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A GRAMMATICAL APPROACH TO CUSTOMIZATION OF SHAPE AND COMPOSITE MATERIALS

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ABSTRACT

With the increasing use of composite materials in Mechanical and Aerospace industries, an approach is required to facilitate designing of components using composite materials, while ensuring customization of the shape such a way that multiple design goals for the components are satisfied. Existing design methods may be used in some cases, where the component shape and loadings are simple. While a significant amount of research has been conducted to study the properties of composite materials, little attention has been paid to find out a design approach such that (1) the user requirements in the very general form may be used directly and as the input for the design, (2) the best possible composite material are selected to meet multiple desired functions, and (3) shape variation is analyzed in order to enable mass customization of the design. Thus an approach is required that will be able to handle both the shape and the material in order to design a load bearing component using composite materials. In this research the focus is to develop a design approach that will consider the user requirements for a composite component in its very general form and generate component shape and material details in a systematic order so that the designed component can withstand a given loading condition.

Consequently, the Primary Research Question is:

How to simultaneously explore shape and composite materials during the design of a product to meet multiple property and functional goals?

The wide range of properties, covered by various fiber-matrix combinations, along with their directional property characteristics, maximizes the flexibility of the designers, while designing composite material products. Meeting multiple property goals, however, complicates the design process as both the composite material selection and the component shape formation becomes highly intricate with the loading conditions and a number of matrix calculations needs to be performed to determine theoretical value of composite material properties.

A grammar is a formal definition of a language written in transformational form. To address these issues, in this research a grammatical approach is developed that will generate a shape grammar to perform shape optimization, and then incorporate a composite material selection system and loading analysis techniques of Solid Mechanics in order to design load bearing components of irregular shape.

The approach will be able to consider the user requirements in the very general text form, convert them to the design requirements for the component, generate optimized shape based on multiple design constraints, perform the complete design work, and generate the component.

The major contributions include: (1) generating a shape grammar to represent functions of the load bearing component such a way that mass-customization of shape is possible, (2) developing a composite material customization system in order to satisfy directional property requirements, and (3) introducing a unique laminate design approach in order to satisfy design property requirements at the critical cross-sections locally that

can result in highly efficient design compared to conventional design method. Verification of the approach will focus on its application to simultaneously explore shapes and customization of composite materials.

CHAPTER 1

PRIMARY CHALLENGES, RESEARCH QUESTION AND OBJECTIVES

1.1 Challenges with Composite Material Design

Use of composite materials ranges from the design of the daily life consumer products to the application in aerospace industry. Composites are the most important materials to be adapted for aviation since the use of aluminum in the 1920s. High-speed forward-swept-wing airplanes like Grumman's experimental X-29 or the Russian Sukhoi S-27 Berkut would not have been possible without the development of composite materials to keep their wings from bending out of shape (Day, 2000). Another common example of a composite would be disc brake pads, which consists of hard ceramic particles embedded in soft metal matrix. Example of composite is also found in shower stalls and bathtubs which are made of fiberglass. Imitation granite and cultured marble sinks and countertops are also widely used. The most advanced examples are performed routinely on spacecraft in demanding environments (Wikipedia, 2012). The concept of composite material involves combining two or more materials to achieve multiple properties, when none of the individual materials possess all of the properties at the same time (Aboudi, 1991; Mazumdar, 2002; Barbero, 2010; Mottahed and Manoochehri, 1997). One useful feature of composites is that they can be layered, with the fibers in each layer running in a different direction. This allows materials engineers to design structures that behave in certain ways. For instance, they can design a structure that will bend in one direction, but not another. The designers of the Grumman X-29 experimental plane used this attribute of composite materials to design forward-swept wings that did not bend up at the tips like metal wings of the same shape would have bent in flight (Day, 2000). Thus one of the advantages of using composite materials over the conventional engineering materials (metals) is the ability to manipulate their directional properties (Herakovich, 1984; Hart-Smith, 1992; Herakovich, 1997; Mazumdar, 2002). Designers also utilize the characteristics of composite materials to achieve several design goals, which might include reduction of weight, increasing designed life of engineering components, reducing costs of production, maximizing reliability, ensuring safety of rotational structures, etc. (Ashby, 1993; Kokan and Gramoll, 1994; Ashby, 2005; Aronson, 1999). Thus composite materials hold a very important place in devising the most cutting-edge technologies of the modern science and engineering.

In the conventional mechanical design approach, material is selected following an ordered set of tasks that perform the selection from a given set of material list. The tasks are as follows:

a) Prediction of the shape and size according to the possible functions of the component-to-be-designed
b) Analyzing loading condition to predict the failure circumstances
c) Identifying property requirements assuming an acceptable factor of safety.
d) Selecting Materials from a given pre-set material list
e) Evaluate performance of the designed component against the design requirements

f) Modify the design and the dimensions until the performance is near to whichever optimum is considered most important

Analysis of failure characteristics for composite materials and laminates involve comparatively large matrix calculation, which becomes more complicated when irregular shapes and directional properties are considered during design. Thus, with the exceptions of some cases where the component shape and loadings are simple like large plat body, cylindrical shape, etc., this existing material selection approach (Ashby, 1995; Ashby, 2005; Edwards, Abel et al., 1994) is not readily applicable for orthotropic composite material design as for the isotropic material design. Consequently there is a need to develop an approach to design of load bearing components using composite materials.

Load bearing components usually perform more than one function. They may be required to carry bending moments, withstand high or low pressure, transmit heat and electricity or provide resistance to corrosion, etc. On the other hand, the designer has one or more goals to achieve during the design, such as to make the component cheap, light, or safe. Recent advancements in composite materials make it possible for designers to design a component that can perform functions while meeting multiple goals. However, compared to the design process using conventional materials (such as, metals), design process using composite material is much more complicated. Thus a fundamental challenge lies in designing a load bearing component using composite material while considering its design loading constraints, weight reduction, cost efficiency, and other requirements.

1.2 Challenges with Customizing the Shape: Introducing Shape Grammar and Grammatical Approach

The basic requirements for a design can be determined from the end user’s expectations. For example, while designing a body structure for an aerospace application, the end user may require a light and strong structure that forms an aero-foil shape. Again, designing an automobile part, the user might not be worried about the weight of the component; rather space limitation along with failure strength could be a major issue. Thus, one of the challenges a designer faces, while designing a component is how the shape of the component would form to meet the user specified space and functional requirements.

When designing a component to satisfy a number of form specifications, the goals can vary from users to users. For centuries these variations of design goals are met by customizing the product according to each individual user. Since the whole system, in this case, need to be designed differently for each individual, the cost of production becomes very high. Mass production was introduced to reduce the cost of production by producing big amounts of components assuming ideal design requirements, which eventually necessitates compromise of the form and property requirements for most of the users. Mass-customization is introduced to address this issue successfully to reduce the overall cost of production while in the same time meeting individual form and property goals. Product family and product platform approach are the most convenient techniques of the application of mass-customization.

A shape grammar is a means of defining a language of irregular shapes of a load bearing component considering the relations between the form and the function for that loading conditions. The concept of shape grammar, originated from architecture, offer the ability to explore a vast range of design shapes (Stiny and Gips, 1971; Stiny, 1980; Agarwal and Cagan, 1997; Agarwal, Cagan, and Constantine, 1999; Agarwal and Cagan, 2000), and can be extended to simultaneously explore shape and material properties.

A grammar is a structured means of describing relationships between the entities of a language – in this case, the language of mechanical design (specifically product family architecture). In this case, the semantics of this language are associated with the behaviors and features of individual components (lexical information) as well as the arrangement among them (syntax), much like the English language is dependent upon both the meaning of individual words as well as their arrangement in a statement.

A grammatical approach is defined as an organized way to enhance the creativity and insight of the designer by defining practical relations between the user functional requirements and the shape variations while dealing with wide material ranges. Using grammatical approach it might be possible to analyze a diverse set of design options (in vast range of shapes); it may simplify the design of composite material products with non-uniform shape, that will carry multiple type of loads, where the shape and loads together define the directional property requirements at different location of the component. A very convenient technique would be the implementation of “Product platform and product family concepts” into shape grammar to mass-customize it. But not enough researches are done in this topic to find out how a grammatical approach will handle the challenge.

1.3 Primary Research Question

Designing a tentative shape for composite material product, based on given functions and design conditions, is very difficult to perform. Only simple shell shapes and outer surfaces of any large component are now being designed using composite material; designing and fabricating complicated irregular shape load bearing components are still under many research interests (Lind and Rechards, 1984; Jones, 1999; Barbero, 2010).

Thus, the Primary Research Question associated with these challenges is:

How to simultaneously explore shape and composite materials during the design of a product to meet multiple property and functional goals?

In response to this research question, this work defines a grammatical approach that will be able to solve complex design problems involving optimization and mass-customization of irregular shapes and directional properties of composite laminates to satisfy multiple design goals. The objective of this work is to device the grammatical approach in such a way that it is capable to mass-customize any complex design space and to provide insight into function, form, and material design.

The overall design approach is a computational method that combines a shape grammar (Stiny and Gips, 1971; Longenecker and Fitzhorn, 1991; Agarwal et al., 1999; Nandi and Siddique, 2011) with composite material selection tool (Nandi and Siddique, 2009; Nandi, Siddique, and Altan, 2011) to generate goal oriented design solutions. Considering that the design space defined by the shape grammar is infinite, an optimization technique is implemented to show the application of such algorithms to guide the generation of purposeful designs. The incorporation of shape grammar language with optimization technique enables mass-customization of the design, and directional property design of composite laminates leads to the following hypothesis:

The incorporation of mass customization of shape into directional material design enable the design of any load bearing component without compromising any design goals and can avoid overdesign in any direction.

Usually a number of design shapes are possible that can satisfy the functional goals of a product. In this work, the grammar will be presented to deal with the range of possible shapes, from which, a number of designs, that are available in the market, will be captured by altering the rules of the grammar. Also, the material design technique will be explored from the selection of possible alternate fiber-matrix composition to the selection of available unidirectional laminates for the same design goals. Furthermore, the philosophy behind this work will be discussed in the context of the different methodologies related to the presented approach to establish a strong foundation of the concept.

1.4 Overview of Design Approach

The grammatical approach proposed in this work focuses on extending shape grammar in a composite material selection technique. The presented approach is divided into four intertwined phases: (i) Phase 1: Functional Design, (ii) Phase 2: Form Design, (iii) Phase 3: Material Selection based on Loading, and (iv) Phase 4: Integrated Material and Shape Design. Figure 1-1 shows the flow-pattern of activities during different phases of the approach. The generation of the initial shape takes place in functional design phase. It begins with geometric entities. In this phase functional requirements, such as types and location of design loads, are addressed by the application of a set of rules defined in the grammar. The form design (Phase 2) is performed using a number of additions or subtractions of different geometric features to the initial entity to generate the basic shape. These geometric feature operations are defined by a set of rules using shape grammar technique. Thus generated basic shape may be the inner shape or the outer shape of a component body, which are specified in the design requirements.

In the Phase 3, composite materials are selected based on loading analysis, the loading details are defined as additional rules in the generated shape grammar to create a design chart that are able to calculate the directional property requirements at different cross sections of the body. Basic knowledge in mechanics is used to define the rules at this stage of the grammar to determine the possible critical sections of the loaded component.

Depending on the goals of the design, the composite material is determined. The composite material selection and customization rules are defined based on a view to meeting multiple directional property design goals. This phase of the approach uses the composite material customization tool (Nandi and Siddique, 2009) to select appropriate composite material for different sections of the component. The set of rules defined to perform the integrated material and shape designs combine as the Phase 4.

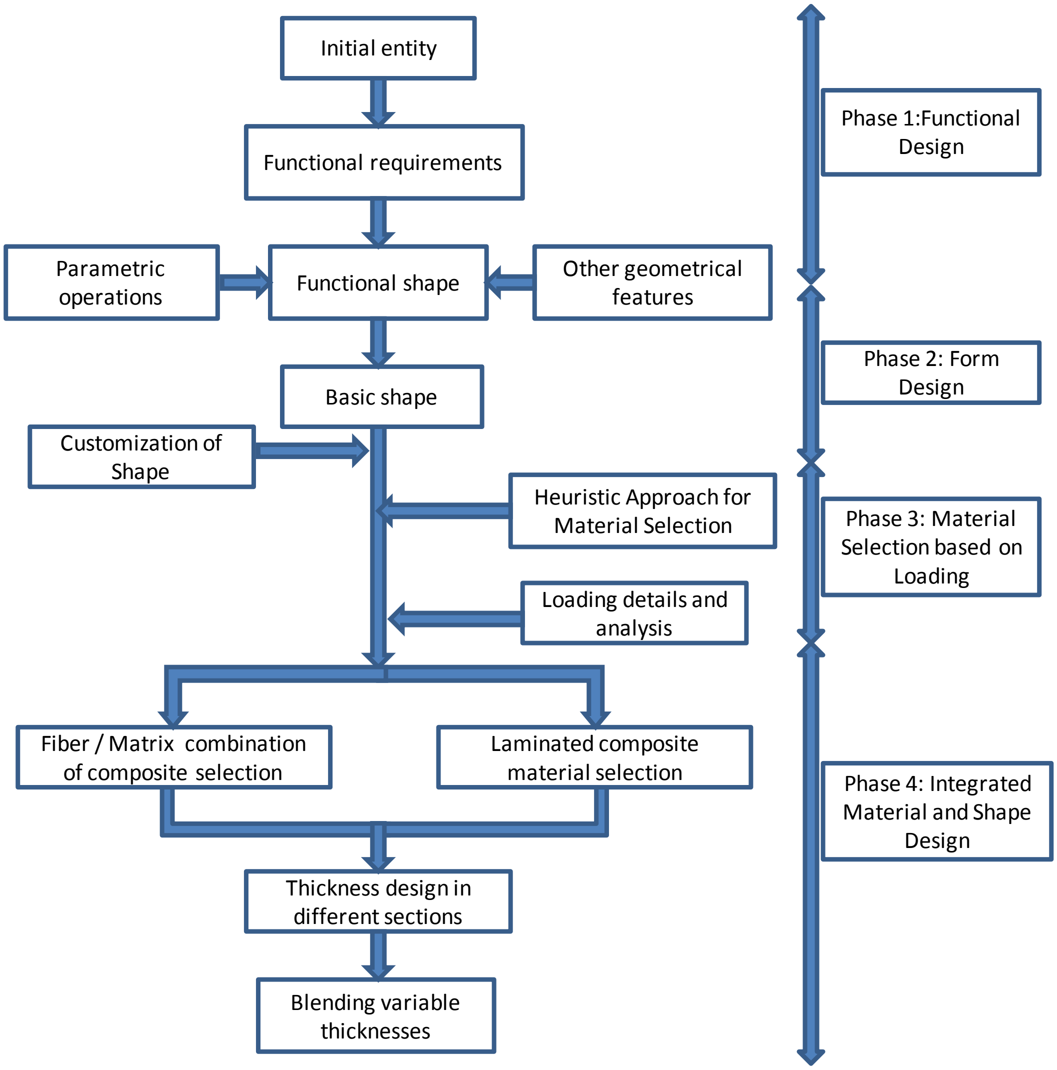


Figure 1-1: Flow pattern of different phases in the approach

The approach presented in this work, uses the four phases and customizes the shape grammar according to a user-interactive system. Functional requirements, received from the users, are decomposed into shape constraints that generate shape grammar rules for the design of the load bearing component. A shape optimization technique is employed to determine the appropriate shape that satisfies the shape requirements, while making sure that the component can be easily designed using a given set of materials in their limited property range. The shape optimization tool is incorporated with a material selection technique, that determines appropriate laminates (or composite materials) and their orientation that are capable of satisfying the defined design goals. An appropriate blending technique is also implemented to ensure that the designed orientation do not create load concentrations at the edge of discontinuity of the laminates. The whole process is termed as “Grammatical Approach” as a whole as this process performs the above techniques by combining them into language made of organized rules.

1.5 Background, Research Questions, and Hypotheses

The goal of this research is to facilitate designing mechanical components using composite materials, while simultaneously considering shape, loading constraints, manufacturing processes, and cost. With these objectives in mind, the Primary Research Question introduced in Section 1 is further explored in the next sub-sections.

1.5.1 Grammatical Approaches to Meet Functional and Space Requirements

The use of grammatical approaches (such as, shape grammar) can be traced to the field of architecture. The styles of Palladio and prairie houses were the examples of successful implementation of such grammar in architecture (Stiny and Mitchell, 1978; Koning and Eizenberg, 1981). Grammatical approach can be used to generate sentence forms, which include strings, graphs, or various types of shapes, or to parse sentences to check for syntax and inclusion in the language (Mullins and Rinderle, 1991; Siddique and Rosen, 1999). Shape grammar approach is used to design structure and shape of products (especially consumer products such as coffee makers, telephones, toasters, and flashlights) (Agarwal and Cagan, 1997). Shape grammars have the ability to generate a wide variety of designs (Stiny, 1980; Longenecker and Fitzhorn, 1991; Stiny, 1991). Graph grammars have been successfully used for designing a family of products, including the platform of the family (Siddique and Rosen, 1999).

Researchers have used grammatical approaches in production system and engineering design (Schmidt and Cagan, 1995; Agarwal and Cagan, 2000). Appropriate grammar has been defined as a language of constructive solid geometry and boundary representations (Fitzhorn, 1990). Parametric grammar has been developed to generate optimal truss structures (Reddy and Cagan, 1995; Shea and Cagan, 1997; Shea and Cagan, 1999). The use of such grammar was extended for designing individual products, and cost expressions were associated with the grammar rules (Agarwal et al., 1999). However, a grammatical approach has not been defined yet that can be used to design components using composite materials.

One of the main challenges in designing a component, that is expected to perform a given set of functions, is how the final shape would appear. The general form of functional requirements from the end user (or designer) could be as simple as texts. For example, while designing a hip replaceable joint the function of the component could be to provide joint between a femur bone and the hip of a person. On the other hand, while designing a turbine blade, the functional requirements could be to provide a shape that will generate rotational or vertical motion from unidirectional wind motion. Thus, the “Requirement” texts may not provide enough information to visualize how the final shape of the component will look like. This motivates the following Research Question:

Research Question 1: How can a shape grammar model be generated in order to represent a component shape that will be used to perform desired functions while meeting space constraints?

In response to this question, a shape grammar is defined that generates shape from an initial geometric entity such as a point, or a line. A single or multiple points can be used to express the framework of the body to meet functional requirements of the component. This framework will experience a set of grammatical rules defining appropriate algebraic operations using proper geometric entities to develop a base body, the formation of which will largely depend on another set of rules defining the functional space requirements for the component. The regular use of these set of rules are then compared with product family and product platform concepts to define the family and platform of the rules. Thus Research Question 1 is addressed with following hypothesis:

The shape of any object can be generated starting from a basic geometric body, with the use of a combination of arithmetic operation of other geometric bodies.

