporting inferences based on collective knowledge [36]. Shortly thereafter, the vision of a machine-interpretable “Semantic Web” was born [37]. The application of the Semantic Web in the field of knowledge management is discussed by

Fensel *et al.* [38]. Earlier efforts in semantic mark-up languages include the Extensible Markup Language (XML), Resource Description Framework (RDF), Ontology Inference Layer (OIL) and Defense Advanced Research Projects Agency (DARPA) Agent Markup Language (DAML). Currently, the Web Ontology Language (OWL) is the de facto standard for developing and representing ontologies. OWL is recommended by the World Wide Web Consortium (W3C) as the ontology language of the Semantic Web. OWL uses RDF/XML as the standard serialization which means that OWL-based ontologies can be parsed through open-source web-based technologies. OWL-DL is a sub-language of OWL that employs Description Logic (DL), which is an implementation of first-order logic. Mocko, Rosen and Mistree [39] have discussed DL in detail and the necessities for its use in engineering information management.

Recent research efforts focused on ontologies and ontology development methods for engineering design include the Product Family Ontology Development Methodology (PFODM) by Nanda *et al.* [40]. In this approach, Formal Concept Analysis (FCA) is introduced to identify similarities among a finite set of design artifacts based on their properties and then to develop and refine a product family ontology using OWL in order to support product family design. Ahmed, Kim and Wallace [41] describe a six-stage methodology for developing ontologies for engineering design. Yans *et al.* [42] used an ontology-based approach to develop product configuration systems. Li, Yang and Ramani [43] propose an Engineering Ontology (EO) based semantic framework for representing design information in documents, thus aiding their efficient retrieval. Chang, Rai and Terpenney [44] describe the development and utilization of ontologies specifically for Design for Manufacturing (DFM). A design ontology development approach is presented

by Storga, Andreasen and Marjanovic [45] that is aimed at achievement of a formal description of the Genetic Design Model System structure. Bock *et al.* [46] combined model-based approaches such as CPM with the open world semantics of ontologies for improving collaborative design. Finally, Barbau *et al.* [47] went further by integrating STEP geometric models and non-geometric product model information with OWL to create semantically rich OntoSTEP models.

Even though there has been several efforts in developing ontologies in the field of engineering design, the successes are not as profound as the ontology development efforts in the biological domain. Knowledge management is hugely popular and important in the biology community. With so much information being collected, the necessity to store it intelligently and reuse has led to a major investment in the development and sharing of ontologies for standardizing knowledge. Once a common vocabulary is used to describe things in a domain, it is possible to perform computational analysis because of the standardization [48]. The largest community ontology project is the Gene Ontology (GO) consortium [49]. Due to the scope of this project and the number of contributors, it was paramount to create a standardized annotation system. The success of the GO led to the creation of the Open Biomedical Ontologies (OBO) consortium [50]. The OBO requires that all of its ontologies be open, orthogonal, instantiated in a well-specified syntax, and designed to share a common space of identifiers [50]. A similar standardized and unifying community approach must be adopted and followed by researchers developing ontologies in all other domains including engineering design in order to achieve the same level of success as the biology domain.

2.3 Efforts tailored towards laminated composites

In contrast to general engineering design, the area of composites design, and in particular laminated composites design, has seen considerably less work with respect to knowledge management and ontological modeling. Verhagen and Curran [9] have developed an ontology that is limited to the composites manufacturing domain pertaining to the field of aerospace. In their case-study, they discovered limitations in the web-based knowledge management tool called Ardans Knowledge Maker (AKM) used to support business tasks of an aerospace OEM. The limitations included AKM's inability to use inference mechanisms and the lack of support for automatic ontology import [9]. Boeing also has incorporated a tight people-centric knowledge management approach, and they have presented some examples of knowledge management in action [51]. **SLACKS** is significantly different in that the design, analysis, materials and manufacturing domains are integrated to effectively aid engineers with collaboration and sharing of information pertaining to laminated composites.

On another note, Sapuan [52] has shown that a knowledge-based system for materials selection is essential for efficient engineering design. Similarly, efforts have been made to efficiently standardize and exchange materials information. For example, the Materials Markup Language (MatML) [53] is one of the popular efforts to create a materials information exchange standard based on XML schemas. However, lack of semantics in XML representation has led to comprehensive development efforts in OWL such as the research performed by Cheung, Drennan & Hunter [54] and Ashino [11]. Ashino and Fujita [55] have proposed an OWL structure for design-oriented materials

selection. Thus, there is a close correlation between engineering knowledge management, information exchange and materials selection. With **SLACKS**, this work demonstrates the integration of the design and analysis domains with the materials domain to address issues such as materials selection involved in the design of laminated composite parts.

SLACKS is built upon the concepts borrowed from a previously developed suite of ontologies for engineering design called the e-Design framework [16,17,18,19,20,21,22,23,24,25]. Figure 12 shows the domains previously covered by the e-Design framework suite of ontologies. The chapters that follow will explain **SLACKS** and its benefits in detail. Chapter 3 will introduce **SLACKS** with relevant background information and then expand the description on its underlying knowledge structure. Chapter 4 will show how **SLACKS** was developed into a knowledge base for storing and retrieving materials information. Then, Chapter 5 will outline the process of integrating the design and analysis domains through **SLACKS** and the advantages of the overall integration.

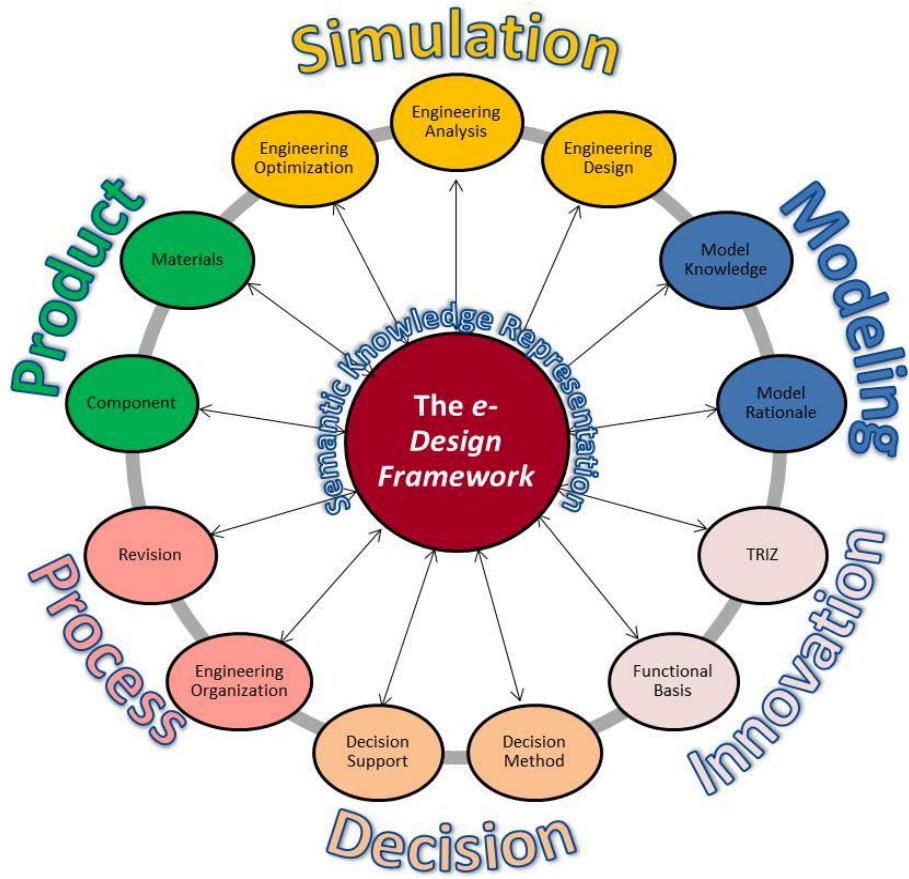


Figure 12: The e-Design framework suite of ontologies

CHAPTER 3

THE SEMANTIC KNOWLEDGE SYSTEM

3.1 Overview of SLACKS

The purpose of **SLACKS** is twofold. Firstly, this development effort is tailored towards the creation of a consistent and efficient knowledge structure for use with the design for laminated composite products and the standardization of concepts in that domain. Secondly, the goal is to support the transfer of relevant product lifecycle related information from CAD/FEA tools and spreadsheets to provide an integrated environment for collaboration between people and software tools within an organization. As a result of these efforts, this work also develops an expert materials selection knowledge base when combined with DL rules that operate on the domain knowledge.

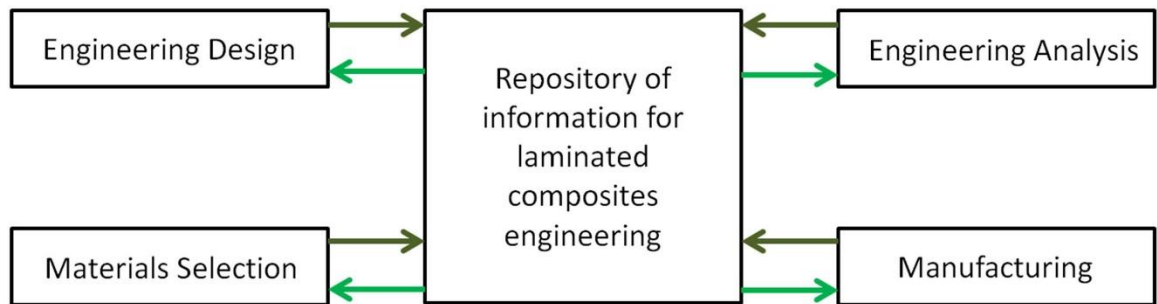


Figure 13: Outline of integration in SLACKS [6]

Figure 13 outlines the relevant domains that are integrated in **SLACKS**. **SLACKS** is written in OWL-DL as mentioned earlier in Chapter 2. The tool used to develop ontologies for **SLACKS** is Protégé-OWL which is developed in the Java programming language. Protégé is built around the open world assumption which states that just

because an instance has been implemented in an ontology does not mean that the instance is complete. This assumption limits the mathematical and semantic reasoning capabilities by removing the use of exact mathematical logic, for example, greater than or equal to, for instance mapping operations. This can lead to assertions in the ontology that are not definitively conclusive and hence, must be explicitly described. Consistency checking is a functionality of many Protégé plug-in reasoners which ensures that the implemented ontology is logically correct. One of the primary consistency checks is satisfiability. For example, the satisfiability check of the PELLET reasoner [56] verifies whether or not it is possible for an instance to be created in a class given the restrictions implemented in the classes. Protégé also supports the Semantic Web Rule Language (SWRL) that assists in making assertions and logical inferences within **SLACKS**. SWRL rules combined with OWL provide the intelligence that makes **SLACKS** an expert system for materials selection in the domain of laminated composite products.

3.2 Reusing existing ontologies

The e-Design framework consists of a suite of previously developed ontologies for the purposes of collaboration and automated reasoning during the engineering design process. This framework of modular ontologies allows the storing and reuse of design knowledge throughout the entire design process and improves communication at all design stages by sharing information in a formal documentation platform [57]. In this framework individual modules can be dynamically linked as needed for a given application. The knowledge base for any specific design may be created by instantiation within the framework with the relevant information [57]. Furthermore, designers will

benefit directly from the improved documentation for access to the most applicable information. Advantages include maintaining the consistency of the information throughout the process while limiting any redundancy in the entering or use of the specific information. More details about the framework can be found in earlier publications [16,17,18,19,20,21,22,23,24,25].

To facilitate the standardization of units, NASA has already developed a ‘Units’ domain ontology which is available from and maintained by the Jet Propulsion Laboratory in their suite of Semantic Web for Earth and Environmental Terminology (SWEET) ontologies on their website. The development of **SLACKS** reuses this ‘Units’ ontology to leverage their work. Reusing existing domain ontologies is one of the primary advantages of developing other related ontologies and is recommended [58]. The value of any property in **SLACKS** that requires units will draw upon the published NASA ‘Units’ ontology.

3.3 Description of SLACKS

A number of generic methodologies to construct ontologies are available apart from specific methodologies for engineering design as described in Chapter 2. Pinto and Martins [58] give an overview of these generic development methodologies such as the Tove, Enterprise and Methontology methodologies. However, none of these methodologies are a de facto standard. The common steps involved in the ontology development lifecycle as summarized by Pinto and Martins [58] in 2004 involves Specification, Conceptualization, Formalization, Implementation, Maintenance,

Knowledge Acquisition, Evaluation, and Documentation. **SLACKS** was developed along these lines.