Researchers has investigated different types of modeling and designing techniques (Stiny and Gips, 1971) that use a set of rules that are termed as the grammars, and when such rules play with possible shapes of a product, the grammatical technique is called shape grammar. The concept of shape grammar though originated in the architecture hundreds of years ago, it has, over the past decade, drawn interest from architects, fine arts and fashion designers, brand commodity developers, mechanical designers, and even the structural and civil engineers (Stiny and Gips, 1971; Stiny and Mitchell, 1978; Stiny, 1980; Koning and Eizenberg, 1981; Longenecker and Fitzhorn, 1991; Stiny, 1991; Reddy and Cagan, 1995; Agarwal and Cagan, 1997; Shea and Cagan, 1997; Agarwal et al., 1999; Shea and Cagan, 1999; Agarwal and Cagan, 2000; Pugliese and Cagan, 2002; McCormacka, Cagan, and Vogel, 2004; M¨uller, Zeng, Wonka, and Gool, 2007; Thomas H. Speller, Whitney, and Crawley, 2007; Orsborn and Cagan, 2009). The main reason for this interest is the ability of shape grammar to deal with an infinite number of possible shapes while designing and/or developing a new product. This Research Question is addressed in Chapter 2.

1.5.2 Mass Customization and Shape Grammar

This is an era of mass-customization. Product platform and product family concepts are very efficient techniques for mass-customization. This technique has been successfully applied to the production of many products. Increasing demand for customization is also driving shape design techniques to employ mass-customization in it. Although, many researchers have taken place on the implementation of shape grammar for the efficient shape design (Stiny, 1980), little research has tried to implement product platform and product family concept in shape grammar. This work leads to the following Research Question:

Research Question 2: How to implement product family and product platform concepts in shape grammar technique in order to determine the shape ranges that will be used in the shape optimization that will take place?

Design for product variety is a relatively new research field, but it has received considerable attention in the management (Baker, Magazine, and Nuttle, 1986; Sanderson and Uzumeri, 1992) and engineering (Rothwell and Gardiner, 1990; Simpson, Lanutenschlager, and Mistree, 1997) literatures. The basic concept of a family of products or multi-products approach is to obtain the biggest set of products through the most standardized set of base components and production processes (Stadzisz and Henrioud, 1995). Characteristics of product family range from flexible modular designs (Chen, Rosen, Allen, and Mistree, 1994) to robust and scalable designs (Rothwell and Gardiner, 1990) to standardized, flexible products. Martin (Martin and Ishii, 1996) identified commonality, modularity and standardization; Rothwell (Rothwell and Gardiner, 1990) emphasized robust design; Simpson (Simpson et al., 1997) related change in form and function to highlight mutability, modularity and robustness, which, they suggest are the core characteristics of product families. Some of the other characteristics that have been stressed in other literatures for designing product families are: commonality, and standardization. Application of different mass-customization concepts to automotive platform commonality (Siddique, Rosen, and Wang, 1998) was also investigated.

Different approaches to providing families of products through the use of common platforms have been proposed. Wheelwright (Wheelwright and Clark, 1992) suggest designing "platform projects" that are capable of meeting the needs of a core group of customers but are easily modified into derivatives through addition, substitution and removal of features. McGrath (McGrath, 1995) also stresses the need for a well designed product platform for a family of products. Parts commonality has been viewed as a means of cost reduction. McDermott (McDermott and Stock, 1994) in their paper describe how the use of common parts can shorten the product development cycle for savings in both time and money in the manufacturing process. Having a common assembly and manufacturing process is another important aspect of developing common product platforms. MacDuffie (MacDuffie, Sethuraman, and Fisher, 1996) looked at how variety affected manufacturing within the automotive industry by studying empirical data.

From a general perspective (in most cases) all products have platforms and a set of similar products have the potential to be produced from a common platform.

Development of common product platforms, in general, has a component perspective and an assembly process perspective associated with it. The component perspective specifies the common components present and different relationships among them. The assembly process perspective specifies assembly information, which will be used to specify if all the members of the family can be produced from the same assembly line. One of the objectives of developing common platform is to use the same assembly line to provide the necessary varieties. Component perspective of the platform commonization process has also been explained (Siddique and Rosen, 1999).

In this highly competitive market, individually customized commodities can no longer survive due to the high production and labor cost they incur; the cost effective way of production – "mass-production" are also struggling because of their inability to meet individual customer requirements with the gradual rise in the satisfaction level of the customers. Customers in this era know that they have plenty of options to select from and thus they demand customized product at a similar price of mass produced products. This increasing demand has driven the concept of "mass-customization" to complement and in certain cases replace the previous concepts of production. The two terms product family and product platform are related to each other and comes together as an efficient means to mass customize a product. The Research Question will be addressed in this work based on the following hypothesis:

Considering shape of a component as a product of engineering interest, the set of shape rules can be compared to the family of that product, and in that case, the individual rules will behave as the members of the family.

In this research the idea is investigated that product family and product platform concepts can be applied to the shape grammar to develop an efficient approach for shape and structural design. The grammatical approach for the design of a Hip-replacement joint has been presented (Nandi and Siddique, 2010, 2011) as an example case for the approach. In this part of the work, the design part of the approach is not considered; rather the shape grammar of the example is used for the demonstration. The whole set of shape grammar rules is presented in Chapter 3 as a family, from which an effort is made to develop a platform of the rules. With that the applications of product platform and product family concepts are demonstrated in shape grammar.

1.5.3 Integration of Composite Material Selection Based on Loading

The recent advancements in composite materials give new opportunities for designers to design/select materials that satisfy targets for multiple properties. Since composite materials provide a wider variety of properties; a proper selection from these composites may provide closer achievement of the property goals. Different models have been developed (Hill, 1964; Hashin, 1972; Herakovich, 1984; Hashin, 1990; Aboudi, 1991; Aboudi, Pindera, and Arnold, 1993; Ashby, 1993; Ravichandran, 1994; Herakovich, 1997; Kant and Babu, 2000; Mazumdar, 2002; Yeow-Cheong, 2005; Liu, 1997) that can be used successfully to predict the property of micro-composites.

However, compared to the selection process of conventional engineering materials, the introduction of composite materials makes the material selection process complex. This is because the composite materials are a combination of different homogeneous and non-homogeneous materials, comprised of reinforcement and matrix. Composites are also expensive and can be difficult to fabricate, but provide an enhanced shaping capability and an ability to tailor the reinforcement by satisfying directional property requirements, thus leading to efficient material utilization and high performance structures (Chen, Sun, and Hwang, 1995; Vallbo, 2005). So, a selection must consider all these constraints at the same time. Consequently, the following Research Question:

Research Question 3: How to select appropriate composite materials in order to satisfy directional property requirements at the critical sections of a component?

Compared to the development of material property analysis and other works in the contemporary composite technology, only a few researchers have focused on developing processes for selection of appropriate composite materials with specific property goal(s). Researches that have focused on material selection primarily differ in the use of different prediction models. These researches used approaches comparable to the conventional material selection.

A graphical selection technique was suggested (Ashby, 1993; Edwards and Abel, 1994) and thus extended the conventional material selection process to the selection of composite materials. In his excellent work he gave a very comprehensive demonstration of how metal and ceramic composites can be selected. He suggested that different properties can be organized according to the design requirements of the final product and thus these properties can be grouped as “Performance indices”. These performance indices, when plotted against each other, can be visually analyzed to make a good selection between different composite options.

Ashby (1993) used the term “Design limiting properties” for the group of properties such as density, young’s modulus, strength, toughness or fracture toughness, linear thermal expansion coefficient, specific heat, thermal conductivity, and thermal diffusivity and explained how these properties becomes prominent and acts as “Performance indices” while selecting materials with desired properties.

Zhao and Hoa (1996) developed a knowledge-embedded database system for composite material selection. This database system is very simple to use and brings several combinations of composite and allows the user to make the final selection decision. However, this tool makes the selection from a given database of composite properties. Hence, no new combination of fiber and matrix materials can be suggested to achieve the property goals. Furthermore, the directional properties of laminated composites are not considered in this work.

Li, Cui, and Wang (2001) used a similar approach to develop a knowledge-based expert system for fiber reinforced plastic composite design. Although this expert system considers the layers and the orientations of composites to some extent, the selection range still remains limited by the specified knowledge-based files, which are pre-determined.

Mazumdar (2002, p. 62) suggested weighted property comparison method that makes selection simplified by defining relative importance among different property factors. This method can be useful for cases in which more than one factors are used for material selection purposes, particularly when the requirements of some of these factors are more flexible than others.

Several other researchers are working to develop a new system (Youssef, 1994, 1995; Prasad, 1996) to integrate activities (e.g., manufacturing, assembly, etc. (Bader, 2001; Boothroyd, 1994; Aronson, 1999; Edwards, Abel et al. 1994)) to have benefits in cost and time savings. According to Gürdal, Z. (Gürdal, Haftka, and Hajela, 1999), the performance of a composite laminate depends on its composition, microstructure, and processing conditions, i.e., cure cycle.

Other researchers (Bader, 2001; Bergamaschi, Bombarda, Piancastelli, and Sartori, 1989; Ashby, 1995) have also worked on the material selection for composites, emphasizing the final structural shape of the fabricated product and associated cost for manufacturing. But, none of these research produced successful approach to select a percentage combination of filler material in a matrix with a specific fiber orientation to achieve multiple desired thermal and mechanical directional properties in the final product. Thus this basic and important part of the design process deserves a new research approach to find a tool for selecting the appropriate multi-property and multi-functional material.

The Research Question mentioned above leads to following hypothesis:

The property prediction technique of composite materials using established micromechanical models and lamination theory can be reverse engineered to predict the composite materials that can meet multiple design property goals with acceptable accuracy

In the work, an RMS index method is developed to make best selection from a multidimensional database duly generated for multiple property ranges. The composite fiber-matrix selection approach using the RMS index method is demonstrated in Chapter 4. A mega-model of a material look-up table is created in order to implement the heuristic search algorithm.

The RMS index method is then extended to design load bearing components using composite materials. This complete package of composite material design approach is presented in Chapter 5.

1.5.4 Selecting Commercially Available Laminated Composite Materials

The wide range of properties offered by composite materials can be obtained by varying fiber-matrix volumetric ratio. Also the directional properties of laminated composite materials can be easily manipulated by varying the angle of orientation with respect to the direction of the load. Theoretically it is possible to design composite laminates with any fiber-matrix ratio, and in any orientation. But in practice, only a selective number of laminates with given fiber volume fraction are produced and sold by the companies depending on their market demands. So, it is necessary for a designer to perform the selection of laminates from a list of available composite laminates to make it commercially viable. The manual selection process of composite laminates can be very cumbersome for the designers when multiple design goals need to be satisfied in the load bearing component that is being designed. This leads to following Research Question:

Research Question 4: How to design a load bearing component using commercially available laminated composite materials with limited property range in order to satisfy directional properties and design requirements?

To address to this Research Question, following hypothesis is considered:

Any component made of a number of mixed composite laminates is manufacturable as long as their matrix material is same.

This issue is addressed by extending the composite fiber-laminate combination selection method into the selection of laminates. A list of commercially available laminated composite materials is available with predicted properties for ideal state of the products. When combining these laminates, only lamination theory will be required in order to predict properties of products made by this laminated combination. This list, as should be inspected by the quality assurance department of the industry, should ensure manufacturability of the designed product. Research Question 4 is addressed in Chapter 6.

1.5.5 Validation of the Hip-replacement joint design example

The overall idea of this approach is to contribute a unique design approach that can use the theoretical prediction techniques of thermo-mechanical properties for any fiber-matrix composite combination and/or laminated composite materials, and reverse engineer the properties in order to achieve desired property goals. The approach is demonstrated using a very simplified example that can help the designers understand the unique approach easily. Since the goal of this work is not to design a problem, rather find out a better way to design, the only validation shown in Chapter 5 by performing FEA analysis of a Hip-replacement joint design example for appropriate loading conditions, and comparing the results with hand-calculations.

1.6 Thesis Outline

Chapter 2: A brief review of related work in shape grammar will be given. A shape grammar generation technique for irregular and complex shapes will be demonstrated using functional decomposition of shapes. The demonstration examples will include developing shape grammars of an irregular shape Hip-replacement implant, and an aerofoil shape of wind turbine blade.

Chapter 3: Mass-customization, product family and product platform design, and application of mass-customization in the use of shape grammar will be presented. Mass-customization will be demonstrated by generating a number of commonly used shapes using this technique.

Chapter 4: A component for composite material selection will be presented with a demonstrative example where multiple design objectives are satisfied.

Chapter 5: An approach for design of irregular shape load bearing composite structures will be presented. A Hip-replacement joint will be designed in order to demonstrate the approach. The results of the demonstrative example will be validated using commercially available FEA tools. The same example will be used for the demonstration in Chapter 6. So, the validation of this example will only be shown in this chapter only.

Chapter 6: The grammatical approach will be presented to design load bearing components using commercially available laminated composite materials. An appropriate blending technique will be introduced for composite laminate design that can help avoid stress-concentration at discontinued layers. Additionally, the formulation of an optimization model for shape modeling will be discussed in terms of form and functional requirements.

Chapter 7: The concluding remarks will present a summary of the work, the contributions made, and discuss possible future works, and limitations of the approaches.

CHAPTER 2

GENERATION OF CUSTOMIZED SHAPE GRAMMAR TO MEET FUNCTIONAL AND SPACE REQUIREMENTS

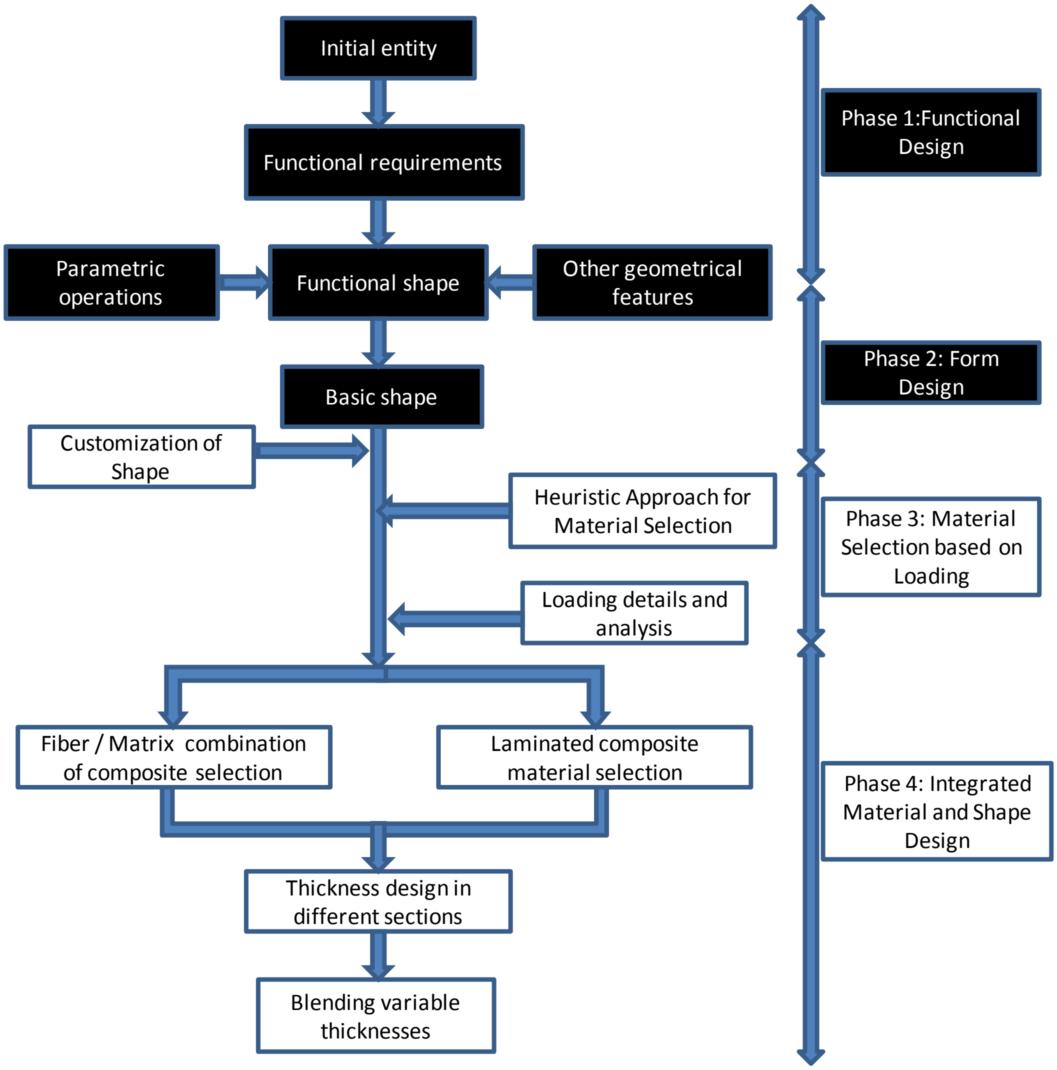


Figure 2-1: Functional and Form Design Phase

2.1 Introduction

Shape grammar technique, an efficient means of shape generation method (Stiny and Gips, 1971), was introduced in optimization methodologies because of its unique ability of to represent a range of shapes in an highly organized way (Stiny and Gips, 1971; Stiny and Mitchell, 1978; Stiny, 1980; Koning et al., 1981; Longenecker and Fitzhorn, 1991; Stiny, 1991; Reddy and Cagan, 1995; Agarwal and Cagan, 1997; Shea and Cagan, 1997; Agarwal, et al., 1999; Shea and Cagan, 1999; Agarwal and Cagan, 2000; Pugliese and Cagan, 2002; McCormacka et al., 2004; M¨uller et al., 2007; Speller et al., 2007; Orsborn and Cagan, 2009). A number of researches have successfully taken place in order to develop shape grammar of different consumer products, including coffee make, and the shape of automotive vehicle, and then an optimization technique was employed to determine efficient design of those products, no shape grammar is developed yet that can represent the irregular shapes with dimensional ranges, such as, size range of wind turbine aerofoil shape, or the ranges of dimensions of Hip-replacement implants, that can be efficiently used in the optimization of shapes for obtaining best design. So, an appropriate shape representation technique, i.e., a shape grammar is required that can help shape optimization to get the optimal solution by providing easy way to handle shape ranges. In this chapter a set of shape grammar rules are developed for a customized Hip-replacement implant shape design in order to demonstrate the technique. The same procedure is used to develop the general aerofoil blade shape grammar as an additional example.

Hip-replacement joints are designed to meet shape specifications for each individual patient. Because the height and shape of bones of every patient are different than the other, the design of Hip-replacement implant should consider a huge range of shapes. Again, the development of modern wind turbine design demands that the most efficient shape is achieved. Multi-objective optimization becomes necessary to determine optimized shape with largest possible size and lowest possible costs (Wauquiez, 2000; Mansour, 2005; Xudong, Shen, Zhu, and Sorensen, 2009). A small variation in shape can make a big difference in efficiency. However, finding optimized shape exploring all possible sizes can be computationally too expensive. A number of approaches have been proposed in order to find an efficient means of optimization (Xudong et al., 2009). Use of shape grammar can help these approaches to handle shape optimization with maximum efficiency. This motivated Research Question 1, which is addressed in this chapter.

How can a shape grammar model be generated in order to represent a component shape that will be used to perform desired functions while meeting space constraints?

In response to this question, two examples of shape grammars are defined in this chapter that generates shape of a Hip-replacement joint, and a shape of wind turbine blade from initial geometric entity such as a point, or a line. These grammars are comprised of sets of grammatical rules defining appropriate algebraic operations that use proper geometric entities to develop a base body, the formation of which will largely depend on another set of rules defining the functional space requirements for the component. Figure

2-1 shows the shape grammar representing Phase 1, and 2 of the grammatical approach presented in this work. The regular use of these set of rules will then be compared with product family and product platform concepts to define the family and platform of the rules in Chapter 3.

2.2 Definition of Shape Grammar Components

A shape grammar derives designs in the language it specifies by successive application of shape transformation rules to some evolving shape, starting with an initial shape (Agarwal and Cagan, 2000). Stiny (1980) defined shape and shape grammar and its different Boolean operations, a few of which (needed for this work) are as follows:

Shape: A shape is a limited arrangement of straight lines defined in a Cartesian coordinate system with real axes and an associated Euclidean metric.

Sub-shape and identity relations for shapes: One shape is a sub-shape (part) of another shape whenever every line of the first shape is also a line of the second shape.

Shape union: The shape union of shapes S_1 and S_2 is the shape consisting of all of the lines in S_1 or S_2.

Shape intersection: The shape intersection of shapes S_1 and S_2 is the shape consisting of just those lines in both S_1 and S_2.

Transformation of shapes: The Euclidean transformations provide for new shapes to be produced by changing the location, orientation, reflection, or size of a given shape.

(In the case example, presented in this chapter, a sweep operation took place to produce outer shape of the product, which is an example of such transformation)

The shape grammar formalism: The shape grammar formalism allows for algorithms to be defined directly in terms of labeled shapes and parameterized labeled shapes. (In the case example, the labeled lines are used to explain the rotation and formation of the base structure a-b-c-d-e.)

Thus shape grammar defines a set of shapes called a language. This language contains all of the shapes s generated by the shape grammar that have no symbols associated with them. Each of these shapes is derived from the initial shape by applying the shape rules; each is made up of shapes or sub-shapes of shapes in the set S. In engineering, shape grammar has been used to create a shape of component with desired specifications, and to compare them with the capabilities of a traditional production system (Agarwal and Cagan, 2000).

2.3 Illustrative Example: Generating Shape Grammar of a Hip-replacement Joint

2.3.1 Problem Description of Hip-replacement Joint

Hip-replacement joint implant devices are commonly used to treat painful arthritic conditions that result in loss of mobility. The operation consists of sawing off portions of the femur, reaming the femoral cavity to allow for implant insertion, and hammering the implant into the femur. The hip portion of the implant is similarly installed, often with screws. The femur portion of the implant includes a stem onto which the highly polished ball is attached. All components are available in a number of sizes so that the operating physician can optimize the components for a particular patient. So, it could be a very useful system if the design and sizes can be varied using shape grammars. Figure 2-2 shows a total hip replacement inserted into a human femur and hip.

Shape and size constraints are provided by the designer, depending on the size and shape of the hip where the component is to be placed. Some general shape and size constraints are as follows:

Shape constraint: The stem of the component (top portion) have to be round, this part is designed to be fit inside a highly polished ball. The root will have a 3° taper at the bottom. There is an angle between the root and the stem of about 36.5°.

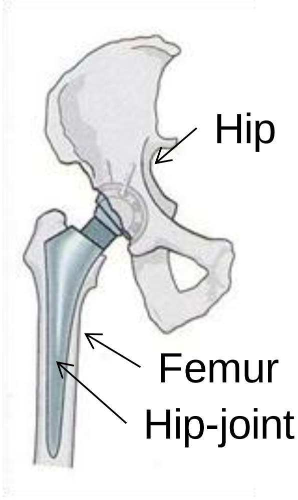


Figure 2-2: A total hip replacement inserted into a human femur and hip (Hamrock, Schmid, and Jacobson, 2005)

Size constraint: The inside diameter of the polished ball where the stem will be inserted, is 0.500 in (12.7 mm), this defines the outside diameter of the stem. For the proper observation and maintenance of the component, it is required to place some sensors inside the component. So, a hollow body is expected. The thickness of the surface is assumed to be maximum 4 mm.

2.3.2 Defining the Shape Grammar of Hip-replacement Joint

Functional Design Phase

Rule 1: Defining initial shape

The usual position of the lower part of hip and the location of upper portion of femur are considered for the functional design. The relative motions of these two parts take very important role to define the initial shape. The type of load is also a great factor for an ideal shape.

The basic function of the component is to provide a two-way joint between hip and the femur. So, a number of parametric points can be considered as the initial shape. A minimum of three points are required to express this rule. However, we consider five points for more accuracy as in Figure 2-3.

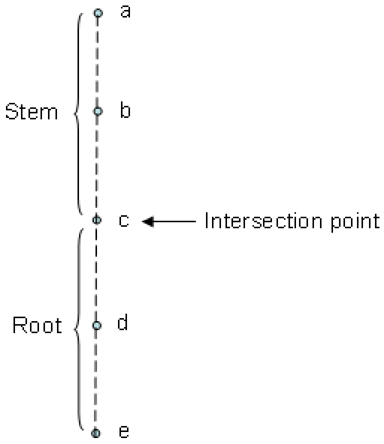


Figure 2-3: Defining initial shape

Rule 2: Defining angle

The actual load applied to a hip joint is extremely complicated and varies from person to person. Gait, step length, etc., all play a role in the biomechanics of walking. Although the direction of applied force can vary by as much as 30°, it is assumed that the load direction is vertical and centered on the stem. This is also a worst-case assumption, as any inclination of the load reduces the bending moment at any section.

Considering all these situations the angle between two main parts (stem and root) of the joint can be defined using first rule as shown by Figure 2-4.

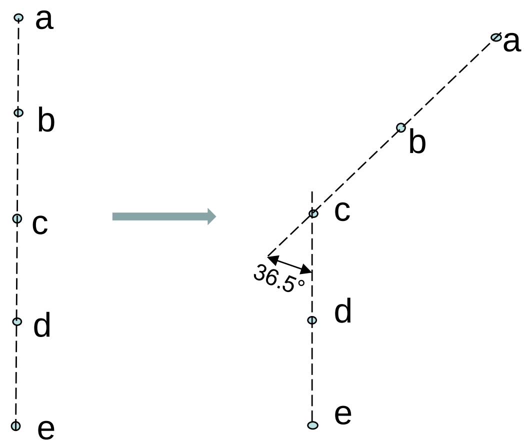


Figure 2-4: Defining angle

Form Design Phase

Rule 3: Defining cross section

The geometrical entity “point” will be replaced by another geometrical entity to define cross section at different locations of the body. The possible entities are square, rectangle, circle, oval, etc. For this example, cross-section for location a, b, and e are selected to be circles, as they are required to set inside round holes either inside the smooth ball or the round bone, while cross-section at location c and d could be a circle, rectangle, oval, etc. To capture the general shape of the component, we consider rectangular section for this example (Figure 2-5). In some practical problems the cross sections could be irregular in shape; however, for this example we will consider regular circles and rectangle only.

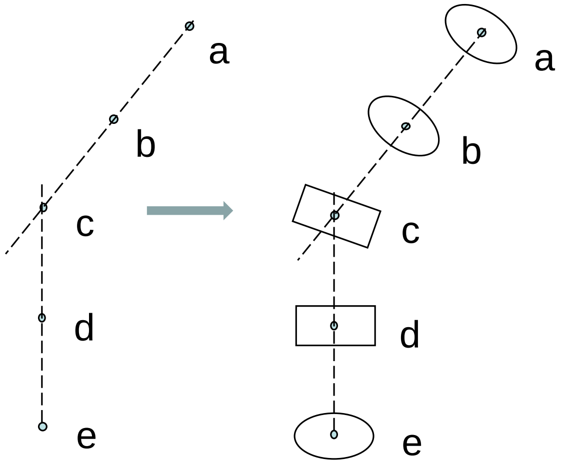


Figure 2-5: Defining cross section

Rule 4: Creating outer shell

The outer shape requirements for this example may be unique for each individual case, as this is going to replace a part of human body, the size of which may vary from person to person. Using the basic sweeping rules as explained by Cagan (Agarwal and Cagan, 1997), a 3D surface can be generated through the cross-sections to generate the initial outer shell of the component (Figure 2-6).

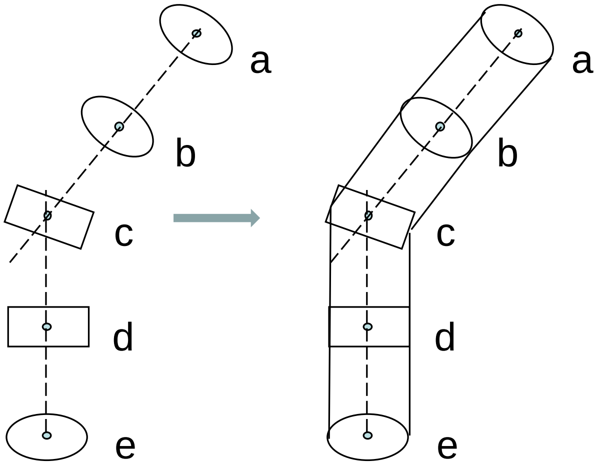


Figure 2-6: Sweep shape

Rule 5: Meeting the outer shape requirements

The dimensional requirements are provided by the user as mentioned before. In this example case we intend to capture the general shape of a Hip-replacement joint. Thus, in addition to those requirements, we consider an elbow shape extrusion extended from the intersection point c, and 3° taper shape at point e. This rule is shown by Figure 2-7.

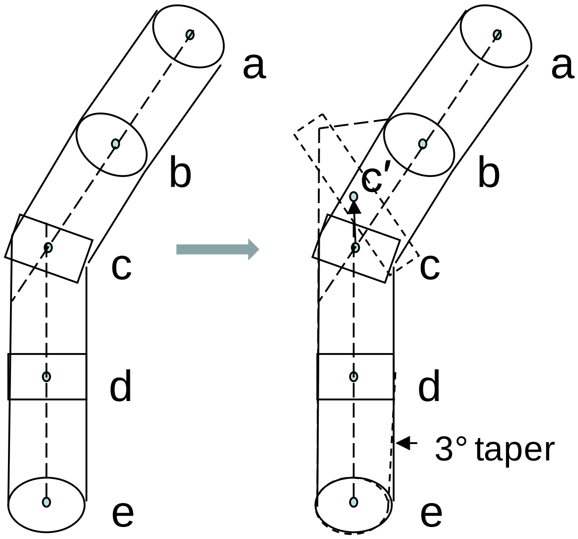


Figure 2-7: Creating outer shell

As can be seen from Figure 2-7, the rectangle at point c is extended to create an elbow. The center of the rectangle is moved upward to a new point c′, but still the angle between the stem and the root remains same which is measured at point c. At the same time circle at point e constricted a bit toward left to create a taper of 3° at the edge. Thus point e will be replaced by point e′.

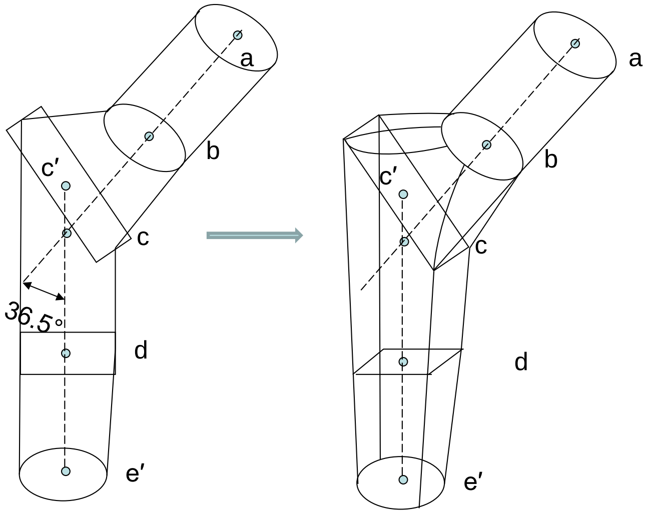


Figure 2-8: Outer shell

Adding the dimensions as mentioned above, the final form of outer shell of Figure 2-8 can be found similar to commercially used Hip-replacement is as shown in Figure 2-9.

Figure 2-9: Commercially available hip-joint of similar look

2.4 Shape Grammar for Wind Turbine Blade

2.4.1 Problem Description

The primary target of this work is to show how a shape grammar can be generated by functional decomposition of shape being inside the space constraint. Additional goal is to show that the product platform and product family design concept in the shape grammatical approach can offer efficient mass customization. Small scale component such as a Hip-replacement joint design was considered in example 1 in this chapter. This example extends the work in the application of comparatively larger scale component -a "Wind Turbine Blade" shape. Depending on location of establishment, wind speed, height of the structure, and other constraints, different designers prefer to design their model in various shapes. Shape grammar is introduced here so that variations of shapes of this product can be handled in an automated and efficient way.

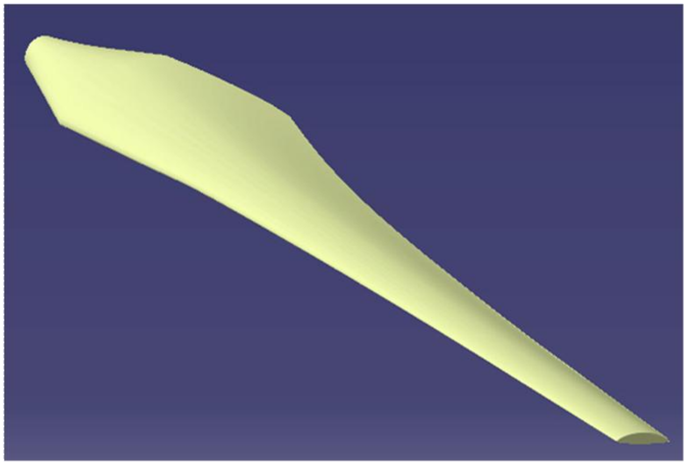


Figure 2-10: A general wind turbine blade shape (Technologies, 2012)

A general/basic shape for a wind turbine blade looks like Figure 2-10. The 3D shape generation can be divided into two main steps. First step involves grammar rules to generate the cross section of the blade. Second step will extend the cross section in the third dimension to generate the blade span in 3D shape.

2.4.2 Defining Shape Grammar for Wind Turbine Blade

The complete grammar for this basic shape design includes the following rules.

Rule To Determine Cross Section

The basic function of the wind turbine blade is to extract kinetic energy from the flow of wind by converting it into rotational motion. To do so, its structure needs to be designed to stand in the way of a wind flow. This initial structure can be represented by a line connecting two points, which is also known as chord of the shape. Assuming the wind direction to be horizontal, the line will be inclined at an angle between 0° and 90° with horizontal axis. The angle of inclination determines how much drag will be exerted on the body by standing against the gust of the wind. This shape range of initial chord structure can be given as in Figure 2-11. In the next rules of the grammar only inclined chord will be considered for further demonstration of the approach.

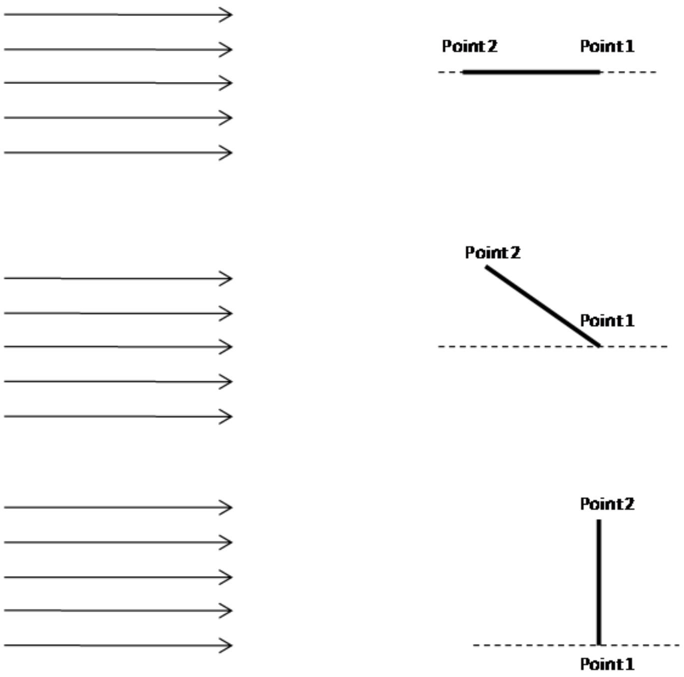


Figure 2-11: Defining initial structure (Chord)

Rule 1: Defining two edges

Leading edge and trailing edge play important roles in creating drag and the vortex in the air. Leading edge is usually created as a part of a circle and the range of other variables are limited by its size. Trailing edge can be circular arc, or a straight line, or a sharp point. Designer has the flexibility to select these variables based on various factors such as wind speed, chord length, allowable noise level, etc.

Thus, using this rule to previous rule, Figure 2-12 can be achieved.

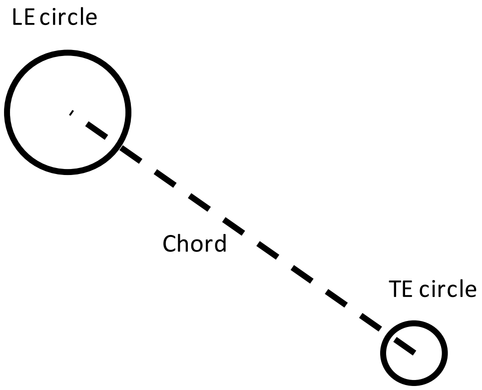
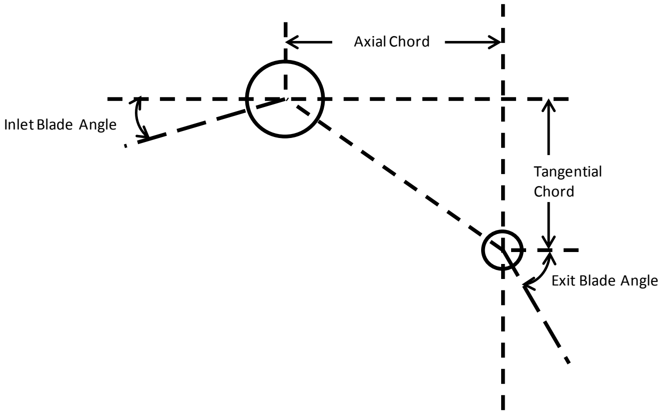


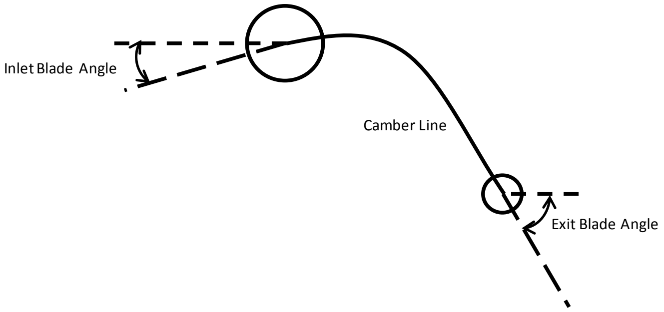
Figure 2-12: Leading and trailing edges in circular shape

Rule 2: Defining inlet and exit blade angle

Inlet blade angle and exit blade angle are also two important parameters that can determine the curvature of the blade shape. “Mean Camber Line” can be generated simply by connecting these lines, which is used in developing NACA aerofoil shape (Jacobs, Edward, and Pinkerton, 1933). Varying these two parameters, and thus varying camber line, any other shape can be generated as will be shown in the later part of the paper. Figure 2-13 (a) shows the two angles with the horizontal axis. Figure 2-13 (b) shows creating camber line by connecting inlet and exit point. It should also be noted that the chord can be divided into axial and tangential sections as parallel and vertical to the horizontal axis.