Figure 14 shows a high-level diagrammatic representation of the concepts as classes in **SLACKS** encompassing the composite materials and DFM laminated composites ontologies. In **SLACKS** the general concepts for components, design models and engineering analyses have been adopted from the e-Design framework. Now, any composite structure composed of laminated composites has the concept of ‘Laminate’, ‘Ply’ and ‘Core’ [1]. These classes are assigned to be sub-classes of the ‘Artifact’ class [32]. This is part of the formalization step. When the formalization is developed in Protégé, the ontology has been implemented. Practically, a laminate can have sub-laminates but a ply cannot have sub-plyes. All laminates will have one to many plies for which the fibers are oriented in certain directions represented by the property of ‘has_Fiber_Orientation’. The set of laminated composite materials is populated in the ‘Fiber-reinforced_Composite’ class which is a sub-class of ‘Composite’ under the ‘Material’ class (Figure 14). Under the ‘Fiber-Reinforced_Composite’ class, we have the ‘Continuous_Fiber’ class under which we have the ‘Laminated’ class [1].

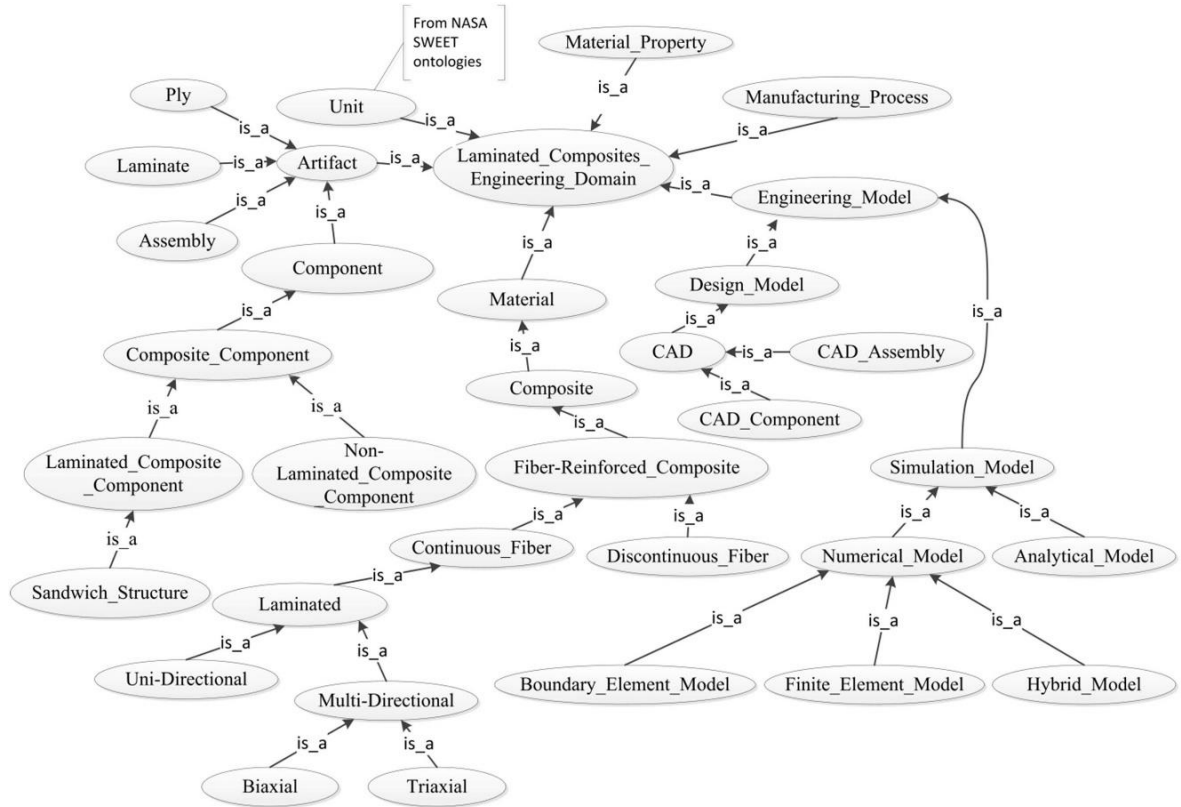


Figure 14: Class structure of SLACKS [6]

The ‘Laminated’ class has sub-classes that define the orientation of the fibers. These classes are excellent examples of class restrictions implemented in **SLACKS**. For example, the sub-class, ‘Uni-Directional’ has a necessary condition that the object property ‘has_Fiber_Orientation’ is exactly one, while the class ‘Multi-directional’ has a necessary condition that it ‘has_Fiber_Orientation’ of a minimum of two. Such class restrictions help to automatically populate instances to the relevant classes without violating the theory of the concepts present in the domain.

The ‘Material’ class in **SLACKS** is categorized based on the OWL structure classification in the MatOnto ontology proposed by Cheung, Drennan & Hunter [54], with one major difference being that the concept of “Hybrid Material” is replaced by the

‘Composite’ class. The high-level classification of the ‘Material_Property’ class in **SLACKS** is based on the structure of the Property ontology presented by Ashino [11]. The datatype properties of the laminated composite materials such as transverse and longitudinal moduli of elasticity are assigned based on the availability and organization of data presented in MIL-HDBK-17. MIL-HDBK-17 is a composite materials handbook series approved for use by all departments and agencies of the Department of Defense (DoD). By organizing and gathering data based on such an influential source, we are able to standardize relevant composite material information in the ontology. A class called ‘Textile’ also exists in **SLACKS** that can represent the fiber properties such as tow, mats and woven fabrics for the lay-up materials used in composite laminates [1]. For instance, all woven fabrics can be always considered to be biaxial materials of the ‘Multi-Directional’ class but not vice versa.

The ‘Ply’ class has references to its parent laminates. In addition, each ply links to its choice of material from the ‘Laminated’ class. Instances of ‘Laminated’ class refer to the fiber and matrix material from the appropriate class in ‘Material’. For example, a laminated composite material having 60% e-glass fiber will have the object property ‘has_Fiber_Material’ of ‘e-glass’ instantiated in the ‘Glass’ sub-class under ‘Material’ and the datatype property ‘has_Fiber_Volume_Fraction’ set to 0.6 [6].

CHAPTER 4

INTEGRATING COMPOSITE MATERIALS KNOWLEDGE

4.1 External composite material databases

This chapter builds upon the composite material ontology research initiated by Liotta [3]. To show the benefits of **SLACKS**, data is consolidated from the publicly available Sandia National Laboratories/Montana State University/Department of Energy (SNL/MSU/DOE) and OptiDAT databases, both of which are related to materials used in wind turbine blades [3]. OptiDAT is a database for the Optimat Blades project that investigated different failure methods that affect material on wind turbine blades. Thus the results can be used as “degradation models and design rules” [59]. The database consists of more than 3000 composite material tests performed in various test laboratories. Since the objective of the project was to find various degradation methods, the database contains many different test types. These test types vary between their loading type, environmental conditions, and geometry. Within the loading type category, each test could differ in whether they were static or fatigue. The geometries differ in the lay-ups and orientations of the laminates [59]. The environmental conditions include different temperature and humidity levels. Included in the OptiDAT database Excel spreadsheet is documentation on all the parameters of the test.

The SNL/MSU/DOE database contains composite material testing for 190 materials for a combined total of 12,000 material tests. The objective of the SNL/MSU/DOE project was to test the same material from the same lab in various loading conditions to make a good approximation of life for a given material [60]. It is important to note that this objective is different from the Optimat Blades project and thus the data structure will

differ to meet the objectives. The majority of the data for this database is for material testing of static and fatigue tests. Other tests include ply drop tests, stress rupture tests, crack growth tests, and environmental tests. Our consolidation focuses on the static and fatigue tests for both databases.

4.2 Getting the data into SLACKS

These databases, which consist of large spreadsheets, contain information about materials and their tests in a manner that is not standardized in anyway. Hence, the overlaps and the differences in the data structure of the two spreadsheets was identified. To import data from the spreadsheets into Protégé, Protégé plug-in called Mapping Master is used. Mapping Master makes use of a Domain Specific Language (DSL) to give users the ability to identify which columns of an Excel file correspond to classes, instances, or properties of instances. This allows a user to simultaneously map instances and their properties from Excel into ontologies. The following code is a sample DSL mapping used in this research:

```
Individual:    @Q*(rdf:ID)    Facts:    has_Material    @A*,    has_lay-up  
@B*,has_volume_fraction @C* (xsd:float)
```

The first piece of the syntax, Individual: @Q*(rdf:ID), determines that the instances to be propagated into Protégé are located in column ‘Q’ and row ‘*’, which corresponds to respective values specified in the input file. Similarly, remainder of the syntax determines the location of the property values that correspond to each instance. The modifier ‘(xsd:float)’ specifies that the properties in that column are all floats. Similarly expressions can be formulated for booleans, strings, and dates. A more detailed reference

for Mapping Master syntax can be found at the website for Mapping Master [61]. Figure 15 below shows a brief illustration of how the instances can be populated in SLACKS with the information from the two different material databases using Mapping Master. Figure 16 presents SLACKS in the Protégé ontology editor after the Mapping Master execution.

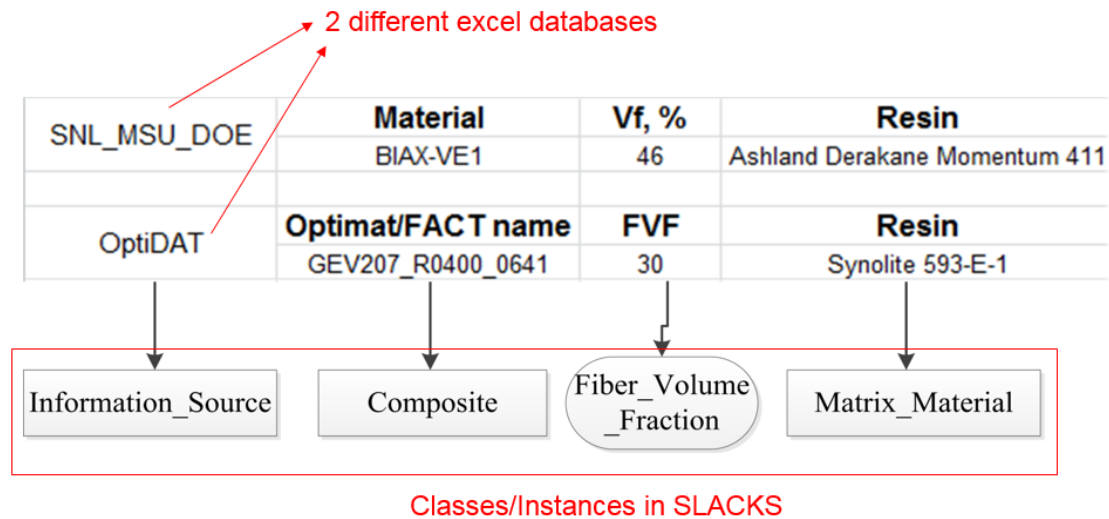


Figure 15: Organization of instances using Mapping Master acting on the two material databases