(a): Inlet and exit blade angles



(b): Creating mean camber line

Figure 2-13: (a) Inlet and exit blade angles. (b) Creating mean camber line

Rule 3: Generating upper and lower surface

Upper and lower surface can be generated by defining camber for different point on the mean camber line. Camber is defined as the vertical distance of the surfaces from each point on the mean camber line. Upper and lower camber from each point is equal and becomes tallest where maximum thickness is achieved. Camber can be defined by simple equations, and thus the surfaces are generated. Figure 2-14 shows thus generated upper and lower surface of an aerofoil shape.

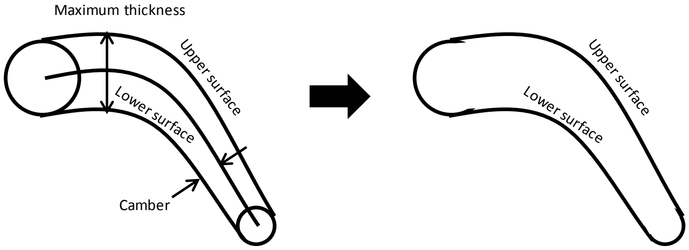


Figure 2-14: Upper and lower surface using camber and thus generated shape

Figure 2-15 (a) shows a set of sketches of widely used cross sections of aerofoil shapes that can be generated using this method (NASA, 2000). Figure 2-15 (b) shows cross sections of two aerofoil shapes of NACA profile that is generated in this method.

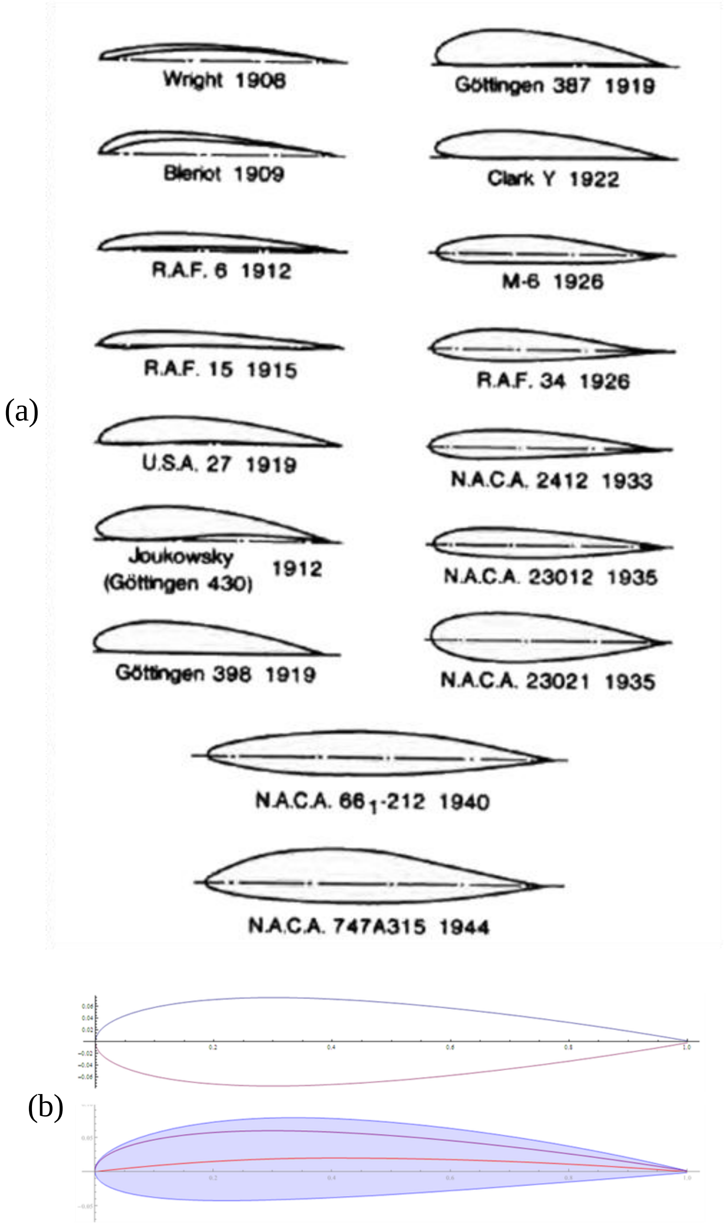


Figure 2-15: (a) Widely used aerofoil shapes, (b) NACA profiles for symmetrical profile and camber profile (Jacobs et al., 1935; Wikipedia, 2010)

Blade Span Design

This step involves two general rules.

Rule 4: Creating path

The path can be a straight line or a curved line depending on various factors. For HAWT, generally the path is a straight line extending from the hub to the tip of the blade. However, in order to better sustain the gusty wind some designers prefer to design slightly bent path inclined backward (Xudong et al., 2009). Figure 2-16 shows a straight line path, the length of which is determines the blade span, and also the swept area of the turbine.

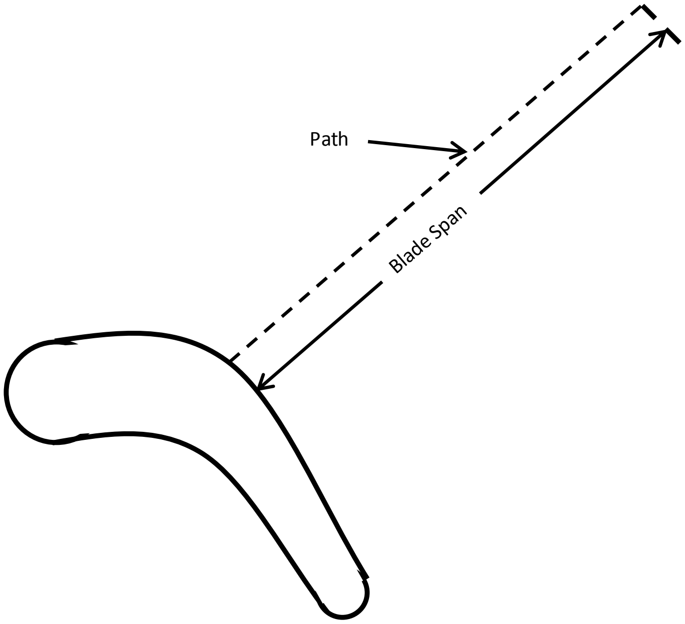


Figure 2-16: Creating path for blade span

Rule 5: Adding Twist Angle and variable area

Twist angle is added to the blade in order to ensure uniform lift and drag force throughout the blade span. This is because the rotation of blade generates higher tangential speed toward the tip of the blade than near the turbine hub. The generated cross section is extruded toward the path with rotating an amount of twist angle per distance. For some models, the cross sectional area is reduced toward the tip of the blade in addition to the twist angle in order to reduce weight load toward the tip, as the hanging blade acts as a rotating cantilever beam. Figure 2-17 (a) shows 3D blade span with twist 0˚ twist angle, and Figure 2-17 (b) shows same blade span with positive twist angle.

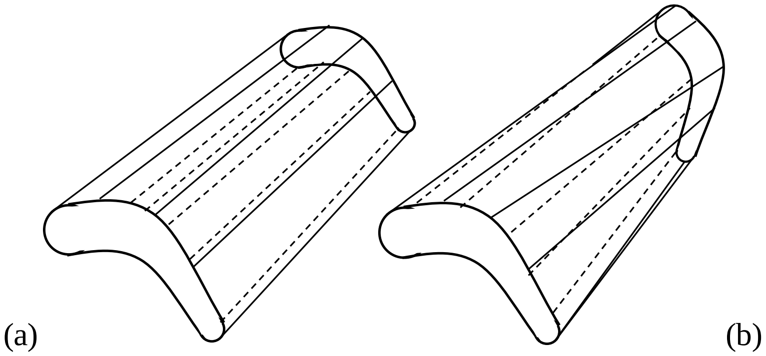


Figure 2-17: Twist angle and generated blade span: (a) with zero twist angle, (b) with positive twist angle

2.5 Summary of Chapter 2

The main focus of this chapter is to device shape grammar rules that can be used to generate any irregular and complex shape of a component to meet its functional and space requirements. This shape grammar generation technique is illustrated using two examples. a) Hip-replacement joints of irregular shape, b) Turbine blades with aerofoil cross section. In the following chapter, both the examples will be further extended to include product family and product platform concepts in generated shape grammar rules in order to explain scope of mass-customization in shape grammar.

CHAPTER 3

MASS CUSTOMIZATION AND SHAPE GRAMMAR

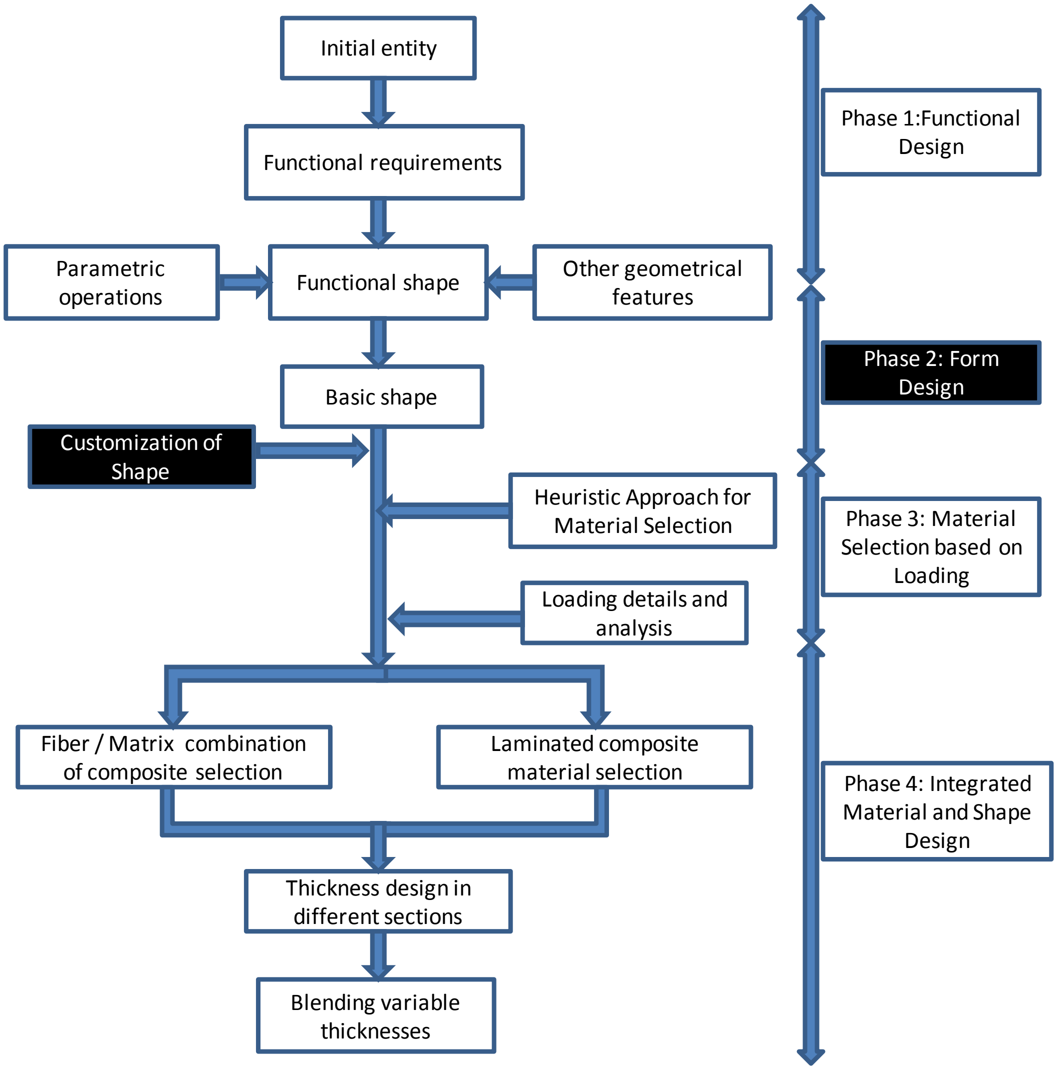


Figure 3-1: Phase 2: Mass-customization

3.1 Challenges with Customization

In this highly competitive market, individually customized commodities can no longer survive due to the high production and labor cost they incur; the cost effective way of production – "mass-production" are also struggling because of their inability to meet individual customer requirements with the gradual rise in the satisfaction level of the customers. Customers in this era know that they have plenty of options to select from and thus they demand customized product at a similar price of mass produced products. This increasing demand has driven the concept of "mass-customization" to complement and in certain cases replace the previous concepts of production. The two terms product family and product platform are related to each other and comes together as an efficient means to mass customize a product.

Researchers has investigated different types of modeling and designing techniques (Stiny and Gips, 1971) that use a set of rules that are termed as the grammars, and when such rules play with possible shapes of a product, the grammatical technique is called shape grammar. The concept of shape grammar though originated in the architecture hundreds of years ago, it has, over the past decade, drawn interest from architects, fine arts and fashion designers, brand commodity developers, mechanical designers, and even the structural and civil engineers (Stiny and Gips, 1971; Stiny and Mitchell, 1978; Stiny, 1980; Koning and Eizenberg, 1981; Longenecker and Fitzhorn, 1991; Stiny, 1991; Reddy and Cagan, 1995; Agarwal and Cagan, 1997; Shea and Cagan, 1997; Agarwal et al., 1999; Shea and Cagan, 1999; Agarwal and Cagan, 2000; Pugliese and Cagan, 2002;

McCormacka et al., 2004; M¨uller et al., 2007; Thomas H. Speller, Whitney et al., 2007; Orsborn and Cagan, 2009). The main reason for this interest is the ability of shape grammar to deal with an infinite number of possible shapes while designing and/or developing a new product.

In this chapter we investigate the idea that product family and product platform concepts can be applied to the shape grammar to develop an efficient approach for shape and structural design. The grammatical approach for the design of a Hip-replacement joint has been presented previously (Nandi et al., 2010; Nandi and Siddique, 2011) as an example case for the approach. In this chapter, the shape grammar of the example is emphasized only. The whole set of shape grammar rules is presented as a family, from which an effort is made to develop a platform of the rules. With that the application of product platform and product family concepts is introduced in the shape grammar technique.

The main focus of this chapter is on implementation of product family design approach in a shape grammar approach. This chapter begins with a brief overview on some of the research performed on shape grammar and grammatical approach, product family design, and common platform development concepts. Then the design of irregular shape objects will be demonstrated using an example of a Hip-replacement joint implant, and application of mass customization on shape grammar will be explained for the example.

3.2 Definition of Mass-customization Components

3.2.1 Product Family Design

Design for product variety is a relatively new research field, but it has received considerable attention in the management (Baker et al., 1986; Sanderson and Uzumeri, 1992) and engineering (Rothwell and Gardiner, 1990; Simpson et al., 1997) literatures. The basic concept of a family of products or multi-products approach is to obtain the biggest set of products through the most standardized set of base components and production processes (Stadzisz and Henrioud, 1995). Characteristics of product family range from flexible modular designs (Chen et al., 1994) to robust and scaleable designs (Rothwell and Gardiner, 1990) to standardized, flexible products. Martin (Martin and Ishii, 1996) identified commonality, modularity and standardization; Rothwell (Rothwell and Gardiner, 1990) emphasized robust design; Simpson *et al.* (1997) related change in form and function to highlight mutability, modularity and robustness, which, they suggest are the core characteristics of product families. Some of the other characteristics that have been stressed in other literatures for designing product families are: commonality, and standardization. Application of different mass-customization concepts to automotive platform commonality (Siddique et al., 1998) was also investigated.

Different approaches to providing families of products through the use of common platforms have been proposed. Wheelwright and Clark (1992) suggest designing “platform projects” that are capable of meeting the needs of a core group of customers but are easily modified into derivatives through addition, substitution and removal of features.

McGrath (1995) also stresses the need for a well designed product platform for a family of products. Parts commonality has been viewed as a means of cost reduction. McDermott and Stock (1994) in their work described how the use of common parts can shorten the product development cycle for savings in both time and money in the manufacturing process. Having a common assembly and manufacturing process is another important aspect of developing common product platforms. MacDuffie (MacDuffie et al., 1996) looked at how variety affected manufacturing within the automotive industry by studying empirical data.

From a general perspective (in most cases) all products have platforms and a set of similar products have the potential to be produced from a common platform. Development of common product platforms, in general, has a component perspective and an assembly process perspective associated with it. The component perspective specifies the common components present and different relationships among them. The assembly process perspective specifies assembly information, which will be used to specify if all the members of the family can be produced from the same assembly line. One of the objectives of developing common platform is to use the same assembly line to provide the necessary varieties. Component perspective of the platform commonization process has also been explained (Siddique and Rosen 1999).

3.2.2 Common Platform Development

From a general perspective (in most cases) all products have platforms and a set of similar products have the potential to be produced from a common platform. Development of common product platforms, in general, has a component perspective and an assembly process perspective associated with it. The component perspective specifies the common components present and different relationships among them. The assembly process perspective specifies assembly information, which will be used to specify if all the members of the family can be produced from the same assembly line. One of the objectives of developing common platform is to use the same assembly line to provide the necessary varieties. In this chapter only the component perspective of the platform commonization process will be considered.

3.2.3 Product Family Concept in Shape Grammar

The shape grammar approach of a product shape design is comprised of a set of interchangeable rules that can be compared to the members of a family. Thus if the set of rules is considered as the family of that product shape design, there will be a group of rules that will remain same for any of the similar shape design. In this work we define these rules as the common platform for the shape family. As the product platform provides the common ground for all members of the product family, these platform rules also provide the common shape that is inherent in all members of the family. While generating a shape grammar for any similar shape, different members (additional rules) of the family (set of rules) will be used in conjunction with the platform rules to define the grammar for a family member shape. In the next sections of this chapter, we will use a Hip-replacement joint family to illustrate this concept.

The general technique of shape grammar involves initiating each grammar from an initial shape that could be a set of points or a line or some other simple geometric entity. Different arithmetic and/or geometric operations take place on the initial shape to bring out the final design shape. These operations are represented by the rules in the grammar and usually defined by the designer (Stiny and Gips 1971; Stiny 1991). Defining rules for each and every variation of shapes is an inefficient and a cumbersome task, and it largely depends on the skill of the designer. For a given product, to develop any shape, there are a number of rules that every grammar have to follow. These common rules define the platform of the grammar family, and there are additional variety rules that will help the platform rules to capture any particular shape the designer may want. The platform rules along with the additional sub-rules are explored in this chapter with the possible variations that can be made.

3.3 Development of Product Family Representation for Hip-replacement Joint Grammar

To illustrate that the product platform and product family design concept in the shape grammatical approach can offer efficient mass-customization, we consider the example of designing a Hip-replacement joint that is used to provide a joint between hip and femur of a patient. Depending on structural variation of different persons, step length and gait of each person, there are various shapes of Hip-replacement joints available. Shape grammar is introduced here as a part of Phase 2 of the grammatical approach as shown by Figure 3-1, so that variations of shapes of this product can be handled in an automated and efficient way.

A general/basic set of shape rules for a Hip-replacement joint grammar is shown in Figure 3-2. As developed in Chapter 2, the complete grammar for the basic shape design includes following five rules; four of them being common to every grammar family, and an additional variety rule that determines the final shape of the Hip-replacement joint. These four common rules are considered as the platform for the Hip-replacement joint shape families. The four platform rules and the variety rules are described below.

Rule 1: Determining Initial shape

The basic function of the Hip-replacement joint is to provide a two-way joint between hip and the femur. So, a number of parametric points can be considered as the initial shape. A minimum of three points are required to express this rule. The central point will couple with other two points each time to create stem and the root of the Hip-replacement joint structure. While trying to capture commercially available Hip-replacement joint shapes, it is found that these roots and stems may be required to bent somewhere in the mid-span. So, an initial structure of five points has to be considered instead of three for more accuracy as given in Figure 3-2 (a)

Rule 2: Defining Angle

In case of biomechanics of walking, the actual load applied to a hip joint is complex and varies from person to person. Although the direction of applied force can vary by as much as 30°, it is assumed that the load direction is vertical and centered on the stem. This is also a worst-case assumption, as any inclination of the load reduces the bending moment at any location. Considering all these situations, the angle between two main parts (stem and root, as shown in Figure 3-2) of the joint can be defined using the first rule, as shown in Figure 3-2 (b).

Rule 3: Defining Cross-sections

The cross-sections at different location of the hip replacement joint depend on various factors. Usually the operating physician drills a hole inside the femur where the root of the Hip-replacement joint is to be inserted. In this case a simple circular section for the root is an easy selection for the design. This not only simplifies the operation, it can also simplify the design and fabrication of the designed component. However, with the course of time, as the person will be mobile, there is a chance for the replaced component to be displaced or dislocated from its original place inside the femur. To solve this problem, many orthopedic surgeons prefer irregular cross-section root that can prevent circular movement of the component.

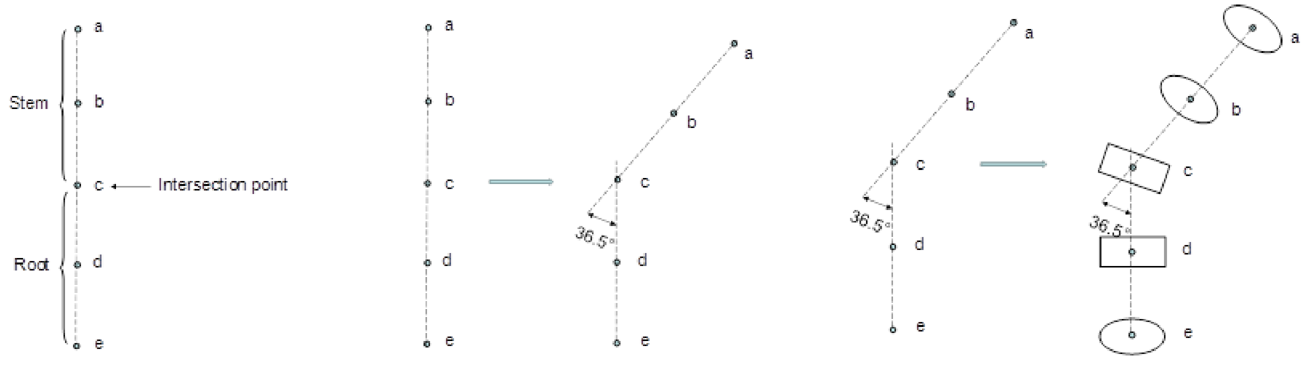
While applying the cross-section rule, the geometrical entity “point” is replaced by another geometrical entity to define cross-sections at different locations of the body. The possible entities are square, rectangle, circle, oval, etc. Cross-sections of the stem (location a, and b of the basic shape) are always considered to be circles, as they are required to set inside round holes inside the smooth ball. Cross-sections of different locations of the root can be of any shape depending on the surgeons recommendations and the shape of the inside hole of the femur.

Rule 4: Sweep Shape Rule

The outer shape requirements for Hip-replacement joint may be unique for individual cases, as this is going to replace a part of human body, the size of which may vary from person to person. Using the basic sweeping rules, as explained by Agarwal and Cagan (Agarwal and Cagan, 1997), a 3D surface can be generated through the cross-sections to generate the initial outer shell of the component (Figure 3-2 (d)). Sometimes a number of additional members of the grammar-family may be required to be combined with the platform rules as variety rules in the grammar to generate the outer shape from the initial shape. Following is a variety rule that is used to meet the outer shape of the product.

Rule 5: Variety Rules

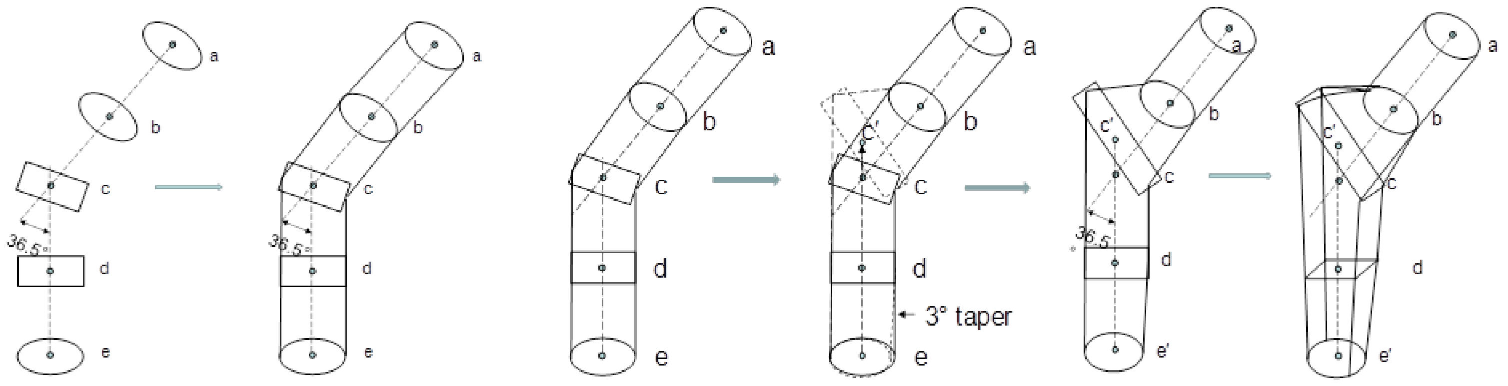
The dimensional requirements, such as angle between root and stem, cross-sectional dimensions, height of the implant, etc., are considered to be provided by the users. To capture the general shape of a Hip-replacement joint, a shoulder, a bent, or a curved root, etc, may be generated using additional rules. These additional rules are considered as part of the family, but as these rules depend on the ultimate shape of each product, they are not considered as the part of the platform of the grammar family. As given by Figure 3-2 (e) the general/basic shape of a hip replacement joint is created that has an extended shoulder and a taper at the end of root.



(a) Defining initial shape

(b) Defining angle

(c) Defining cross section



(d) Sweep shape

(e) Outer shell

Figure 3-2: Generating outer shell of the Hip-replacement joint using common shape rules

3.4 Exploring the Design Space and Capturing Shapes of Commercially Used Hip-replacement Joints Using the Common Platform Concept

One of the advantages of using shape grammars is their ability to generate a wide variety of designs simply by manipulating the rules. By modifying only a few of the rules in the grammar, different designs can be produced. In this chapter design space of Hip-replacement joints are explored to observed different possible designs for a given range of specifications.

3.4.1 Variation of Angle

As mentioned above, this rule determines angle between the root and the stem of Hip-replacement joint. Some designers prefer to use an optimal angle of 36.5 as a constant value (Hamrock et al., 2005), but this angle preference may be different for different designers. From Schüenke (Schüenke, Ross, Schulte, and Schumacher, 2006), it is found that the femoral neck, normally, forms an angle of 45˚ -60˚ with the shaft of the thigh bone (Figure 3-3 shows the supplementary angles), which disagrees with previous designer. This acts as a lever in easing the action of the muscles around the hip joint. An increase or decrease in this angle beyond the normal limits (45˚-55˚) causes improper action of the muscles, and interferes with walking (Qian, Song, Tang, and Zhang, 2010).

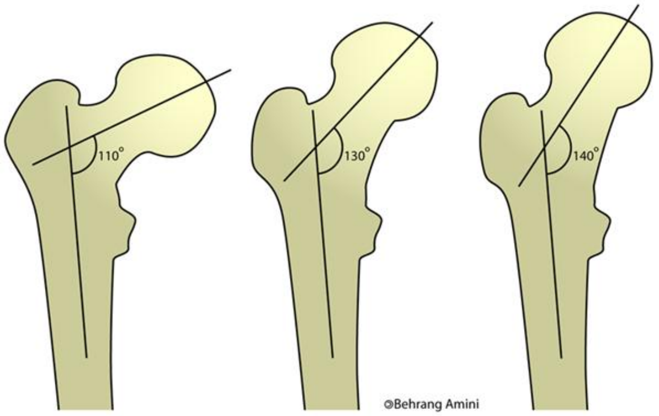


Figure 3-3: Femoral neck angles (Healthhype.com, 2006-2011)

Thus, in general, the shape grammar has to deal with a design angle range between 30˚ and 60˚. In that case, the designs in Figure 3-4 can be produced.

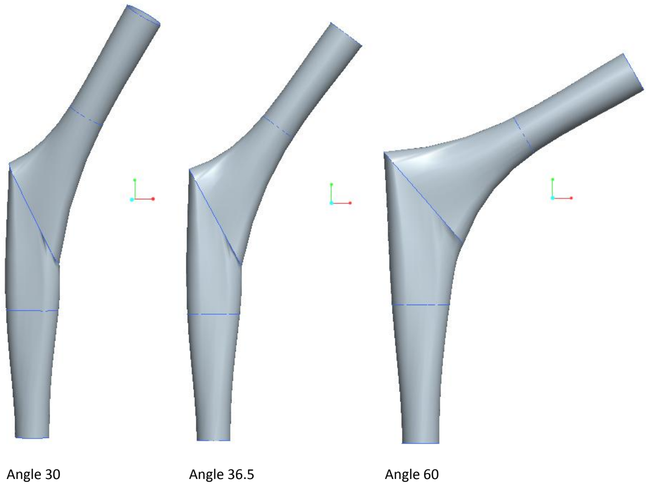


Figure 3-4: Variation of shapes with changes of rules for determining angles

3.4.2 Variation of Rule for Defining Cross-Section

This rule defines the cross sections of the component at different locations. Depending on the shape and size of the femur cavity the cross sectional dimensions may vary. The shape of the cross sections could be a circle, oval, or even some irregular shape. Here are some of the designs generated by such variation in this rule. With these variations different shapes are captured that are close to the commercially used Hip-replacement joint shapes.

Figure 3-5: Hip-replacement joint of various shape (Netream, 2009)

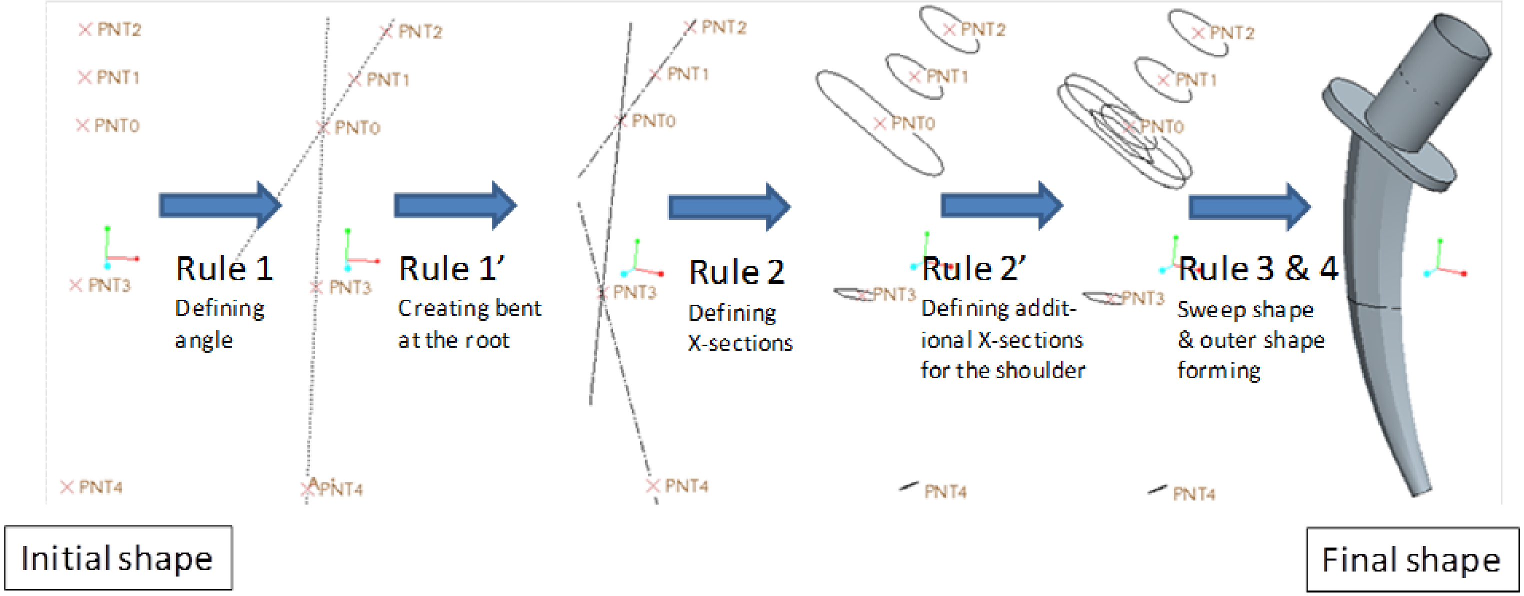


Figure 3-6: Capturing commercial shape with the application of shape platform rules

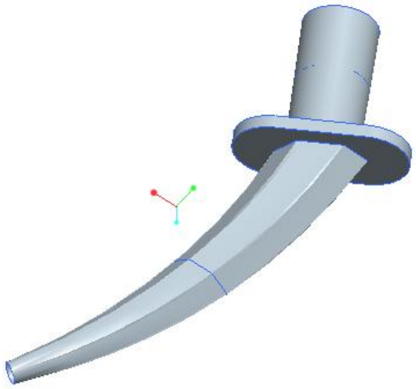


Figure 3-7: A Hip-replacement joint model created by the grammar to capture a shape similar to Figure 3-5

Figure 3-5 shows a special shape of Hip-replacement joint with six-sided cross section for the root that gradually becomes round at the edge. There is also an additional plate like extension at the intersection between the root and stem. As described by Figure 3-6, an additional rule from the family of rules is implemented.

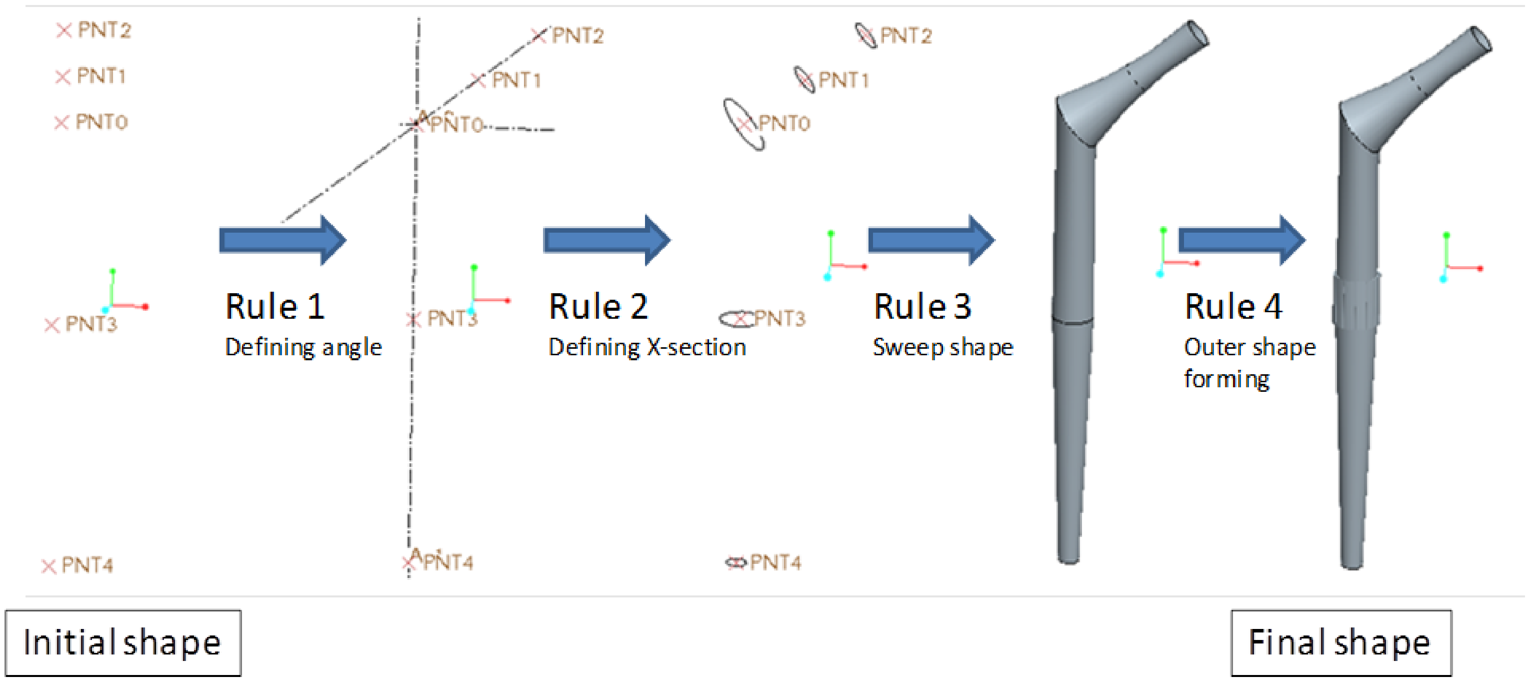


Figure 3-8: Capturing commercial shape with the application of shape platform rules

Figure 3-9: A narrow shape Hip-replacement implant

(Science photo library, 2012)

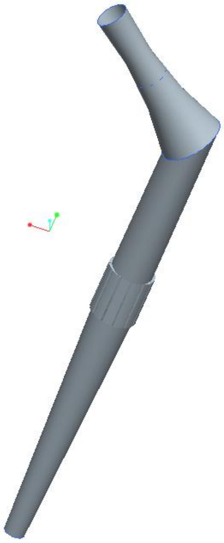


Figure 3-10: Generated similar shape using grammar

Figure 3-8 shows another application of the rule platform in the Hip-replacement joint grammar to capture a narrow shape Hip-replacement joint as shown by Figure 3-9 and Figure 3-10.

Figure 3-11 (a) below shows Mehta short Hip-replacement joint. The “Metha Short Hip System” (Aesculap Implant Systems, 2012) represents a unique shape of implant for prosthetic treatment of the hip joint. Its design and position affords high primary stability with immediate load bearing. Figure 3-11 (b) shows the shape generated by the grammar applying the product platform rules.

The grammar for the Metha short hip system, as shown by Figure 3-12 involves two additional rules to be applied in different order. Thus it shows that the rules may or may not be applied in the same order to generate every grammar or family of rules.