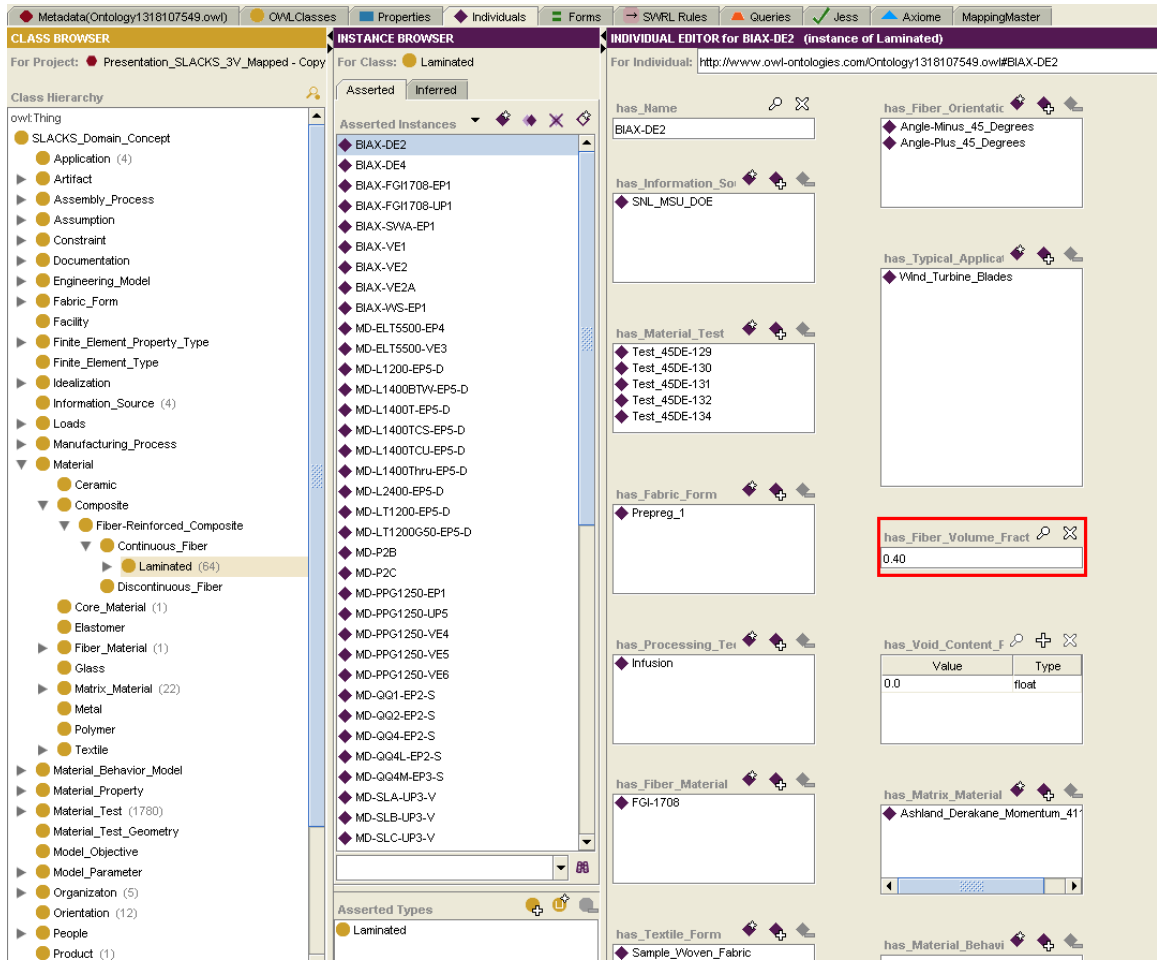


Figure 16: Materials populated in SLACKS as viewed in Protégé using the Mapping Master plug-in

4.3 Reasoning and Querying in SLACKS

Additional reasoning capabilities are needed to properly structure the instances into their proper classes. Two types of reasoning operations can be used to achieve this: class restrictions and SWRL rules. An example of class restriction was discussed in the previous chapter. The following is an example of a SWRL rule:

$$\text{Composite} (?c) \wedge \text{has_Material} (?c, ?m) \wedge \text{swrlb:equal} (?m, "UD1") \rightarrow \text{Uni-Directional} (?c)$$

This rule first identifies all instances of the ‘Composite’ class and names them as the variable ‘?c’. Next, it names their property ‘has_Material’ as ‘?m’. If the property of the individual is equal to ‘UD1’ i.e. if ‘?m’ = ‘UD1’, then the right half of the rule is parsed. Thus the individual “?c” is mapped to the class ‘Uni-directional’. Similar rules are used in the **SLACKS** to get around the open world assumptions of Protégé-OWL. The class restrictions and consistency checking, mentioned earlier, are used to determine whether the SWRL mapping is accurate.

The SPARQL query language makes use of Resource Description Framework (RDF) structuring to query the ontology. RDF uses URI structuring to name the relationship between two objects. This formatting is called an RDF triple because it uses three URIs: The first object, the second object, and the name of the relationship between the two objects. Using the triple structure, RDFs allow structured and semi-structured data to be mixed, exposed, and shared across different applications. Thus SPARQL is not Protégé specific and can be used within other RDF based frameworks. But, this comes with a drawback in that it cannot make use of the Protégé class structure for its querying purposes. The following query arranges all instances of the material tests of the database with the longitudinal modulus of elasticity greater than 60 in descending order and the results are shown in Figure 17.

```
SELECT ?label ?has_Material ?has_volume_fraction ?has_e ?  
FROM <http://edesign.ecs.umass.edu/ontologies/Framework2.0/  
SLACKS_DFM.owl>  
WHERE {  
?Composite rdfs:label ?label.
```

```

?Composite:has_Material ?has_Material.
?Composite:has_volume_fraction ?has_volume_fraction.
?Composite:has_e ?has_e.
FILTER(?has_e>60)}
ORDER BY DESC(?has_e)

```

SQWRL rules can be used to make querying in Protégé much more expressive. This is due to the fact that SQWRL is an OWL specific query language that can make use of an ontology class structure for its queries. Thus the original SPARQL query can be extended to include a restriction that the designer not only wants to find composite materials within a given modulus range, but in addition ones that are uni-axial. The following code shows how such a query would be expressed. The output of the query is shown in Figure 18.

```

Composite(?x) ^ has_e(?x,?e) ^ swrlb:greaterThan(?e,60) ^ has_Material(?x,?m)
^ swrlb:contains(?m,"UNI") -> sqwrl:select(?x) ^ sqwrl:select(?e)
^sqwrl:count(?x)

```

Results			
label	has_Material	has_volume_fraction	has_e
DOE-MSU:MD-P2B:P2B-1100	MD-P2B	55.0	107.0
DOE-MSU:MD-P2B:P2B-178	MD-P2B	55.0	107.0
DOE-MSU:MD-P2B:P2B-172	MD-P2B	55.0	100.0
DOE-MSU:MD-P2B:P2B-179	MD-P2B	55.0	99.2
DOE-MSU:MD-P2B:P2B-402	MD-P2B	55.0	98.2
DOE-MSU:MD-P2B:P2B-175	MD-P2B	55.0	97.3
DOE-MSU:MD-P2B:P2B-400	MD-P2B	55.0	96.4
DOE-MSU:MD-P2B:P2B-401	MD-P2B	55.0	95.4
DOE-MSU:UNI-ELM3610-UP3:13	UNI-ELM3610-UP3	53.0	63.0
DOE-MSU:UNI-ELT5500-UP3:428T	UNI-ELT5500-UP3	59.0	62.8
DOE-MSU:UNI-ELT5500-UP3:402	UNI-ELT5500-UP3	59.0	62.5
DOE-MSU:UNI-ELT5500-UP3:425T	UNI-ELT5500-UP3	59.0	61.9
DOE-MSU:UNI-ELT5500-UP3:429T	UNI-ELT5500-UP3	59.0	61.7
DOE-MSU:UNI-ELT5500-UP3:418	UNI-ELT5500-UP3	59.0	61.5
DOE-MSU:UNI-ELT5500-UP3:426T	UNI-ELT5500-UP3	59.0	61.5
DOE-MSU:UNI-ELT5500-UP3:431T	UNI-ELT5500-UP3	59.0	60.8

Figure 17: Results of a SPARQL query to find instances of high-modulus composite materials [6]

SQWRLQueryTab		Rule-1
?x		?e
Doe_MSU_Materials428T-UNI-ELT5500-UP3		62.79...
Doe_MSU_Materials425T-UNI-ELT5500-UP3		61.90...
Doe_MSU_Materials431T-UNI-ELT5500-UP3		60.79...
Doe_MSU_Materials402-UNI-ELT5500-UP3		62.5
Doe_MSU_Materials429T-UNI-ELT5500-UP3		61.70...
Doe_MSU_Materials427T-UNI-ELT5500-UP3		60.09...
Doe_MSU_Materials418-UNI-ELT5500-UP3		61.5
Doe_MSU_Materials426T-UNI-ELT5500-UP3		61.5
Doe_MSU_Materials13-UNI-ELM3610-UP3		63.0
Doe_MSU_Materials430T-UNI-ELT5500-UP3		60.20...
Doe_MSU_Materials420-UNI-ELT5500-UP3		60.59...
Doe_MSU_Materials410-UNI-ELT5500-UP3		60.59...

Figure 18: Results of SQWRL query to find high-modulus uniaxial composites [6]

The following paragraphs explore both the original naming structure of the databases and the subsequent Protégé naming structure in **SLACKS**. Figure 19 depicts the translation of the naming structure of each material test in the OptiDAT database [59]. It can be seen from the figure that without the translation presented here, it would be very hard to discern what this seemingly random string of letters and numbers represents. However, in Protégé each material and material test has been separated into its own individual class. For each individual composite material in the class, there are properties for the embedded information. Figure 20 depicts such an instance and shows how the properties have been represented.

The above example shows how information from two differently organized composite material databases can be cohesively combined and reasoned upon. It can be seen from this execution that the problems of inconsistent naming structures is easily resolved and that the functionality of **SLACKS** allows for added reasoning not available with the original flat database structure. Moreover, our work provides a standardized repository and an expert system for accessing composite materials information.

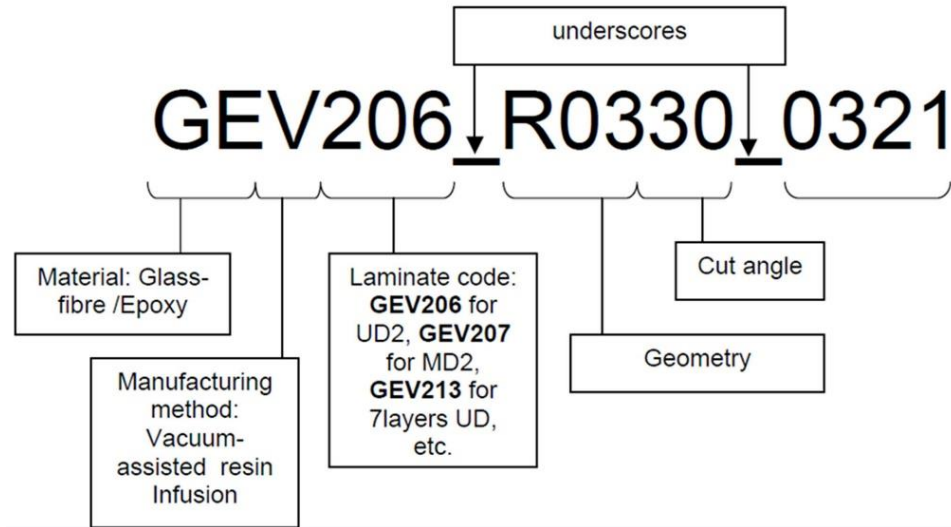


Figure 19: OptiDAT database material naming structure [6]



Figure 20: Instance of a composite material represented in Protégé after mapping [6]

CHAPTER 5

INTEGRATION OF PRODUCT LIFECYCLE DOMAINS

5.1 A wind turbine blade case study

Laminated composites are heavily used in the wind energy industry especially to make wind turbine blades [6]. To understand the intricacies in the design process of a product made of laminated composites, lay-ups/plies of laminates were modeled for a 30 meter wind turbine blade model provided by SIEMENS Specialized Engineering Software located in Waltham, MA using their surface-based composites engineering software 'FiberSIM' [6]. The FiberSIM software suite provided is integrated within Creo/Elements Pro software from Parametric Technology Corporation (PTC) located in Needham, MA. This integration essentially makes the sequential lay-ups of laminates relate to the actual geometric model of the panel or structure. FiberSIM is used by design engineers for laying up plies and laminates of composite structures based on an approximate structural topology of the blade determined during the early design stages. The software can then show various characteristics of the fibers and simulate draping based on the complexity of geometry within a manufacturing setting. Once the lay-ups are defined, the information can be transferred to FEA software. This study deployed the Composite PrepPost (ACP) module from ANSYS located in Canonsburg, PA for FEA purposes. The information from FiberSIM is transferred to ANSYS using the HDF5 interface. HDF5 is a file format or library for storing and managing data. Furthermore, finite element analysis based on specific loading conditions allows determination of deflection, stresses and failure plies of the wind turbine blade. FiberSIM records the information regarding the plies, laminates and cores of the composite structure. This is

part of the composites design process. The information about plies and laminates along with other design parameters can be exported to an XML file that has a schema called EnCapta XML. Another important point to be noted is that FiberSIM stores its materials data in a file called MaterialsDB.xml for the engineers to add or modify material parameters. The ANSYS Engineering Knowledge Management (EKM) tool also stores and provides XML files for simulations relevant to the ANSYS Workbench projects [6].