Figure 3-11: (a) “Metha Short Hip System” Hip-replacement joint, (b) Similar Hip-replacement joint created by the grammar

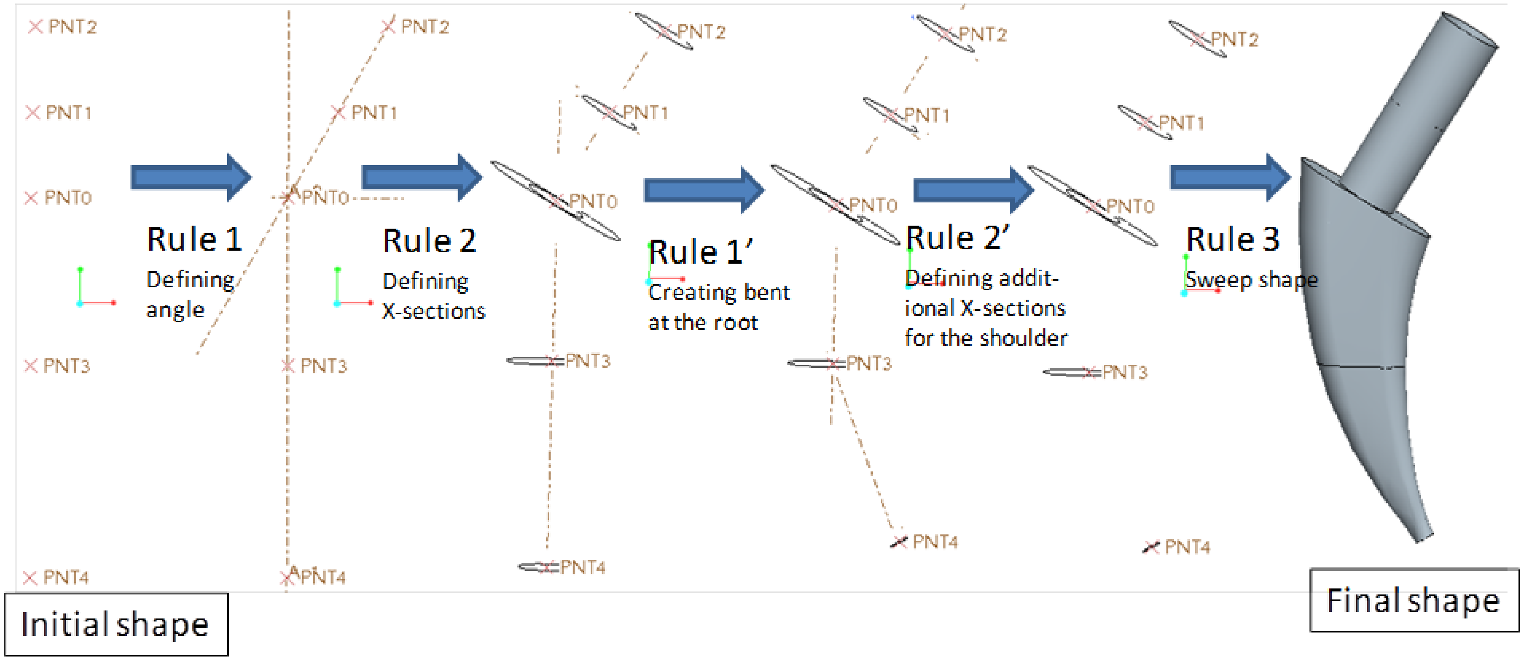


Figure 3-12: Shape formation using different rules

Thus the generation of different shapes using the rules family (grammar) shows that four members (rules) are common in all grammars presented in this chapter. Generation of any similar shapes will require these rules and some additional variety rules customized for each product to achieve the variety of their outer shapes. Thus, the use of this platform presented in this chapter can organize the generation of grammar while designing any Hip-replacement joint shape. This also enables pre-selected rules to take place every time a new grammar is being developed, and thus simplifies the design process.

3. 5 Summary of Chapter 3

In this chapter a customization approach of a shape grammar is presented for design of customized Hip-replacement joints. A platform for the Hip-replacement grammar rules has been established that can be used to make the customization possible. The rules family of the example is also extended to include design using composite materials/laminates. The results indicate that customization of shape grammar can ease the whole customization of the product for those cases where shape, size, and design all can vary for each item of the same product. Using the shape grammar family rules it is possible to capture the shape of any commercially available Hip-replacement joint by some minor changes in the rules in the grammar. It is also possible to further customize the rules by altering the dimensions inside the rules according to customers’ requirements.

One of the advantages of using shape grammar is that it can handle infinite number of shapes at the same time while performing each of the rules. Handling a large number of shapes usually consume a lot of computational time. The formation of shape grammar systematically reduces the range of shapes, which can result in significant reduction of overall computational time compared to any other optimization techniques. An appropriate technique to implement shape optimization technique using the Hip-replacement joint shape grammar will be shown in next chapter as a part of the material and loading design phase of the grammatical approach.

CHAPTER 4

COMPOSITE MATERIAL SELECTION APPROACH

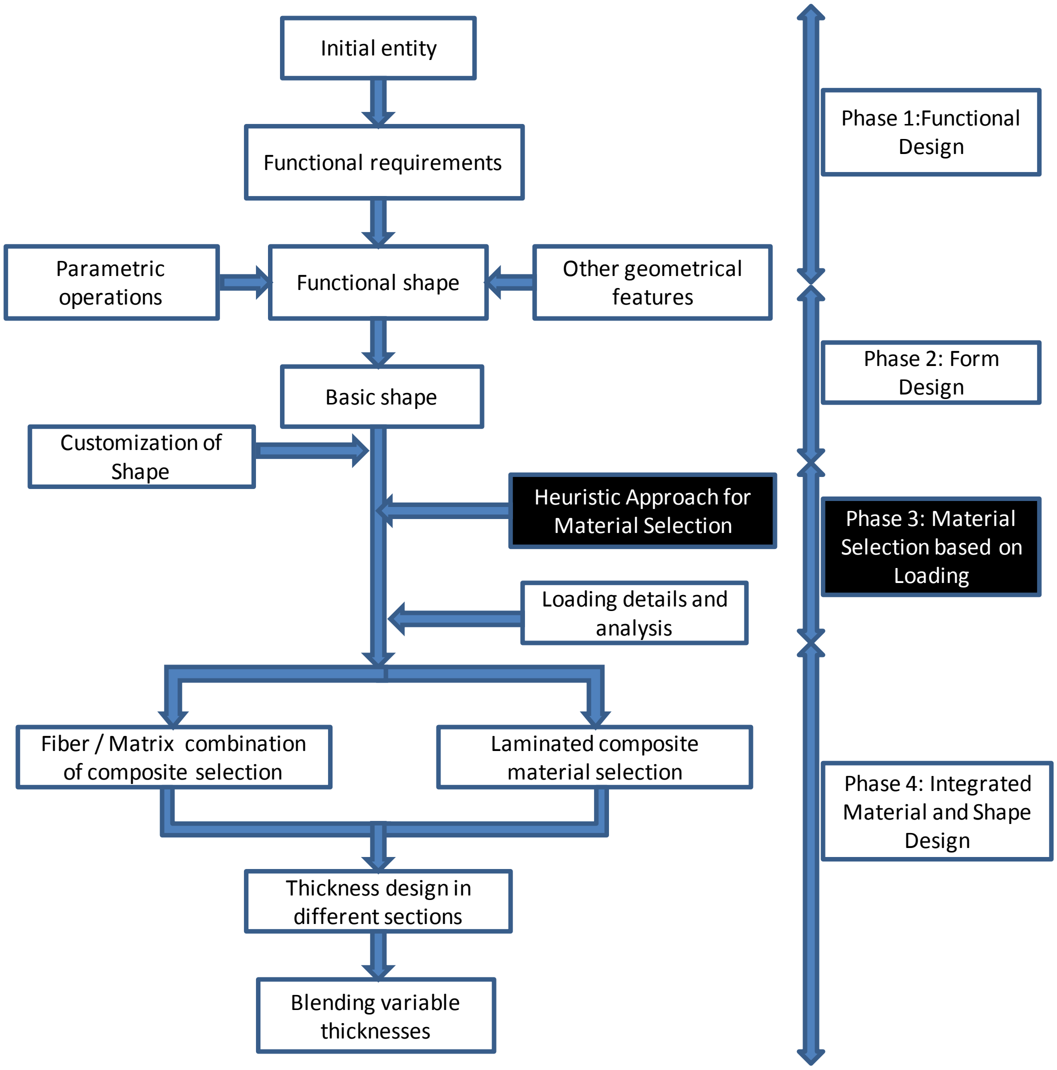


Figure 4-1 Composite material selection approach

4. 1 Introduction

The selection of appropriate materials is an important part of the design process for load bearing components and structures. The performance and life of an engineering structure, under a given loading condition, are limited by the properties of the material of which it is made, and by the shapes to which the material can be formed. The basic shape is addressed by the grammatical approach during Functional and Form design phase in Chapter 2 and 3, and this defines the performance of the component. Addressing selection of appropriate materials will be the next step for the approach as this phase of the grammar will allow achievement of the ultimate design goals.

Engineering components usually perform more than one function. They may require carrying bending moments, withstand very high or very low pressure, transmitting heat and electricity or providing resistance to wear and tear, etc. On the other hand, the designer has one or more goals to achieve during the design, such as to make the engineering component as cheap, light, or safe, as possible. Selection of appropriate material is the very first and most critical step to achieve all these functions and goals. In the traditional approach (Ashby, 1995; Ashby, 2005; Edwards, Abel et al., 1994) material selection involves choosing material from the conventional engineering materials with a single and specific property limit. However, it becomes more and more complicated and erroneous when multiple property and functions are targeted and a trade-off becomes eminent between different properties.

Research Question 3 is addressed in this chapter and also in Chapter 5:

How to select appropriate composite materials in order to satisfy directional property requirements at the critical sections of a component?

In order to address to the research question stated above, in this chapter, a mega-model of material selection tool is developed in two consecutive phases in this chapter (Figure 4-1), and are described as follows. The first phase presents an approach that involves determining the best combination of micro-mechanical models for prediction of most common properties of composite materials. A number of previous works from different researchers are considered to compare and select best combination of models. These semi-empirical models are implemented in different stage of this work while determining expected properties of the material combination. This work primarily focuses on the selection and implementation of appropriate micromechanical models for prediction of properties of composite materials. Here the best fitting micromechanical models are chosen for the most accurate prediction of different properties. Furthermore, the lamination theory (Taylor, Dong, and Pister 1959; Dong, et al. 1962; Achenbach, 1975; Herakovich, 1984; Aboudi, 1991; Hart-Smith, 1992; Herakovich, 1997; Gürdal et al., 1999; Kam and Lai, 1999; Yeow-Cheong, 2005) is incorporated with those models to reach the closest property goal. For simplicity of explanation, the example case presented in this paper, is limited to select from only fourteen types of fibers, one matrix (Epoxy), three types of layered ([θ/0/-θ], [0/θ/-θ/0], and [0/θ/0/-θ/0]) unsymmetrical laminates and in twelve specific orientations for each type, where θ is the angle between the fiber axis and laminate axis. Table 4-1 is used as a source of the basic material properties for different fibers and matrices used in this example.

In the next chapter (Chapter 5), an extension of the composite material customization tool is demonstrated that considers a load bearing component, and designs different sections based on the loading criteria. This section presents a grammatical approach to simultaneously consider the shape and selection composite materials for a load-bearing component. Selection of composites involve determining the fiber and matrix, their volume fraction, and number of layers in different location of the component. A Hip-replacement joint is designed using composite material to illustrate the approach.

4.2 Property Prediction from Micro to Laminate Level

The major achievement of the present approach is the incorporation of micromechanical models with lamination theory that can ensure meeting property goals in a specific direction without over-designing in its transverse. There are a number of works done where such multilevel property predictions are made, and then the predicted results are compared with the experimental results in order to validate the property prediction approach. A micromechanics based methodology to simulate the complete hygro-thermomechanical behavior of plain weave composites is developed (Mital, Murthy and Chamis, 1996). This methodology is based on micromechanics and the classical laminate theory, which predicts a complete set of thermal, hygral and mechanical properties of plain woven composites, generates necessary data for use in a finite element structural analysis, and predicts stresses all the way from the laminate to the constituent level. Predicted results compare reasonably well with those from detailed three-dimensional finite element analyses as well as available experimental data.

The stiffness properties of the twill composites are predicted by developing analytical models (Chaphalkar and Kelkar, 1999) which agree with the tensile test results. Three dimensional micro-mechanical models are developed in order to predict thermo-mechanical properties of woven fabric composite laminates (Vandeurzen, Ivens, and Verpoest, 1996; Sheng and Hoa, 2001). A constitutive model for macro-mechanically characterizing the non-orthogonal material behavior is extended to an integrated micro- and macro-constitutive model to predict the mechanical properties of woven composites during large deformation based on the microstructure of composites (Xue, Cao, and Chen, 2004). Simple and conventional analytical techniques are applied in order to predict the tensile properties of woven composites which show excellent agreement with the experimental data and the 3D finite element results.

Micromechanics models for plain weave composites are presented using in-house computer code interfacing with FEA tools, and developing analytical model using the theory of elasticity (Tan, Tong and Steven, 2006). Using an experimental testing program it is concluded that the failure strengths are closely related to the fiber volume fraction of a yarn, and the mechanical properties are closely related to the overall fiber volume fraction of the composites.

The calibration of a general micro/macro-mechanical model for composite materials and its application to the case of fiber reinforced composite laminates are presented (Toledo, Nallim, and Luccioni, 2008). Application examples showing the non-linear response of laminae and laminates obtained with the calibrated model and comparisons with experimental results are presented. The results show that the calibrated model describes the behavior up to failure of composite laminates. The failure mode of the composite produced by the failure of one or more of its components can be identified. Mechanical behavior of particulate reinforced materials are predicted by developing analytical model (Zong, Wang, Li and Xu, 2009), and the predicted data and modeling results are verified previously published experimental data.

4.3 Composite Material Selection Tool

The composite material selection tool, presented in this section is developed with a focus to create a user-friendly environment for the designer. As this tool deals with very large databases and these databases may need to be updated from time to time, an online system is suggested where the database along with the selection tool can be saved in a central selection server. The architecture of the selection tool is shown in Figure 4-2.

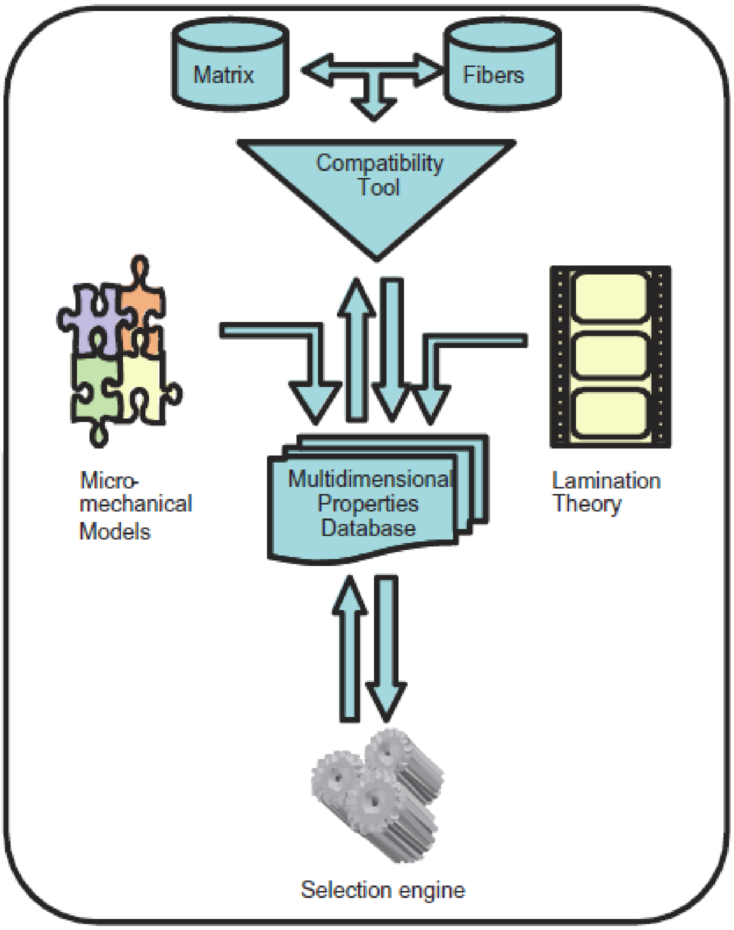


Figure 4-2: Architecture of the composite material selection tool

Table 4-1: Properties of engineering materials, fibers, and matrix (Herakovich, 1997)

Property	**Density, ρ**		**Modulus, E**			**Strength, σ_u**	
Units	**g/cm^3**	**lb/in^2**	**GPA**	**Msi**	**Poisson's ratio, ν**	**MPA**	**ksi**
Material							
Metals							
Steel	7.8	0.284	200	29	0.32	1724	250
Aluminum	2.7	0.097	69	10	0.33	483	70
Titanium	4.5	0.163	91	13.2	0.36	758	110
Fibers							
AS4	1.8	0.065	235	34	0.2	3599	522
T300	1.76	0.064	231	33	0.2	3654	530
P100S	2.15	0.078	724	105	0.2	2199	319
IM8	1.8	0.065	310	45	0.2	5171	750
Boron	2.6	0.094	385	55.8	0.21	3799	551
Kevlar 49	1.44	0.052	124	18	0.34	3620	525
SCS-6	3.3	0.119	400	58	0.25	3496	507
Nicalon	2.55	0.092	180	28	0.25	2000	290
Alumina	3.95	0.143	379	55	0.25	1585	230
S-2 Glass	2.46	0.09	86.8	12.6	0.23	4585	665
E-Glass	2.58	0.093	69	10	0.22	3450	550
Sapphire	3.97	0.143	435	63	0.28	3600	522
Matrix materials							
Epoxy	1.38	0.05	4.6	0.67	0.36	58.6	8.5
Polyimide	1.46	0.053	3.5	0.5	0.35	103	15
Copper	8.9	0.32	117	17	0.33	400	58
Silicon carbide	3.2	0.116	400	58	0.25	310	45

This system contains two basic databases. The first database contains information about different types of fibers, metals, and ceramics. The second database contains property information of different types of matrix material. These various fibers, metals, or ceramics, and the matrix materials are distinguished for their compatibility in all possible combinations. Table 4-1 shows a list of materials that are compatible to each other. However, because of limited manufacturing facility, the designer may not consider some combinations for the design. For an example, Ceramic fibers (SCS-6, Carbon, etc) reinforced Titanium alloy composite requires Rapid Infrared Manufacturing (RIM) process under an argon atmosphere (Warrier, Chen, Wu, and Lin, 1994). RIM process is very expensive and may not be available to the designer. Again, some very high viscous matrix materials may be very difficult to disperse or may require special arrangements to disperse inside micro-sized fibers. Use of Asphalt as a matrix material creates similar situation with Glass fiber. The compatibility tool is a Go-No go screening concept where the database is created and modified by the designer based on his/her personal experience. All these databases will contain up-to-date information about various composite synthesizing methods and are always updatable for new innovations (Figure 4-2).

Different pre-selected micro-mechanical models for different properties and the lamination theory are incorporated with the databases to create a multidimensional properties database (Figure 4-3). The selection engine follows different stages of a heuristic search algorithm and a set of choice is made.