5.2 Details of the wind turbine blade case study

Wind turbine blades are usually manufactured using composite materials due to their inherent structural requirements such as low weight and rotational inertia, high rigidity, and resistance to fatigue and wear, because they are subjected to aerodynamic, inertial loads and severe environmental conditions. The most common fiber material used is the E-Glass fiber and the matrix is usually epoxy. A typical blade construction consists of outer composite skin layers with layers of plies supported by a main spar or shear web. The shear web is made up of the core structure and is commonly Balsa wood in the case of wind turbine blades. Manufacturing methods vary for different structures involving composite materials as described in Chapter 1. Wind turbine blades are mostly manufactured by resin infusion processes, RTM being an example (section 1.1.4.5). Sheets of fabric are laid up by hand on top of one another on a mold and injected with resin, and then cured after heating to form one-half of the airfoil structure. The two halves are then bonded using adhesives to form the whole blade. Figure 21 shows the airfoil cross-section of a wind turbine blade.

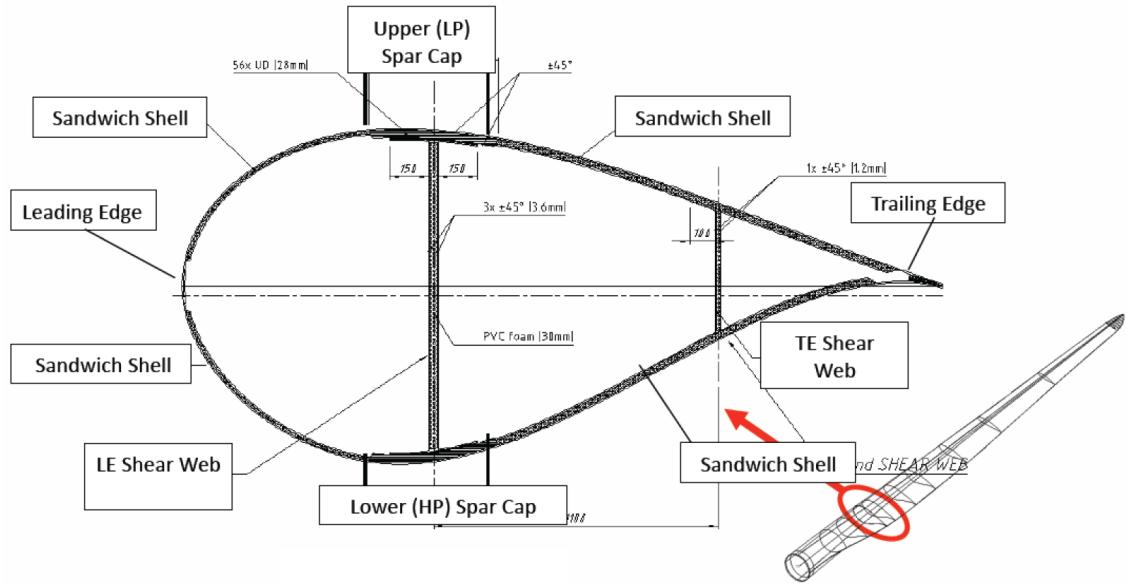


Figure 21: Airfoil cross-section of a horizontal-axis wind turbine blade [2]

5.2.1 Design of the wind turbine blade in Creo and FiberSIM

Airfoil sections are created in Creo/Elements Pro by importing coordinates of the profile that are formatted in text using the import feature built into the software. Then, the spines of both the airfoil halves of the blade are defined and a surface is swept through the sections with the spines acting as chains. This gives us the whole blade of length 30 m to start with. It is to be noted that any geometrical changes to the part must be addressed using the text file that was used to import the coordinates.

The whole blade model is an assembly of 3 parts: the upper half-blade, the lower half-blade and the shear web. The lower half-blade is considered here for illustrating the composite lay-up. The CAD normal in Creo/Elements Pro determines the direction of lay-up. On opening the FiberSIM Graphical User Interface (GUI) from within the CAD interface, we can create a “Laminate” for the lay-up surface. A snapshot of the interface is shown in the Appendix. This laminate includes the list of all the plies to be laid up on

the mold. However, a coordinate system specific to the laminate must be setup so that the zero-degree fiber direction is known for ply reference during modeling. This is done using a “Rosette”. The “Ply” option is used to create 64 plies for the lower half-blade laminate as per preliminary design criteria based on topology optimization. A robust design will have the number of plies increases towards the root, leading edge, trailing edge, and the spar cap of the blade. A number of geometric entities have to be referenced to create a ply. These geometric entities are first created in Creo and then mapped to the plies in FiberSIM to determine the area on the laminate mold where the ply will exist. The material properties for each ply are also assigned using the customizable material database available within FiberSIM in MaterialsDB.xml format. A similar approach is taken for the rest of the CAD parts that require the composite lay-up. FiberSIM also shows the wrinkling or draping effects of the fibers over sharp contours in 3-D space by using the “Net Producibility” option. Figures 22, 23 and 24 illustrate the FiberSIM GUI for certain important steps during the setup of the ply lay-ups.

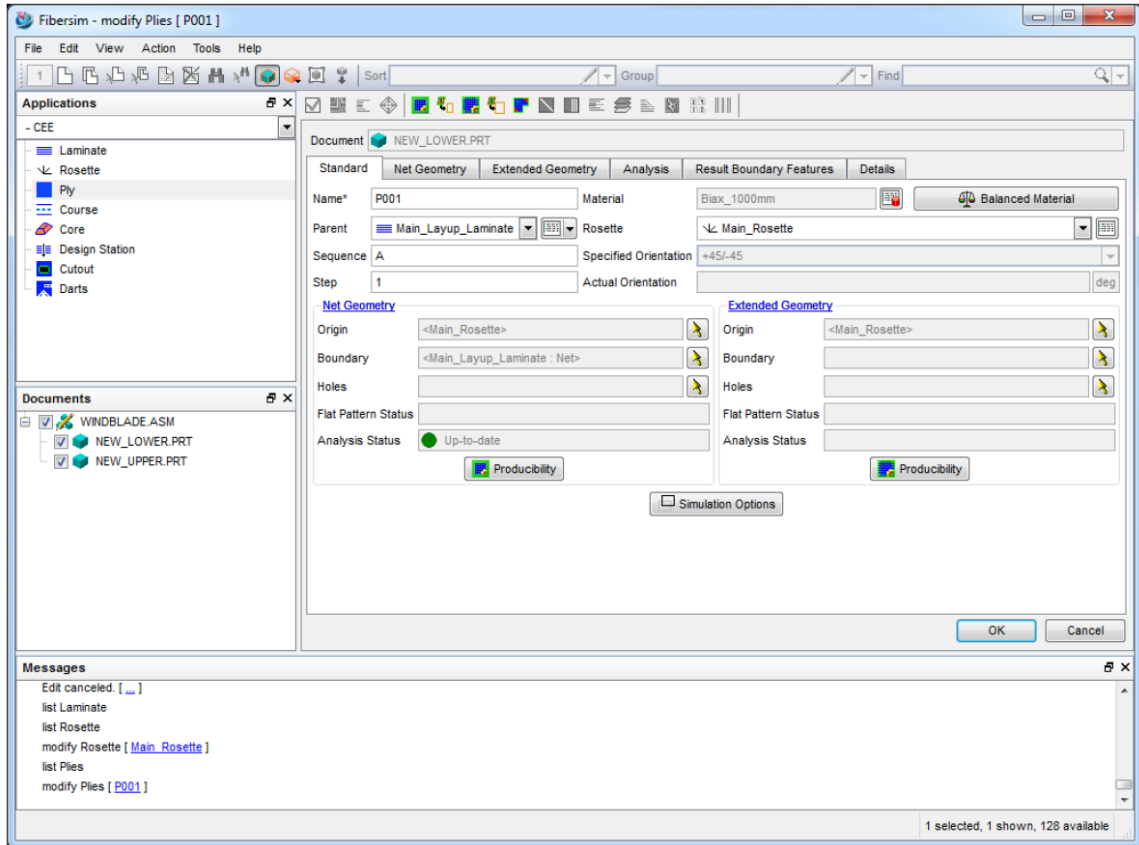


Figure 22: Describing the first ply (full-body biaxial material) for the lower half of the blade

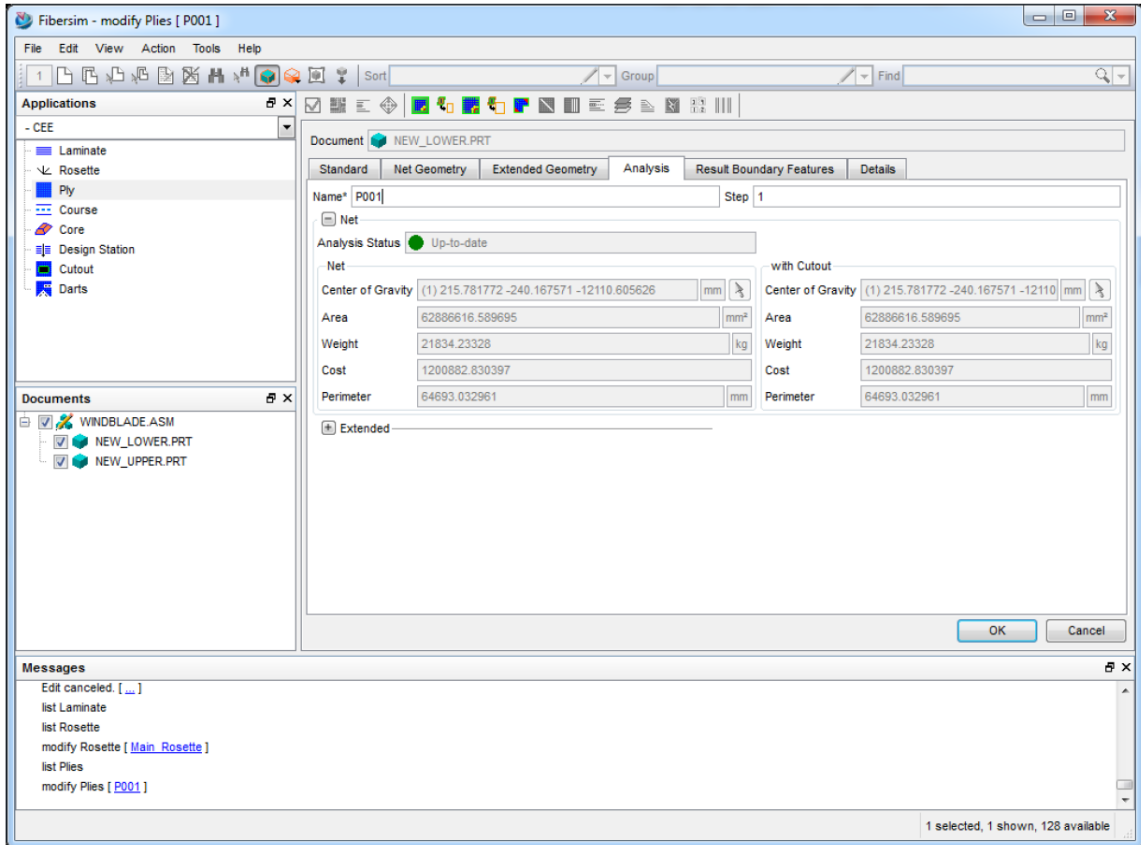


Figure 23: Analysis status of the first ply of the lower blade

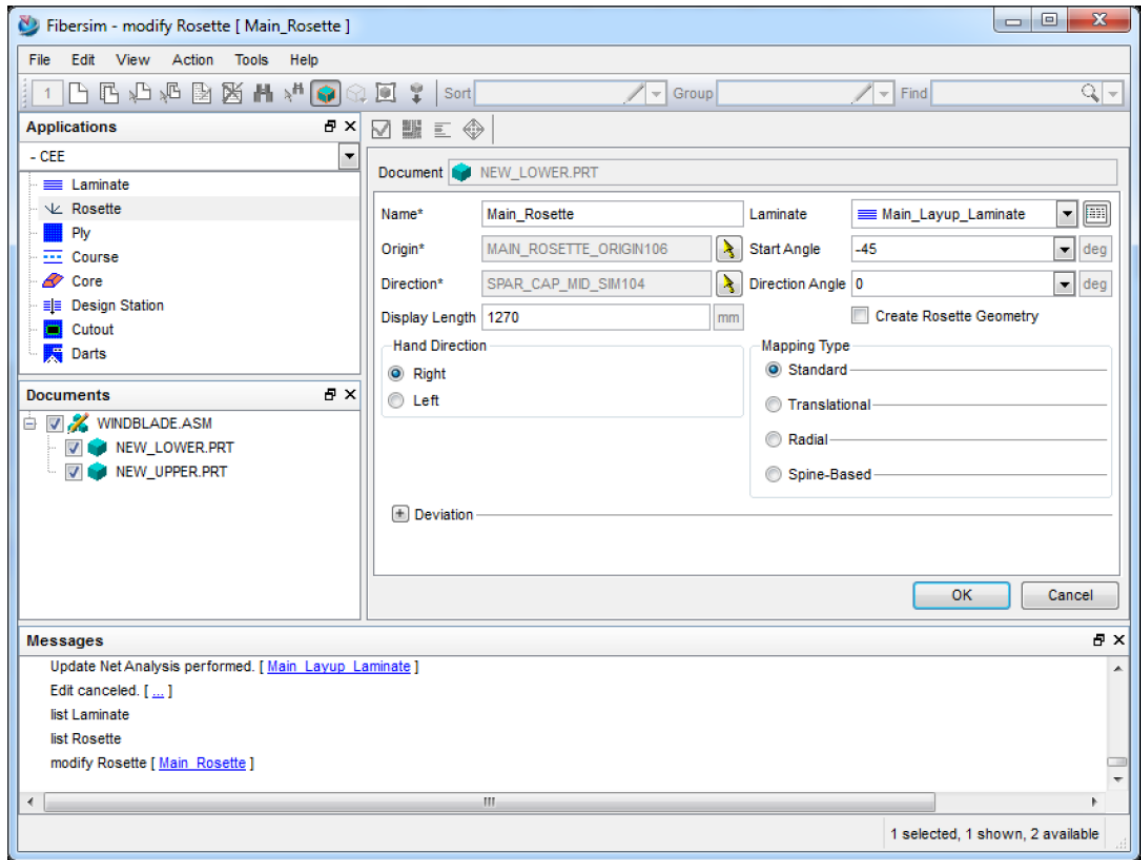


Figure 24: Describing the main rosette for the laminate of lower blade

5.2.2 Finite Element Analysis of the wind turbine blade in ANSYS

Once the composite model is ready, the model from FiberSIM is exported as a HDF5 file to be imported into “ACP (Pre)” module in ANSYS Workbench for FEA along with the CAD model. The HDF5 file contains a database of all the geometry coordinates, orientations, material data, and other essential parameters for describing the plies of a laminate as shown in Figure 25.

The project workflow for the analysis in ANSYS Workbench is shown in Figure 26. The ‘Geometry’ in ACP (Pre) is the master model. The blade assembly (.asm file created in Creo) is imported into DesignModeler. Only the surfaces and none of the FiberSIM

data are actually imported. The ‘Mechanical’ component of ACP (Pre) allows us to generate the mesh model by assigning dummy data to material and thickness. A fine mesh has to be created so that the FiberSIM data can be imported properly. The ‘Setup’ component then starts the preprocessing of data on update. Here, we can import a HDF5 file consisting of the FiberSIM data. However, the import is not seamless and certain data input errors will have to be debugged carefully using the various options inside the ‘Setup’ component. The material properties and engineering constants including failure data may also have to be added to ‘Engineering Data’.

Once imported, the fiber directions, ply thicknesses and other useful information is visualized in the ACP (Pre) GUI. Figure 27 shows fiber directions for a ply at the root of the hub. The green arrows show fiber directions and the purple shows the lay-up direction. The shell element meshing, loading and boundary conditions are setup in the “Static Structural” module. The blade is assumed to rotate about the rotor axis normally at a constant tip speed ratio of 7 with oncoming wind speeds of 12 m/s. Thus, a fixed support is assumed at the root of the blade model. The thrust ‘ T ’ is calculated using a simple equation in Blade Element Momentum (BEM) theory [62]. Assuming a 3-blade wind turbine, the thrust is given for 1 blade by

$$T = \frac{1}{6} \rho \pi R^2 u^2 C_l$$

where ρ is the density of air, taken as 1.225 kg/m³, ‘ R ’ is the radius, which is the length of the blade equal to 30 m, ‘ u ’ is the free stream wind speed of 12 m/s, and C_l is the lift coefficient taken as 0.89. This gives us a thrust of approximately 74000 N. The lift force due to flow over airfoil sections, varies along the length of the blade due to the chord and twist geometry, and is highest at the tip according to BEM theory. From various

equations, an averaged value is taken from the root to the tip equivalent to a distributed load of 107350 N and cast uniformly on the blade, while the root of the blade is fixed [63]. A rotational inertia load is applied to the blade body due to blade rotation and the resulting centrifugal force, which is given by the mass (from FiberSIM) times the square of angular velocity times the nominal radius (the center of mass lies about 10 m from the root). The model is then solved using the ANSYS solver. The results are then transferred to “ACP (Post)” module where ‘scenes’ can be created to visualize the required local or global results including transverse or shear stresses and strains, or ply failure regions based on failure criteria such as Tsai-Wu or Hill [64]. Figure 28 shows longitudinal stresses on the fibers of a ply with biaxial material.

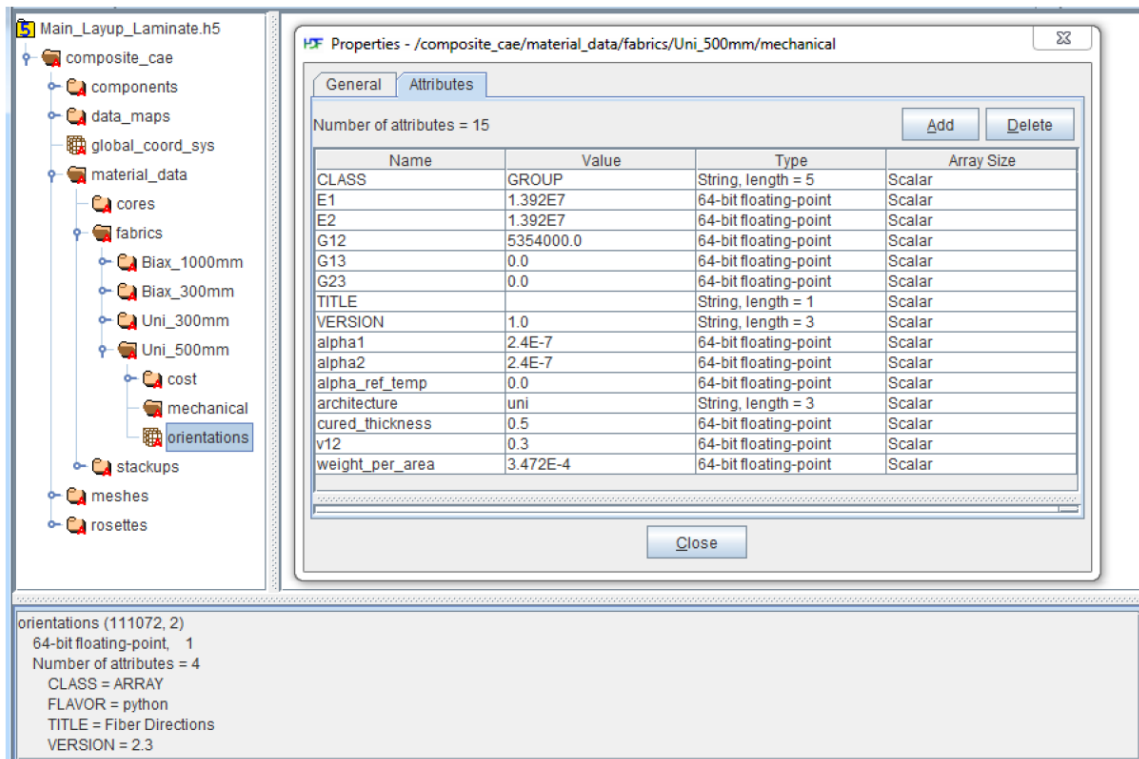


Figure 25: Contents of the HDF5 file showing mechanical properties viewed using ‘HDFView’