A Root-Mean-Square (RMS) index concept is introduced in this tool, which is considered as the index for the selection. All possible combinations of fiber and matrix materials are analyzed for different orientations and using the application of lamination theory, the directional properties are considered during analysis. Thus the multidimensional chart is obtained; each dimension stands for different property requirements. An RMS value is obtained for each composite combination according to the merits of closeness to the multiple property goals, which enables the tool to make the best selection. Finally the selected composite laminates are sorted according to their RMS index, and the expected properties are calculated using similar models. The tabulated result is shown as output to the designer. The basic properties of the materials from which selections are made are tabulated in Table 4-1. Combining these fibers with different matrix materials, it is possible to achieve a very wide range of properties. Finally the selected options from the list are sorted according to their merits and the expected properties by these combinations are calculated using the similar models. The tabulated result is shown as output to the user end.

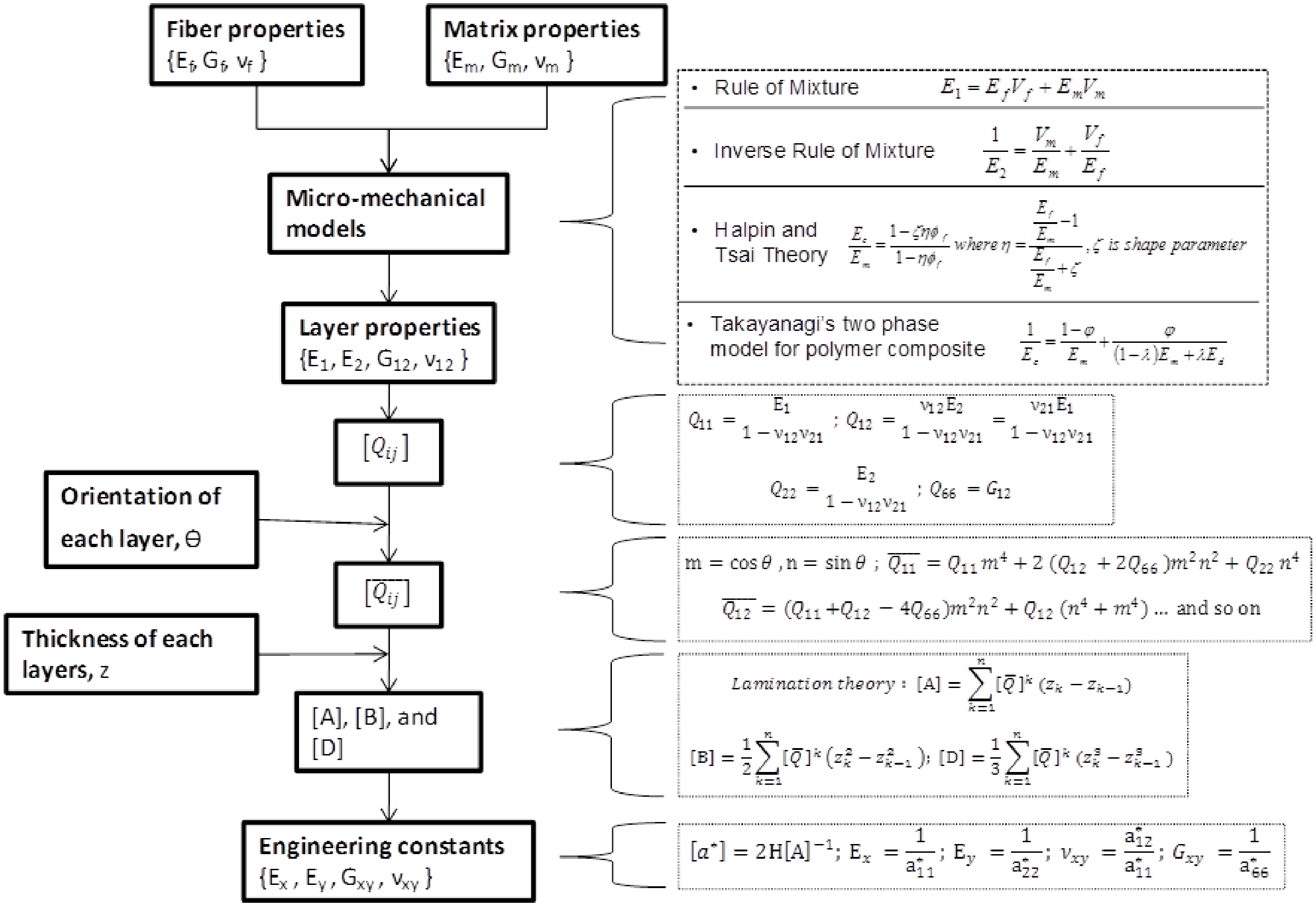


Figure 4-3: Composite material selection flow chart

4.4 Steps to Develop Material Charts and Selection of Material – Heuristic Algorithm

The steps to select materials based on property requirements, using a heuristic algorithm, are discussed next. The steps involved are as follows:

Step 1: Categorizing the properties

For convenience of selection, in this approach the properties are divided into three different categories. The first category includes direct constraints, such as density, thermal expansion coefficient, etc. The main feature of this category of properties are that for a specific volume fraction of a composite combination, their values remain unchanged regardless of the change in fiber orientation, number of plies per laminates, etc.

The second category includes the properties that are directly or indirectly related to the fiber volume fraction as well as orientation and number of plies per unit thickness. The examples of such properties are Young’s modulus, Poisson’s ratio, strength, stiffness, etc.

The third category is comprised of the constraints that may vary with different orientation and composition of composites, but this varying does not maintain any definable rules. So any direct mathematical relation is not possible for these constraints and/or properties. However a sort of statistical relations could still be developed in cases where enough experimental results are available. The examples of this category are the costs, manufacturing processes, etc.

In the first step of this approach, the required properties are categorized according to their behavior with other related constraints.

Step 2: Feasibility screening

The main purpose of this step is to narrow down the computational domain to a limited range, where only potential combinations of composites are possible, thus eliminating chances of unnecessary calculation and converging towards the goal. This also increases the pace of overall system/properties and/or constraints of the first category are considered in this step to determine the range of material combinations that meet the requirements. Material charts are created for each property using appropriate model, tabulating the approximate property for different fiber volume fraction. The charts are then narrowed down by chopping off the part that gives properties outside the required range or values. Fiber volume fractions of the remaining combinations are considered for further analysis in the next steps.

Step 3: Creating multidimensional chart

In this step appropriate micromechanical models and lamination theory are incorporated to determine properties of composite in different fiber orientation, with different compositions. A multidimensional chart is created comparing multiple numbers of properties and constraints of the second type (each property or constraint adds one dimension to the chart) while varying the volume fraction of fiber, different orientations of fiber direction, and different number of plies in each stack (varying thickness in acceptable range). Different micromechanical models are selected for different properties that can make best-fit prediction of the properties of different composition of composites.

Step 4: Centralization of the ranges

In this step the property deviation from the allowable range in the multidimensional chart is determined by simply deducting the value from the higher or lower limit as appropriate. This creates a similar multidimensional chart containing some zeroes and positive values.

Step 5: Normalizing the deviations

At this stage the centralized charts need to be in a comparable scale of equal range for all properties. This is achieved by dividing the data of the multidimensional table with the highest number in each associated chart. The new chart is generated with values ranging from 0 to 1.

Step 6: Determining RMS values

The Root-Mean-Square for each fiber-volume fraction for different orientations is determined combining different property values related to each fraction. This gives an index for measuring the combination of best selection.

Step 7: Selecting the option with lowest RMS value

The RMS value generated in the last step is used as an index for this selection. The lower the RMS value, the closer the property achieved. The target is to get zero RMS to achieve all property in that fiber-matrix-laminate-orientation combination.

Step 8: Applying other constraints

If “Cost” and other constraints are involved, then the selection tool in this work will consider these constraints so that the final selection decision can be made

4.5 Material Selection for Epoxy with Specific Requirements – An Example

4.5.1 Problem Description

To demonstrate the composite material customization tool, a simple arbitrary case is assumed where the designer intends to design a product with an Epoxy composite having directional properties as follows:

Density, less than 1.5 g/cm^3

Thermal expansion coefficient, in between 15μ/°C to 20μ/°C

Young’s modulus in axial direction should be between 40 and 60 GPa

Young’s modulus in longitudinal directions should be between 25 GPa and 30 GPa

Poisson’s ratio, between 0.15 and 0.2

Shear modulus, between 4 and 5 GPa

4.5.2 Detailed Steps for Fiber Material Selection for Epoxy Composite

The steps required (Section 4.4) to solve this material selection problem is presented next.

Step 1: Categorizing the properties

As explained in previous section, the density and the thermal expansion coefficient are directly related to the volume fraction of composites and they remain unchanged with any change in fiber orientation and other variables. So, these two properties fall in Category 1. Similarly, Young's modulus, Poisson's ratio, and shear modulus fall in category 2. In this simple case we do not have any requirements for property category 3.

Step 2: Feasibility screening

The Table 4-2 shows a partial view of the chart for determining density of different types of composites with different volume fractions. The shaded elements in each column indicate the acceptable density range for each type of composites. This screening phase allows us to disregard the composites having fiber volume fractions outside these limits.

Table 4-2: Feasibility screening using density

V_f	Steel	Aluminum	Titanium	AS4	T300	P100S
0	1.38	1.38	1.38	1.38	1.38	1.38
0.01	1.4442	1.3932	1.4112	1.3842	1.3838	1.3877
0.02	1.5084	1.4064	1.4424	1.3884	1.3876	1.3954
0.03	1.5726	1.4196	1.4736	1.3926	1.3914	1.4031
0.04	1.6368	1.4328	1.5048	1.3968	1.3952	1.4108
0.05	1.701	1.446	1.536	1.401	1.399	1.4185
0.06	1.7652	1.4592	1.5672	1.4052	1.4028	1.4262
0.07	1.8294	1.4724	1.5984	1.4094	1.4066	1.4339
0.08	1.8936	1.4856	1.6296	1.4136	1.4104	1.4416
0.09	1.9578	1.4988	1.6608	1.4178	1.4142	1.4493
0.1	2.022	1.512	1.692	1.422	1.418	1.457
0.11	2.0862	1.5252	1.7232	1.4262	1.4218	1.4647
0.12	2.1504	1.5384	1.7544	1.4304	1.4256	1.4724

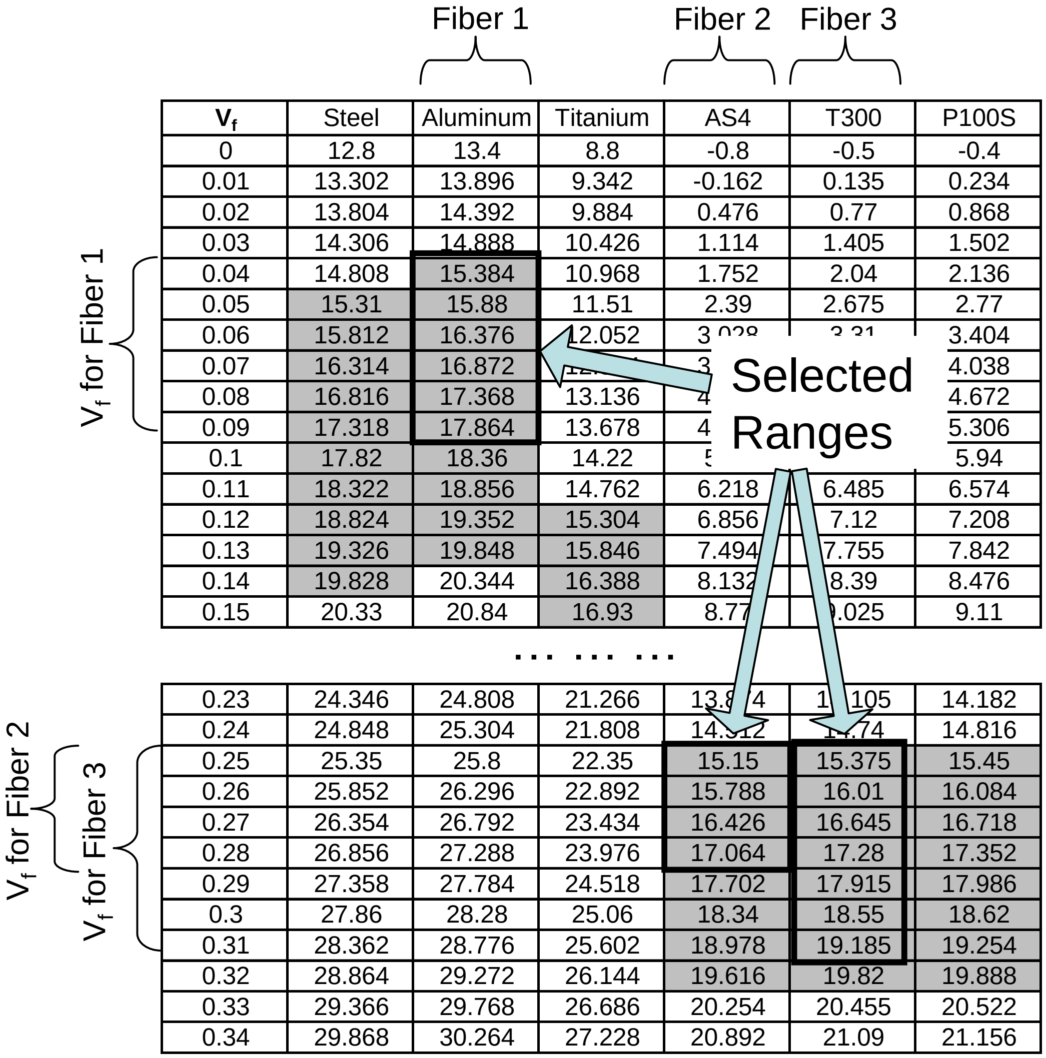
The next screening phase for this example is carried out from the chart of thermal expansion coefficient vs. volume fraction of different types of composites. Table 4-3 gives the partial view of this screening phase.

In the Table 4-3, the shaded elements indicate the acceptable range of fiber volume fraction for thermal expansion coefficients of the corresponding fibers. Superimposing Table 4-2 and Table 4-3 brings the elements inside the dark boxes indicating the ranges that meet the requirements of both screening phases. Hence, various combinations of composites associated with these boxed ranges will be considered for further analysis in this example.

Step 3: Creating multidimensional chart

In this part of the approach a multidimensional chart is created; the number of dimensions depends on the number of properties and variables dealing with the selection. In this demonstration case we have four remaining properties E_x, E_y, ν_{xy}, and γ_{xy}, and four variables such as, fiber volume fraction, fiber orientation, number of plies in laminates, and fiber and matrix combinations. Thus it creates a virtual chart of eight dimensions.

Table 4-3: Feasibility screening using thermal expansion coefficient



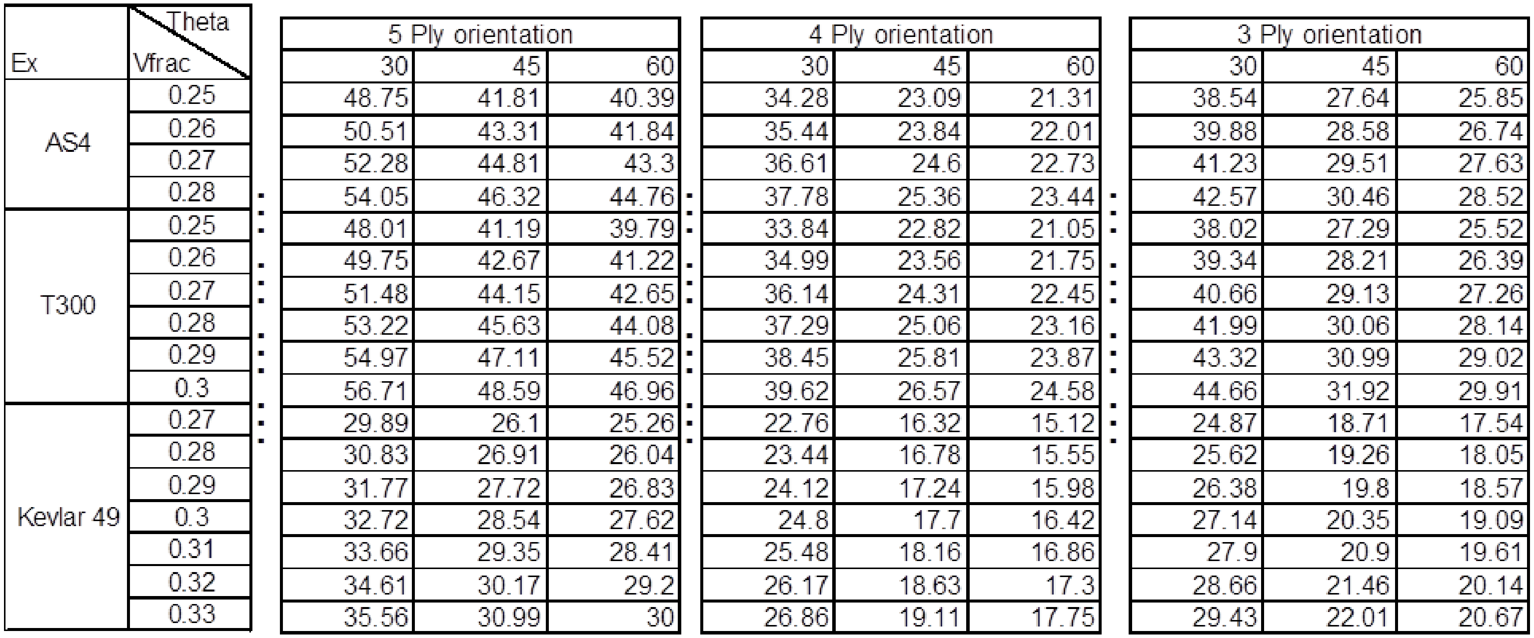
V_f	Steel	Aluminum	Titanium	AS4	T300	P100S
0	12.8	13.4	8.8	-0.8	-0.5	-0.4
0.01	13.302	13.896	9.342	-0.162	0.135	0.234
0.02	13.804	14.392	9.884	0.476	0.77	0.868
0.03	14.306	14.888	10.426	1.114	1.405	1.502
0.04	14.808	15.384	10.968	1.752	2.04	2.136
0.05	15.31	15.88	11.51	2.39	2.675	2.77
0.06	15.812	16.376	12.052	3.028	3.31	3.404
0.07	16.314	16.872	[illegible]	[illegible]	[illegible]	4.038
0.08	16.816	17.368	13.136	[illegible]	[illegible]	4.672
0.09	17.318	17.864	13.678	[illegible]	[illegible]	5.306
0.1	17.82	18.36	14.22	[illegible]	[illegible]	5.94
0.11	18.322	18.856	14.762	6.218	6.485	6.574
0.12	18.824	19.352	15.304	6.856	7.12	7.208
0.13	19.326	19.848	15.846	7.494	7.755	7.842
0.14	19.828	20.344	16.388	8.132	8.39	8.476
0.15	20.33	20.84	16.93	[illegible]	[illegible]	9.11
0.23	24.346	24.808	21.266	[illegible]	[illegible]	14.182
0.24	24.848	25.304	21.808	[illegible]	[illegible]	14.816
0.25	25.35	25.8	22.35	15.15	15.375	15.45
0.26	25.852	26.296	22.892	15.788	16.01	16.084
0.27	26.354	26.792	23.434	16.426	16.645	16.718
0.28	26.856	27.288	23.976	17.064	17.28	17.352
0.29	27.358	27.784	24.518	17.702	17.915	17.986
0.3	27.86	28.28	25.06	18.34	18.55	18.62
0.31	28.362	28.776	25.602	18.978	19.185	19.254
0.32	28.864	29.272	26.144	19.616	19.82	19.888
0.33	29.366	29.768	26.686	20.254	20.455	20.522
0.34	29.868	30.264	27.228	20.892	21.09	21.156

The multidimensional chart is simplified creating four 3D charts. Table 4-4 shows a partial view of the charts. For simplicity we have limited the type of plies to 3 and number of orientation to 12, for this example. The general notation for the unsymmetrical laminates considered in this case study is given in Section 1.