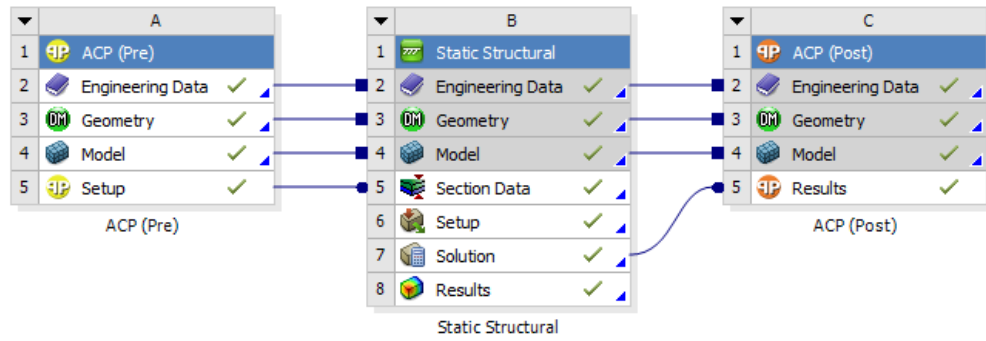


Figure 26: ACP workflow in ANSYS Workbench

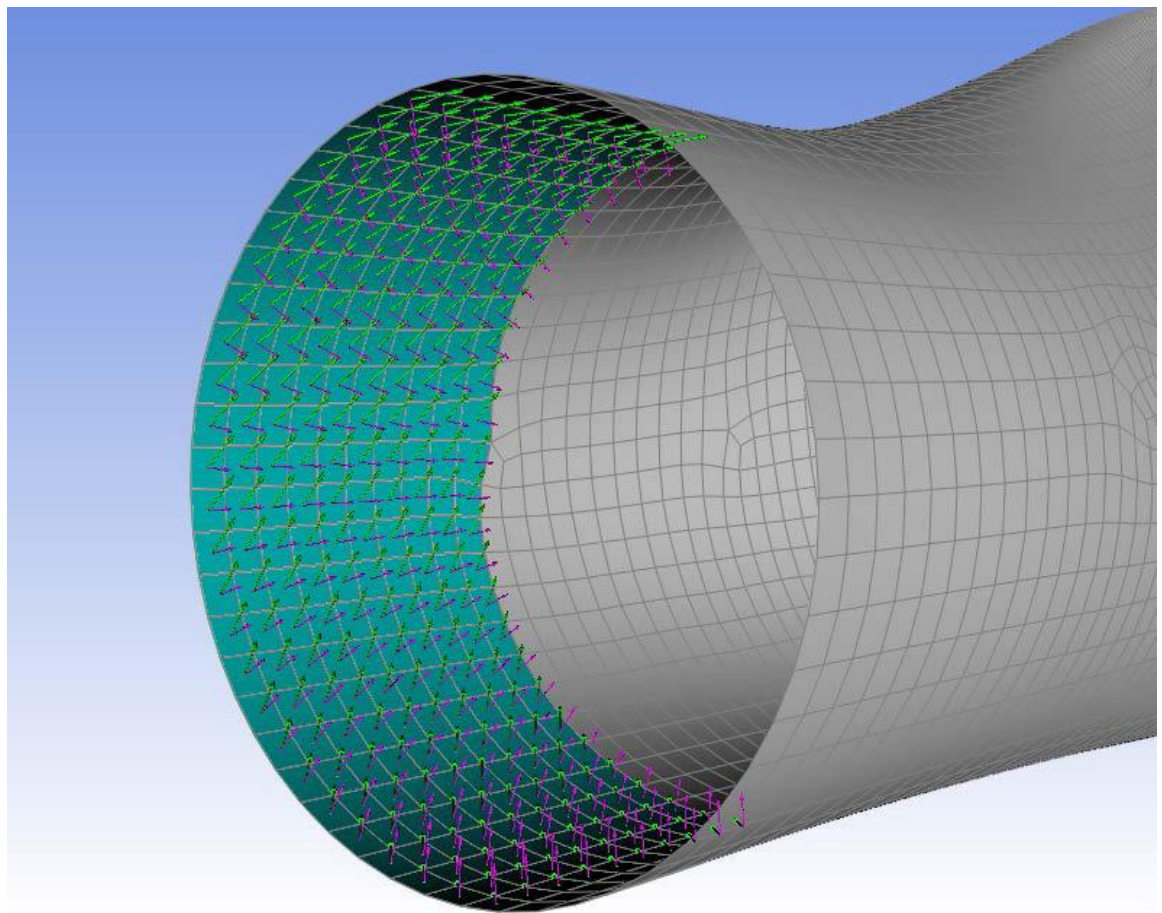


Figure 27: Ply directions for a biaxial ply near the root/hub

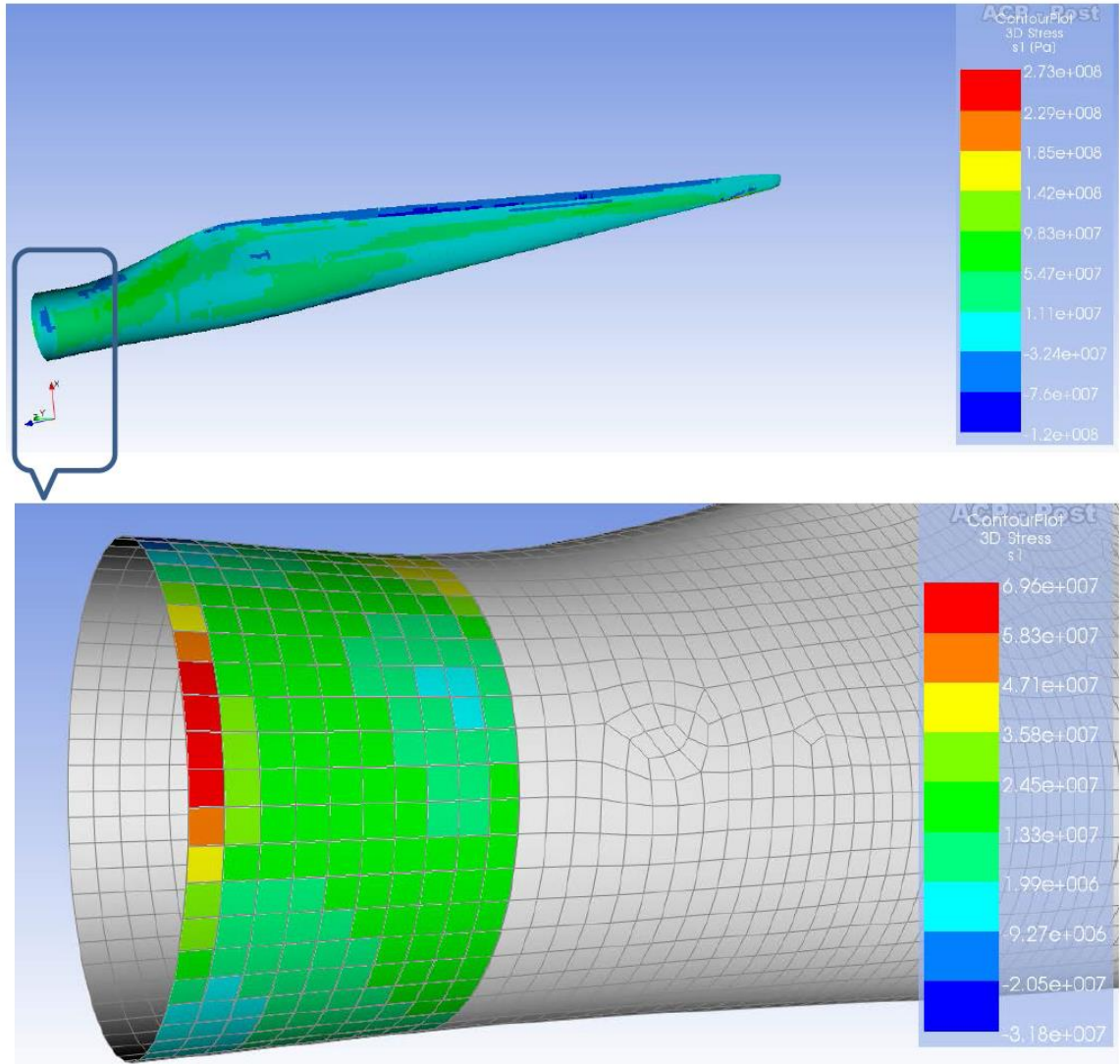


Figure 28: Fiber stresses on a single biaxial ply near the root

5.3 Implementing the blade case study in SLACKS

XML files can be converted to OWL format for efficient integration into **SLACKS**. Many conversion methods have been proposed but the most popular and proven method is the one which involves Extensible Stylesheet Language Transformations (XSLT) [65], part of the Extensible Stylesheet Language (XSL) family. A proof-of-concept of this method can be found in a paper by Rodrigues, Rosa and Cardoso [66]. Other notable works on XML to OWL conversions based on XSLT include those of Bohring and Auer

[67] and of Bosch and Mathiak [68]. XSLT templates help to map any XML-based output from software to existing OWL ontologies and efficiently automate the conversion process. Here, we used Microsoft Visual Studio as the favored XSLT processor. Using this conversion procedure, we can instantiate the classes, properties and other relevant information in **SLACKS**. The process flow snapshots are annexed to the Appendix of this thesis. A snippet of the XSLT code for mapping the relevant information of the blade laminate design 'Laminate_Upper_1' (from Figure 29) is shown below.

```

<xsl:variable name="root" select=""/>

<xsl:for-each select="EnCapta/Document/ApplicationData/Ply">

  <H:Ply rdf:ID="Ply_LU1_001">

    <xsl:for-each

select="$root/EnCapta/Document/ApplicationData/Ply/Name">

      <H:has_Name

rdf:datatype="http://www.w3.org/2001/XMLSchema#string">

        <xsl:value-of select="."/>

      </H:has_Name>

    </xsl:for-each>

    <xsl:for-each

select="$root/EnCapta/Document/ApplicationData/Ply/Sequence">

      <H:has_Sequence

rdf:datatype="http://www.w3.org/2001/XMLSchema#string">

        <xsl:value-of select="."/>

      </H:has_Sequence>

```

```

</xsl:for-each>
<xsl:for-each
select="$root/EnCapta/Document/ApplicationData/Ply/Step">
  <xsl:variable name="step">
    <xsl:value-of select="."/>
  </xsl:variable>
  <H:has_Step rdf:datatype="http://www.w3.org/1999/02/22-rdf-syntax-
ns#">
    <xsl:value-of select="number($step)"/>
  </H:has_Step>
</xsl:for-each>

```

Figure 29 shows an overview of how relevant information is instantiated relating to different domains in the case of the wind turbine blade after the integration. The connection of the ‘Upper_Mold_Part’ component of the ‘Wind_Turbine_Blade_Assembly’ with the design, analysis and manufacturing domains is shown. Instances of various classes and the integration between various domains are presented. Arrows show the object property relationships between the instances [6].

The information gathering phase begins with the design information being mapped from FiberSIM’s EnCapta XML file using the XSLT mechanism as shown in the top half of Figure 30. Then, the bottom half shows the analysis data mapped from the simulation project XML files within ANSYS EKM. Figure 30 shows some of the relevant design (CAD) and analysis (FEA) information mapped into **SLACKS** based on the instances shown in Figure 29. The information regarding ‘Laminate_Upper_1’, instance of the

‘Upper_Mold_Part’ component shown in Figure 29 from the design and analysis models of the wind turbine blade is represented in Figure 30. The ‘has_Step’ and ‘has_Sequence’ properties represent the order of lay-up during manufacturing of the laminate part [6]. The design engineers can have access to the analysis information of the FEA model that includes loads, stresses, deformation and failure criteria. The design engineers can make decisions and infer knowledge on the design faster based on the analysis results. As an example, assume a scenario where the blade deflection represented by the ‘has_Maximum_Deflection’ value should not exceed one meter. This constraint is defined as a customer requirement in SLACKS under the Requirement’ class. Here, the following SWRL implementation will help the engineer to identify such requirement violations in SLACKS:

```

Result_FEM (?r) ^ has_Maximum_Deflection (?r,?m) ^ Requirement (?req) ^
has_Maximum_Allowable_Deflection (?req,?max) ^ swrlb:greaterthan(?m,?max)→
Violation(?r)

```

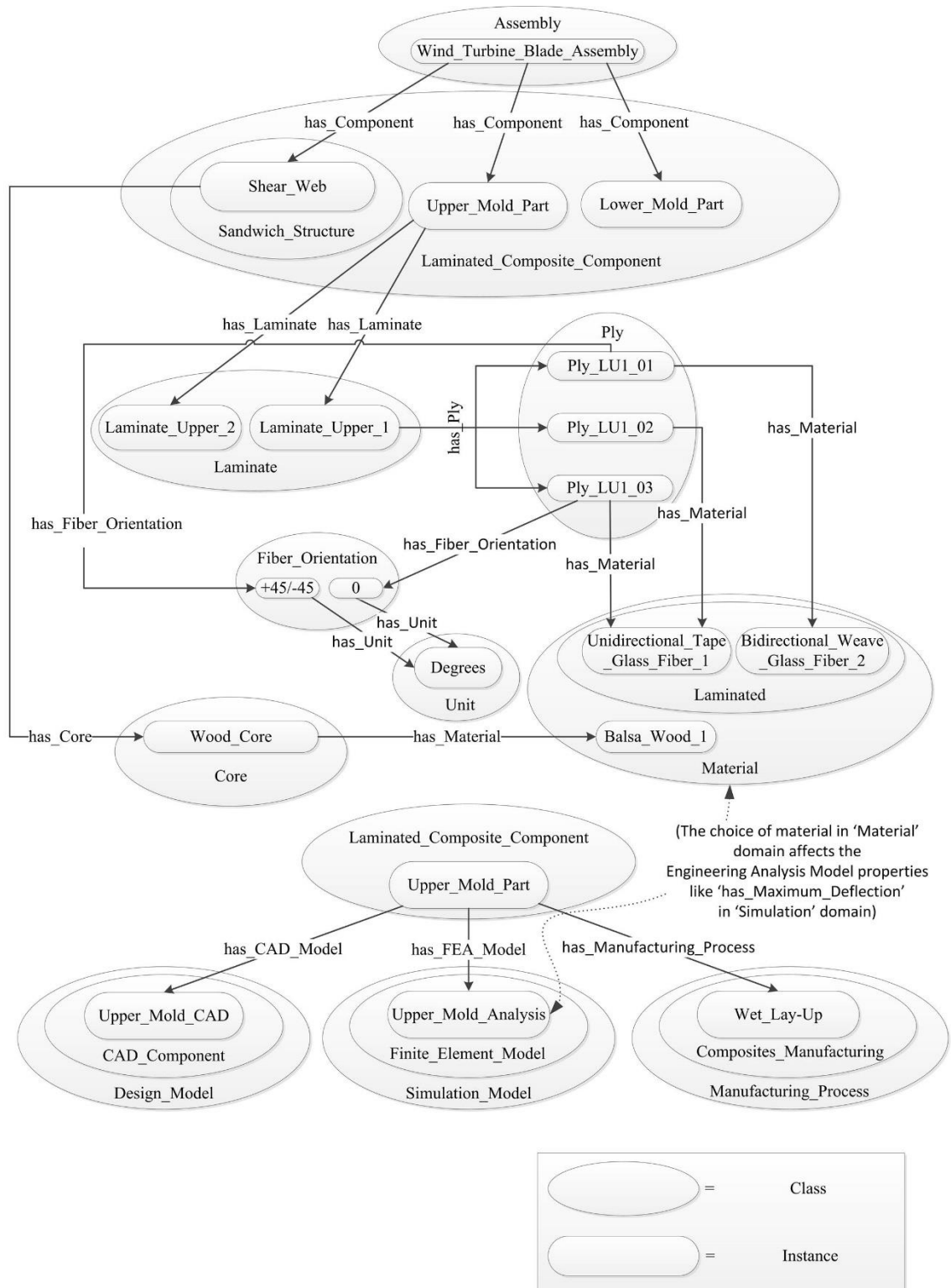



Figure 29: An illustration of how instance knowledge is tightly integrated in SLACKS [6]

Thus, a value greater than one meter will automatically raise a red flag for the design engineer, without any direct input from the analysis engineer who is working on the design review [6].

Hence, if the designer chooses to modify the material type for a specific ply, in a specific laminate for the blade, he or she can do that just by the click of a button. This is possible because **SLACKS** already has a setup for an expert system for materials selection by interfacing with public materials databases for wind turbine blades as explained in Chapter 4. The choice of material for each ply along with the fiber directions affect the structural properties, which are treated as design variables for further optimizing the structure of the blade. Due to the design changes, subsequent analysis in FiberSIM might affect the draping results and allowable tolerance for shrinkage, thus possibly altering the manufacturability of the parts. This could also lead to reassessment of manufacturers or manufacturing processes. A few of the processing techniques that can be mapped to **SLACKS** through the FiberSIM interface include hand layup using flat pattern data or laser projection systems, automated tape layup, and fiber placement through automated deposition machines. This study reveals that once all the necessary information is included in **SLACKS**, the relationships within the laminated composites design information are automatically propagated to other domains, provided the other domains are populated with knowledge in a similar manner. Thus, **SLACKS** enables seamless integration of information across different domains and instant access to all relevant information, since all the domains are interlinked and standardized. Therefore, along with addressing the underlying semantics of the design process, the use of **SLACKS** can be expected to save the design engineer considerable time by having

automated and instantaneous access to the necessary information in a concurrent engineering platform [6].

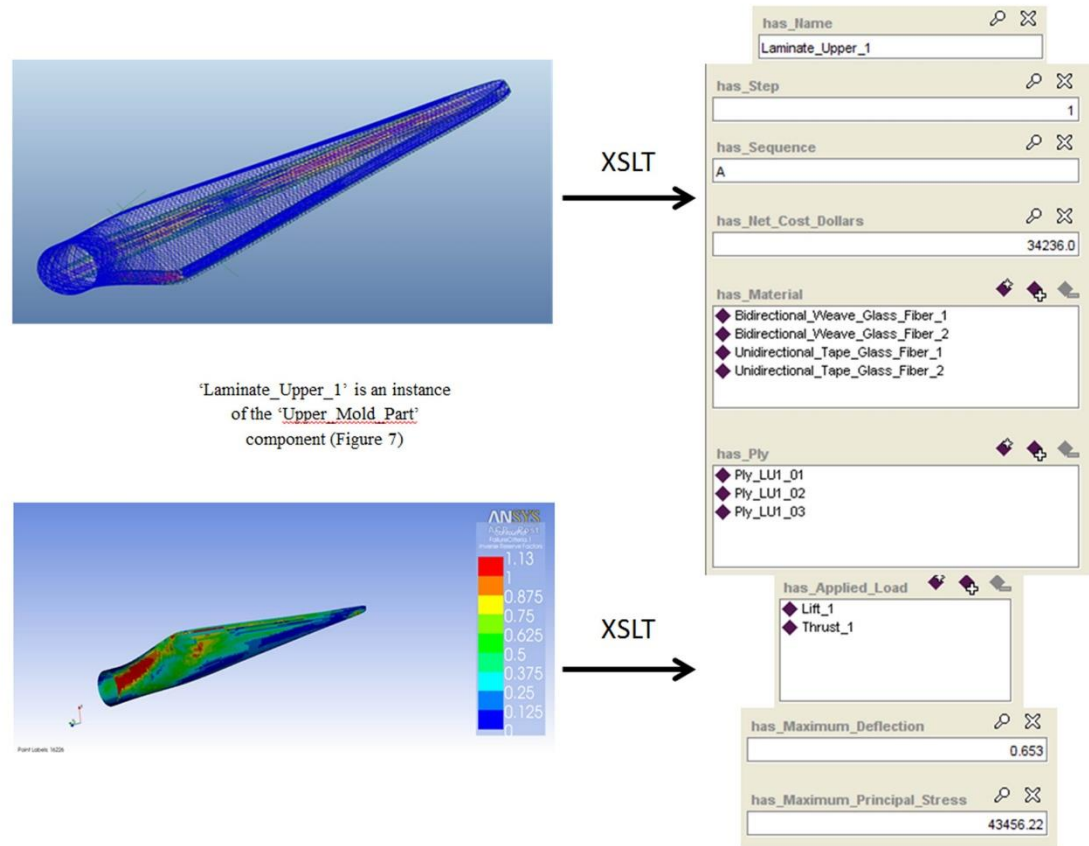


Figure 30: SLACKS capturing relevant CAD (top) and FEA (bottom) information [6]

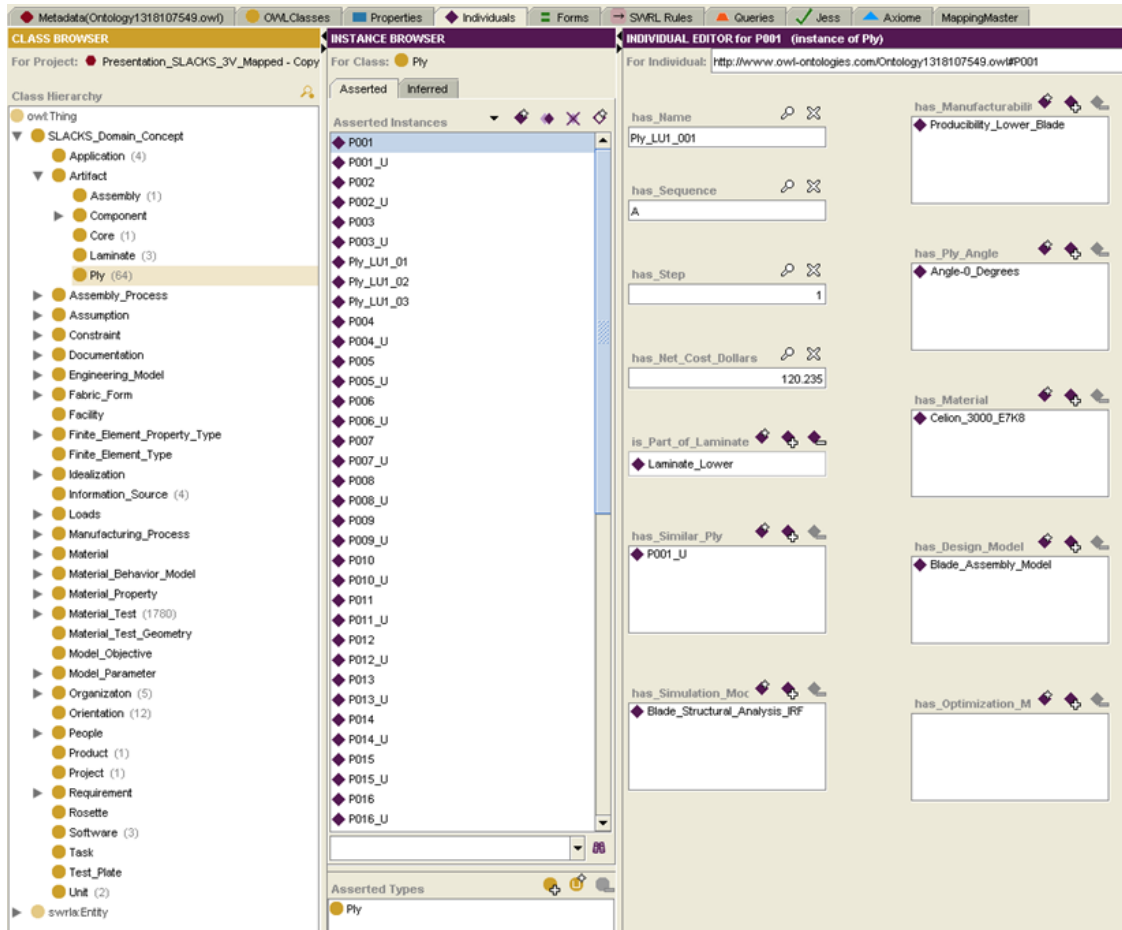


Figure 31: All plies and their related information in SLACKS as seen in Protégé GUI

5.4 Using SLACKS to get materials information displayed in FiberSIM GUI

In this section, we show that the materials information available in SLACKS can be reused by the composites engineering software, FiberSIM. To achieve this, an XSLT was created to convert the OWL ontology with materials information to FiberSIM's 'material' XML format so that FiberSIM can show the associated materials data in its Graphical User Interface (GUI). Figure 32 shows the result of the transformation.

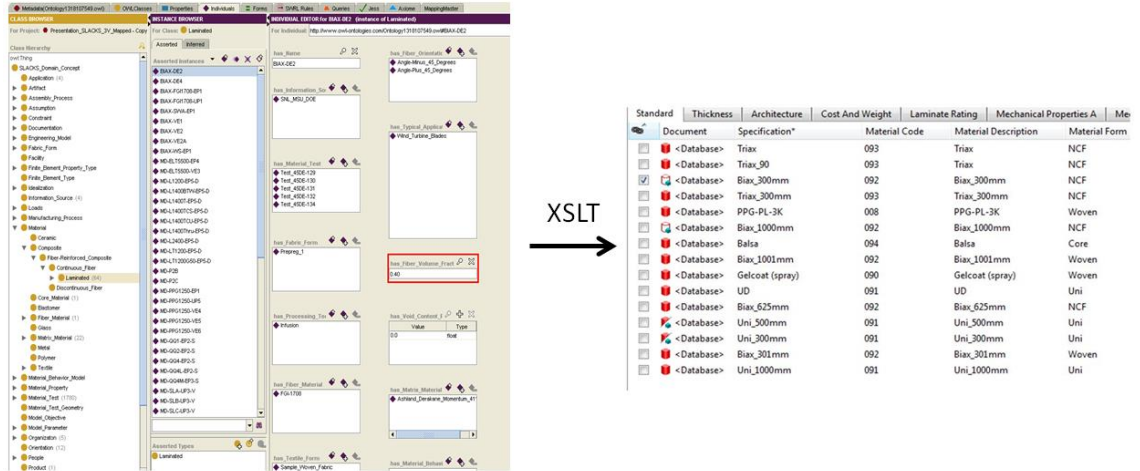


Figure 32: Getting the materials information from SLACKS to FiberSIM using XSLT

This shows that information from SLACKS can also be reused by other software. Thus, SLACKS acts as the central repository to which information is added to create knowledge, and from which information is retrieved and reused while making powerful inferences.

CHAPTER 6

RESEARCH SUMMARY

6.1 Advantages of SLACKS

The case study shows that SLACKS offers an effective and comprehensive knowledge structure to support the design of laminated composite products [6]. Notable efforts to develop pertinent knowledge structures or standardized models, as mentioned in Chapter 2, include STEP and MatML. While STEP has a specific application protocol in the form of AP209 to address data exchange during the design and analysis of composite structures, it does not have any semantics associated with the underlying information. On the other hand, MatML standardizes materials data using XML for information interchange. However, XML too falls short in the area of semantics. As an OWL-DL knowledge structure, SLACKS is fully compatible with the semantic web and is able to incorporate other ontologies and share information among engineers. Thus, the design engineer will be able to see the results of an analysis model from an analyst, enhancing collaboration [6]. The design engineer can also infer knowledge based on the customer requirements to flag design violations instantly. The ability to incorporate materials data from the web in a standardized manner and the integration of such data with the composites design domain is an added advantage. Furthermore, current description logic rules implemented in SLACKS show that we can both query and reason about the knowledge and create new knowledge to assist the engineer in making better decisions. Another important aspect of SLACKS is the ability to store design revision history and document the associated design differences through the use of the XSLT mechanism and SWRL rules. XSLT enables capturing of information during design iterations. In

addition, SWRL rules provide a basis to compare design instances and to automatically generate the salient information in different designs. These features would be difficult to achieve by navigating through the GUI of any CAD/FEA tool [6].

6.2 Limitations of SLACKS

The current SLACKS system has some limitations. The major limitation is the ability to only support knowledge acquisition from spreadsheets and software tools that deliver XML outputs. Another limitation is the inability to incorporate information that is not provided by the source. For example, the EnCapta XML file of FiberSIM provides detailed information regarding the composite lay-up but does not provide any information regarding design intent. Such information must be explicitly added into SLACKS. Further research in knowledge acquisition techniques and improved automation mechanisms along with enriched source files are required to overcome these limitations [6]. Also, the SLACKS and its organizational structure is semi-formally represented and illustrated in this thesis. More input and contribution from domain knowledge experts may be required to refine the ontological structure in order to publish a formal and standardized ontology. Finally, user interaction with SLACKS is limited to current ontology user interfaces. Protégé is a powerful ontology development tool but it provides an awkward user interface for end-users, especially for non-computer scientists. The recent emergence of semantic wikis, such as DataWiki and OntoWiki, offers the promise of a much friendly end-user interface to ontological knowledge bases [69].

6.3 Summary

This research introduces SLACKS, a novel semantic knowledge management system for supporting the design, analysis and manufacturing of laminated composite products [6]. Salient features of SLACKS include 1) a standardized knowledge representation scheme for laminated composites domain for varying material databases, 2) an ontological framework for laminated composite materials and their design for manufacturing, and 3) an integrated engineering design framework for laminated composites that can facilitate and enhance collaboration between domain experts [6]. Through the results of the wind turbine blade case study, this work demonstrates that SLACKS can offer engineers an efficient platform for integrating information among product lifecycle domains and managing the flow of information and access to inferred knowledge throughout the process of designing laminated composite products. As a result of the assimilation and centralization of laminated composite information using ontologies, SLACKS offers an integrated and shareable knowledge base that is seamlessly compatible with the semantic web with unique capabilities for automated reasoning and inferring of new knowledge from existing knowledge.

SLACKS has been developed as a tool to improve the process of engineering laminated composites [6]. However, the underlying ideas and methods of this research are applicable to any other engineering domain where a large volume of unstructured and inconsistent information has to be managed. The core idea involved in this research is the ability of OWL ontologies to integrate various domains, and acquire knowledge from spreadsheets or XML-based software tools using already existing automation mechanisms. Product Lifecycle Management (PLM) tools such as Teamcenter by

SIEMENS PLM Software located in Plano, TX, support XML exports based on their PLM XML schema. This XML information can also be transformed to OWL using the XSLT mechanism, to enrich the domain knowledge base for engineers. Ultimately, it is the compatibility of OWL with the semantic web, and the capability of implementing logic rules and queries, that makes for an efficient knowledge management tool [6].

CHAPTER 7

FUTURE WORK

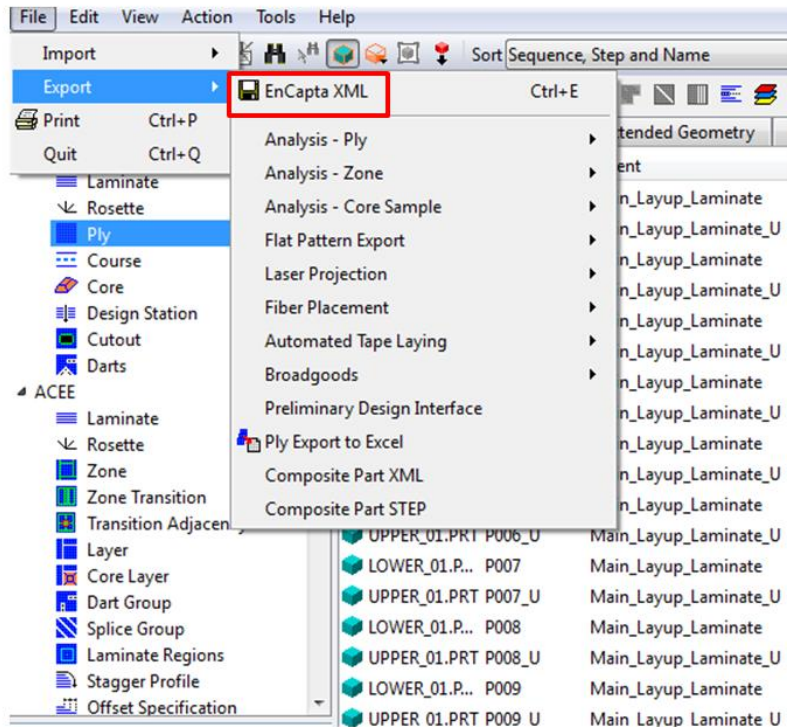
Future work includes extending ontological development of other domains involved in the product life cycle. Moreover, research on improved automation processes of converting information to OWL from XML schemas and spreadsheets can help save time and retain the integrity of information without losing the semantics. In addition, more sophisticated rules can be implemented for better knowledge classification, creation and retrieval. Fiorentini *et al.* [70] discusses in detail about the applications and limitations of rule and description based logic in OWL for their product ontologies. Furthermore, commercial Product Lifecycle Management (PLM) tools like Teamcenter from SIEMENS PLM Software (Plano, TX) or Windchill from PTC (Needham, MA) can store relevant information such as Bill of Materials (BOM). This BOM information can also be mapped to SLACKS to enrich the knowledge base which is useful especially in the case of complex assembly projects for added reasoning [71]. In conclusion, enhancement of SLACKS, as well as creating the necessary search tools that leverage the semantic structure of the developed knowledge model for different use cases, are important.

APPENDIX

XML TO OWL PROCESS OVERVIEW

1) Getting the EnCapta XML from FiberSIM interface:

After defining the geometry of the ply lay-ups and materials in FiberSIM available through the Creo interface, the user can export the lay-up data to the 'EnCapta XML' format by going to File → Export → EnCapta XML in the FiberSIM GUI as shown below.



Exporting EnCapta XML from FiberSIM

Once, the XML file is exported, all the required data is written to the file and it can be used now query for specific information that is relevant to the fulfillment of SLACKS.

2) Getting the necessary information from FiberSIM EnCapta XML:

The snippet below shows an extract from the XML file. Once the XML file is generated, the user needs to identify which of the data points are necessary for the SLACKS knowledge base, so as to generate the relevant XSLT and transform to OWL.

```
<Ply status="local" template_id=":990623491:121439916:" id=":1331243320:901110396:" name="Ply_LU1_001">
  <Name type="FixedString">Ply_LU1_001</Name>
  <Parent type="ObjectLink">:1331242536:3709076663:</Parent>
  <Released type="Boolean">False</Released>
  <CreationVersion type="Integer">201000</CreationVersion>
  <ModifiedVersion type="Integer">201300</ModifiedVersion>
  <DesignBoundary type="FixedString">Net</DesignBoundary>
  <Material type="Material">Celion_3000_E7K8</Material>
  <Sequence type="FixedString">A</Sequence>
  <Step type="Real">1</Step>
  <Rosette type="ObjectLink">:1331242803:130270694:</Rosette>
  <NetBoundaryType type="Integer">11</NetBoundaryType>
  <ExtBoundaryType type="Integer">0</ExtBoundaryType>
  <NetHolesType type="Integer">0</NetHolesType>
  <CG type="FixedString">215.9351679436 -240.2875425601 -12107.9876623641</CG>
  <NetArea type="Area">62869.9147711396</NetArea>
  <NetWeight type="Weight">2182.2042648085</NetWeight>
  <NetCost type="Real">120.2345644697</NetCost>
  <ManufacturingProcess type="FixedString">Manual</ManufacturingProcess>
  <MaterialLayupOrientation type="FixedString">Aligned</MaterialLayupOrientation>
  <COG type="Coordinate3D">215.9351679436 -240.2875425601 -12107.9876623641</COG>
  <COGMinusCutouts type="Coordinate3D">215.9351679436 -240.2875425601 -12107.9876623641</COGMinusCutouts>
  <ExtendPerpendicular type="Boolean">False</ExtendPerpendicular>
  <FSGeomUpToDate type="Boolean">False</FSGeomUpToDate>
  <Color type="FixedString">#00ff00</Color>
  <MaterialOrientation type="FixedString">Celion 3000 E7K8:+45/-45</MaterialOrientation>
```

Getting the necessary information from FiberSIM EnCapta XML

3) Implementing the XSLT code (snippet):

Once the data points to be transferred are identified, an XSLT is created as shown in the snippet below to transform the information into OWL:

```
<xsl:variable name="root" select="/"/>
  <xsl:for-each select="EnCapta/Document/ApplicationData/Ply">
    <H:Ply rdf:ID="Ply_LU1_001">
      <xsl:for-each select="$root/EnCapta/Document/ApplicationData/Ply/Name">
        <H:has_Name rdf:datatype="http://www.w3.org/2001/XMLSchema#string">
          <xsl:value-of select="."/>
        </H:has_Name>
      </xsl:for-each>
      <xsl:for-each select="$root/EnCapta/Document/ApplicationData/Ply/Sequence">
        <H:has_Sequence rdf:datatype="http://www.w3.org/2001/XMLSchema#string">
          <xsl:value-of select="."/>
        </H:has_Sequence>
      </xsl:for-each>
      <xsl:for-each select="$root/EnCapta/Document/ApplicationData/Ply/Step">
        <xsl:variable name="step">
          <xsl:value-of select="."/>
        </xsl:variable>
        <H:has_Step rdf:datatype="http://www.w3.org/1999/02/22-rdf-syntax-ns#">
          <xsl:value-of select="number($step)"/>
        </H:has_Step>
      </xsl:for-each>
    </H:Ply>
  </xsl:for-each>
```

Implementing the XSLT code

4) Executing the XSLT transformation:

The XML editor in MS Visual Studio allows to associate an XSLT to the relevant XML file, perform the transformation and view the output of the execution. To do this, it must be made sure that the XML Editor is ticked, by right-clicking the toolbar in Visual Studio 2010. Then, the parent XML document can be opened in the XML Editor and the relevant XSLT can be associated with the XML document. The XSLT style sheet can be added using the “Properties” window for the XML document and browsing to the respective XSLT style sheet. Once this is done, the “Show XSL Output” button on the XML Editor toolbar should be clicked to view the result of the transformation which would look like the snippet below:

```
<owl:Ontology rdf:about="">
  <owl:imports rdf:resource="http://edesign.ecs.umass.edu/ontologies/Framework2.0/SLACKSed.owl" />
</owl:Ontology>
<H:Ply rdf:ID="P001">
  <H:has_Name rdf:datatype="http://www.w3.org/2001/XMLSchema#string">P001</H:has_Name>
  <H:has_Sequence rdf:datatype="http://www.w3.org/2001/XMLSchema#string">A</H:has_Sequence>
  <H:has_Step rdf:datatype="http://www.w3.org/1999/02/22-rdf-syntax-ns#">1</H:has_Step>
  <H:has_Material rdf:datatype="http://www.w3.org/2001/XMLSchema#string">Biax_1000mm</H:has_Material>
</H:Ply>
<H:Material rdf:ID="Biax_1000mm">
  <H:has_Name rdf:datatype="http://www.w3.org/2001/XMLSchema#string">Biax_1000mm</H:has_Name>
</H:Material>
```

Executing the XSLT transformation

5) Viewing the result in SLACKS:

The generated OWL/XML file can be imported into an ontology editor like Protégé to view or edit the ontology. SLACKS is thus populated with the relevant knowledge in this manner.

The screenshot displays the SLACKS ontology editor interface, which is divided into three main panes:

- CLASS BROWSER:** Shows a class hierarchy starting with 'owl:Thing'. The 'SLACKS_Domain_Concept' is expanded, showing various subclasses like 'Application', 'Artifact', 'Assembly', 'Component', 'Core', 'Laminate', and 'Ply' (with 64 instances).
- INSTANCE BROWSER:** Shows a list of instances for the selected class 'Ply'. The list includes instances like P001, P001_U, P002, P002_U, P003, P003_U, Ply_LU1_01, Ply_LU1_02, Ply_LU1_03, P004, P004_U, P005, P005_U, P006, P006_U, P007, P007_U, P008, P008_U, P009, P009_U, P010, P010_U, P011, P011_U, P012, P012_U, P013, P013_U, P014, P014_U, P015, P015_U, P016, and P016_U.
- INDIVIDUAL EDITOR for P001 (instance of Ply):** Shows the details for the instance P001. It includes several properties and their values:
 - has_Name:** Ply_LU1_001
 - has_Sequence:** A
 - has_Step:** 1
 - has_Net_Cost_Dollars:** 120.235
 - is_Part_of_Laminate:** Laminate_Lower
 - has_Similar_Ply:** P001_U
 - has_Simulation_Moc:** Blade_Structural_Analysis_IRF
 - has_Manufacturability:** Productibility_Lower_Blade
 - has_Ply_Angle:** Angle-0_Degrees
 - has_Material:** Celion_3000_E7K8
 - has_Design_Model:** Blade_Assembly_Model
 - has_Optimization_M:** (empty)

Viewing the result in SLACKS

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