Step 4: Centralization of the ranges

As given by the user requirements, E_x ranges between 40 and 60 GPa, E_y ranges between 25 and 30 GPa, ν_{xy} ranges between 0.15 and 0.2, and G_{xy} ranges between 4 and 5 GPa. If a data in the charts is inside the range of the associated property, the data is replaced by a zero, all other data are replaced by the differences with the upper or lower limit of the associated range whichever is closer to the value. The Table 4-5 gives a partial view of the centralized chart generated for this example case.

Table 4-4: Partial view of multidimensional charts



Ex	Theta / Vfrac	5 Ply orientation			4 Ply orientation			3 Ply orientation		
		30	45	60	30	45	60	30	45	60
AS4	0.25	48.75	41.81	40.39	34.28	23.09	21.31	38.54	27.64	25.85
	0.26	50.51	43.31	41.84	35.44	23.84	22.01	39.88	28.58	26.74
	0.27	52.28	44.81	43.3	36.61	24.6	22.73	41.23	29.51	27.63
	0.28	54.05	46.32	44.76	37.78	25.36	23.44	42.57	30.46	28.52
T300	0.25	48.01	41.19	39.79	33.84	22.82	21.05	38.02	27.29	25.52
	0.26	49.75	42.67	41.22	34.99	23.56	21.75	39.34	28.21	26.39
	0.27	51.48	44.15	42.65	36.14	24.31	22.45	40.66	29.13	27.26
	0.28	53.22	45.63	44.08	37.29	25.06	23.16	41.99	30.06	28.14
	0.29	54.97	47.11	45.52	38.45	25.81	23.87	43.32	30.99	29.02
	0.3	56.71	48.59	46.96	39.62	26.57	24.58	44.66	31.92	29.91
Kevlar 49	0.27	29.89	26.1	25.26	22.76	16.32	15.12	24.87	18.71	17.54
	0.28	30.83	26.91	26.04	23.44	16.78	15.55	25.62	19.26	18.05
	0.29	31.77	27.72	26.83	24.12	17.24	15.98	26.38	19.8	18.57
	0.3	32.72	28.54	27.62	24.8	17.7	16.42	27.14	20.35	19.09
	0.31	33.66	29.35	28.41	25.48	18.16	16.86	27.9	20.9	19.61
	0.32	34.61	30.17	29.2	26.17	18.63	17.3	28.66	21.46	20.14
	0.33	35.56	30.99	30	26.86	19.11	17.75	29.43	22.01	20.67

Table 4-5: Centralized charts

Ex	Theta / Vfrac	5 Ply orientation			4 Ply orientation			3 Ply orientation		
		30	45	60	30	45	60	30	45	60
AS4	0.25	0	0	0	5.72	16.91	18.69	1.46	12.36	14.15
	0.26	0	0	0	4.56	16.16	17.99	0.12	11.42	13.26
	0.27	0	0	0	3.39	15.4	17.27	0	10.49	12.37
	0.28	0	0	0	2.22	14.64	16.56	0	9.54	11.48
T300	0.25	0	0	0.21	6.16	17.18	18.95	1.98	12.71	14.48
	0.26	0	0	0	5.01	16.44	18.25	0.66	11.79	13.61
	0.27	0	0	0	3.86	15.69	17.55	0	10.87	12.74
	0.28	0	0	0	2.71	14.94	16.84	0	9.94	11.86
	0.29	0	0	0	1.55	14.19	16.13	0	9.01	10.98
	0.3	0	0	0	0.38	13.43	15.42	0	8.08	10.09
Kevlar 49	0.27	10.11	13.9	14.74	17.24	23.68	24.88	15.13	21.29	22.46
	0.28	9.17	13.09	13.96	16.56	23.22	24.45	14.38	20.74	21.95
	0.29	8.23	12.28	13.17	15.88	22.76	24.02	13.62	20.2	21.43
	0.3	7.28	11.46	12.38	15.2	22.3	23.58	12.86	19.65	20.91
	0.31	6.34	10.65	11.59	14.52	21.84	23.14	12.1	19.1	20.39
	0.32	5.39	9.83	10.8	13.83	21.37	22.7	11.34	18.54	19.86
	0.33	4.44	9.01	10	13.14	20.89	22.25	10.57	17.99	19.33

Step 5: Normalizing the deviations

The highest values in the charts for E_x, E_y, ν_{xy}, and G_{xy} are found to be 24.88, 27.29, 0.72, and 9.49 respectively. All elements of the charts are divided with the associated highest number and a new chart is generated that consists of a set of data ranging from 0 to 1. Table 4-6 gives a partial view of the charts.

Step 6: Determining RMS values

The RMS value is considered an index for selection in this approach. Each corresponding elements of all charts are squared and added; the mean of these added values are then square-rooted to get the RMS of the associated element of the chart.

For an example, the normalized values for Kevlar 49 – Epoxy composite, having V_f equal to 0.3 and 5 ply orientation as [0/-60/0/60/0], are 0.497588, 0.335654, 0.208333, and 0.046365 successively.

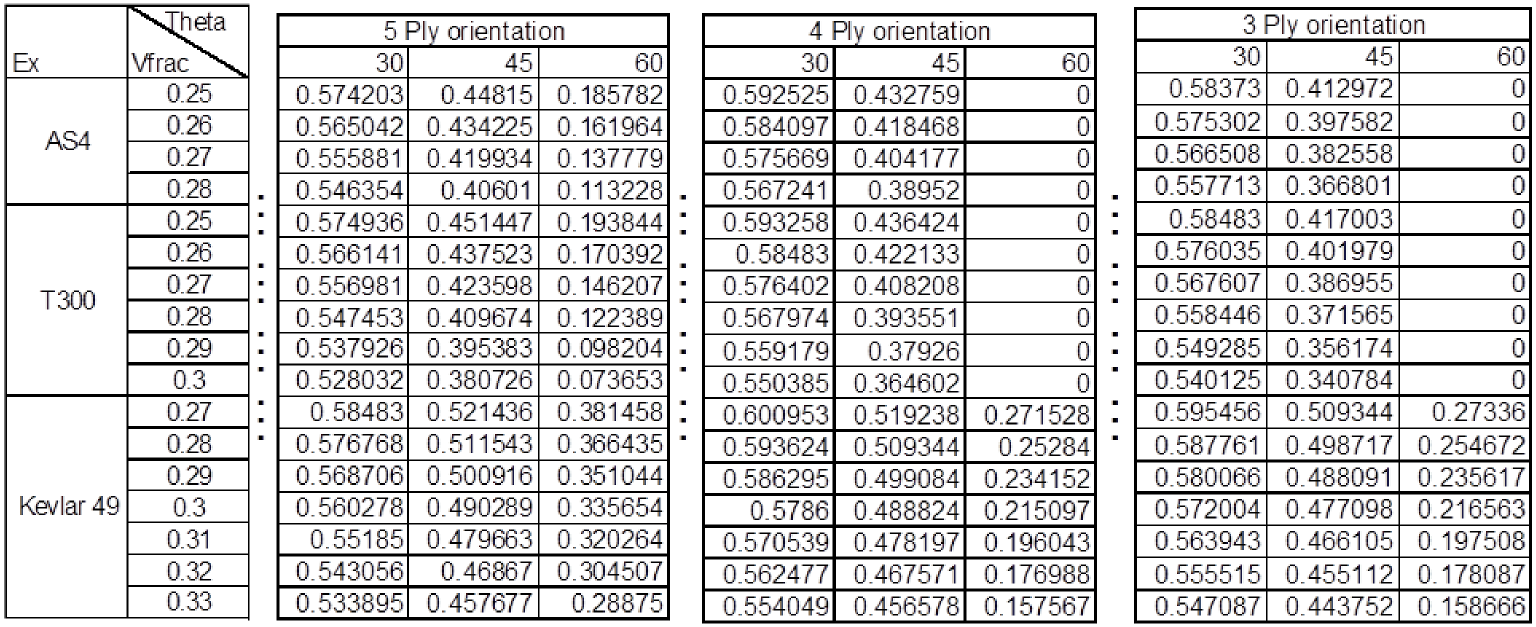
Hence, the RMS value for this combination is

= {(0.4975882 + 0.3356542 + 0.2083332 + 0.0463652)/4}1/2

= 0.318516.

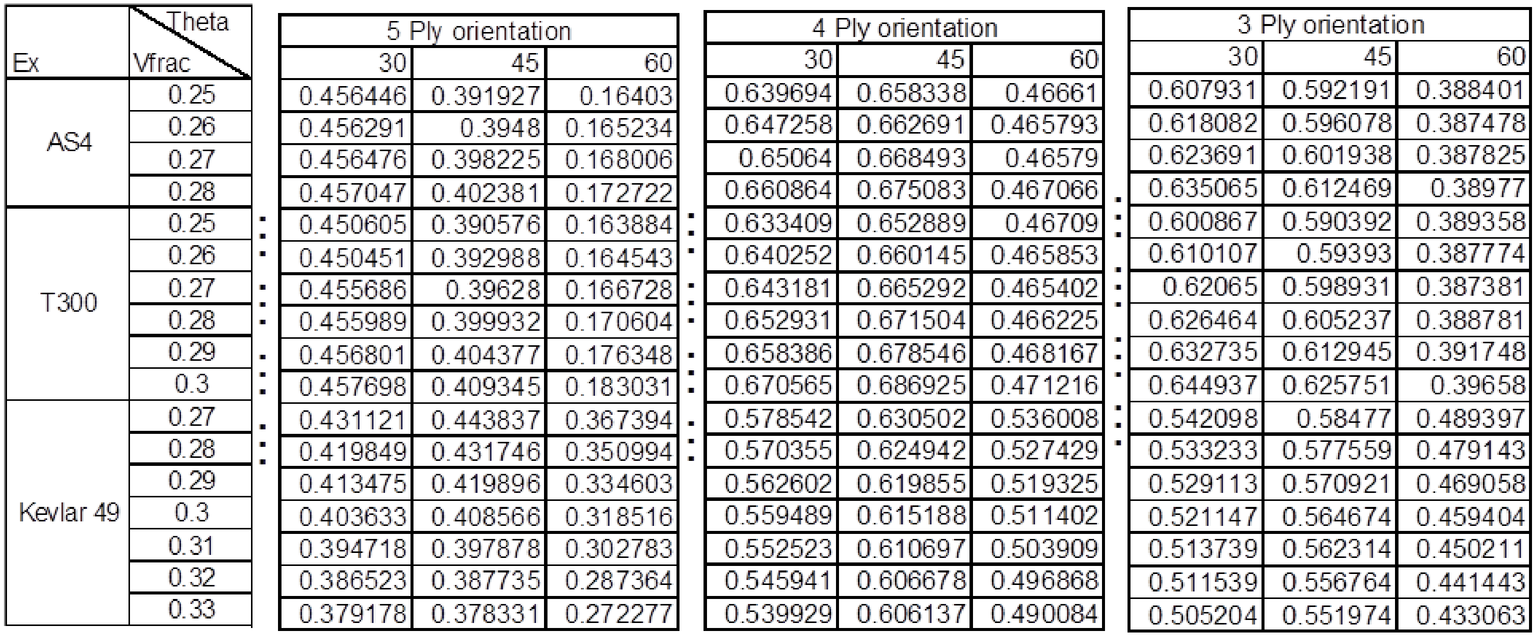
Table 4-7 gives a partial view of the RMS chart.

Table 4-6: Normalized chart



Ex	Theta / Vfrac	5 Ply orientation			4 Ply orientation			3 Ply orientation		
		30	45	60	30	45	60	30	45	60
AS4	0.25	0.574203	0.44815	0.185782	0.592525	0.432759	0	0.58373	0.412972	0
	0.26	0.565042	0.434225	0.161964	0.584097	0.418468	0	0.575302	0.397582	0
	0.27	0.555881	0.419934	0.137779	0.575669	0.404177	0	0.566508	0.382558	0
	0.28	0.546354	0.40601	0.113228	0.567241	0.38952	0	0.557713	0.366801	0
T300	0.25	0.574936	0.451447	0.193844	0.593258	0.436424	0	0.58483	0.417003	0
	0.26	0.566141	0.437523	0.170392	0.58483	0.422133	0	0.576035	0.401979	0
	0.27	0.556981	0.423598	0.146207	0.576402	0.408208	0	0.567607	0.386955	0
	0.28	0.547453	0.409674	0.122389	0.567974	0.393551	0	0.558446	0.371565	0
	0.29	0.537926	0.395383	0.098204	0.559179	0.37926	0	0.549285	0.356174	0
	0.3	0.528032	0.380726	0.073653	0.550385	0.364602	0	0.540125	0.340784	0
Kevlar 49	0.27	0.58483	0.521436	0.381458	0.600953	0.519238	0.271528	0.595456	0.509344	0.27336
	0.28	0.576768	0.511543	0.366435	0.593624	0.509344	0.25284	0.587761	0.498717	0.254672
	0.29	0.568706	0.500916	0.351044	0.586295	0.499084	0.234152	0.580066	0.488091	0.235617
	0.3	0.560278	0.490289	0.335654	0.5786	0.488824	0.215097	0.572004	0.477098	0.216563
	0.31	0.55185	0.479663	0.320264	0.570539	0.478197	0.196043	0.563943	0.466105	0.197508
	0.32	0.543056	0.46867	0.304507	0.562477	0.467571	0.176988	0.555515	0.455112	0.178087
	0.33	0.533895	0.457677	0.28875	0.554049	0.456578	0.157567	0.547087	0.443752	0.158666

Table 4-7: RMS chart



Ex	Theta / Vfrac	5 Ply orientation 30	5 Ply orientation 45	5 Ply orientation 60	4 Ply orientation 30	4 Ply orientation 45	4 Ply orientation 60	3 Ply orientation 30	3 Ply orientation 45	3 Ply orientation 60
AS4	0.25	0.456446	0.391927	0.16403	0.639694	0.658338	0.46661	0.607931	0.592191	0.388401
	0.26	0.456291	0.3948	0.165234	0.647258	0.662691	0.465793	0.618082	0.596078	0.387478
	0.27	0.456476	0.398225	0.168006	0.65064	0.668493	0.46579	0.623691	0.601938	0.387825
	0.28	0.457047	0.402381	0.172722	0.660864	0.675083	0.467066	0.635065	0.612469	0.38977
T300	0.25	0.450605	0.390576	0.163884	0.633409	0.652889	0.46709	0.600867	0.590392	0.389358
	0.26	0.450451	0.392988	0.164543	0.640252	0.660145	0.465853	0.610107	0.59393	0.387774
	0.27	0.455686	0.39628	0.166728	0.643181	0.665292	0.465402	0.62065	0.598931	0.387381
	0.28	0.455989	0.399932	0.170604	0.652931	0.671504	0.466225	0.626464	0.605237	0.388781
	0.29	0.456801	0.404377	0.176348	0.658386	0.678546	0.468167	0.632735	0.612945	0.391748
	0.3	0.457698	0.409345	0.183031	0.670565	0.686925	0.471216	0.644937	0.625751	0.39658
Kevlar 49	0.27	0.431121	0.443837	0.367394	0.578542	0.630502	0.536008	0.542098	0.58477	0.489397
	0.28	0.419849	0.431746	0.350994	0.570355	0.624942	0.527429	0.533233	0.577559	0.479143
	0.29	0.413475	0.419896	0.334603	0.562602	0.619855	0.519325	0.529113	0.570921	0.469058
	0.3	0.403633	0.408566	0.318516	0.559489	0.615188	0.511402	0.521147	0.564674	0.459404
	0.31	0.394718	0.397878	0.302783	0.552523	0.610697	0.503909	0.513739	0.562314	0.450211
	0.32	0.386523	0.387735	0.287364	0.545941	0.606678	0.496868	0.511539	0.556764	0.441443
	0.33	0.379178	0.378331	0.272277	0.539929	0.606137	0.490084	0.505204	0.551974	0.433063

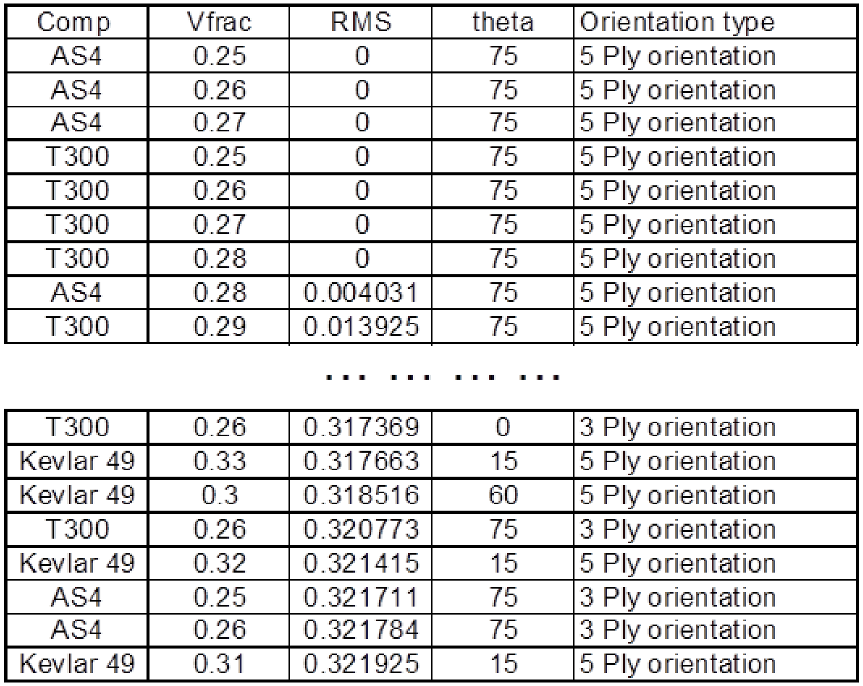
Step 7: Selecting the option with lowest RMS value

This stage of the approach gives the multi-dimensional chart a two dimensional form so that the selection of the perfect combination becomes possible. According to this approach, the combination of composite materials and laminates corresponding to the least RMS value gives the best possible selection. The elements are now ordered from the lowest to the highest RMS values as shown in the Table 4-8.

There are seven options with zero RMS values given by Table 4-8. Any one of these seven composite combinations can completely satisfy the requirements of the example. To be more specific, AS4 fiber composite of 5-ply orientation with volume fraction from 0.25 to 0.27 and T300 fiber composite of similar orientation with volume fraction from 0.25 to 0.28 are the only two options that make the zero RMS zone. To select the best combination from these two options further optimization is required.

Thus the selected composites and the expected range of their properties for this example are tabulated in Table 4-9. One of the selections that meet all the required properties is AS4 as fiber with Epoxy as matrix material and the selected laminate notation is [0/-75/0/75/0]. However, we suggest T300 fiber composite with the same orientation for this selection because this composite also meets the requirements and in addition to that it provides a wider range of volume fraction.

Table 4-8: Sorting data according to RMS values

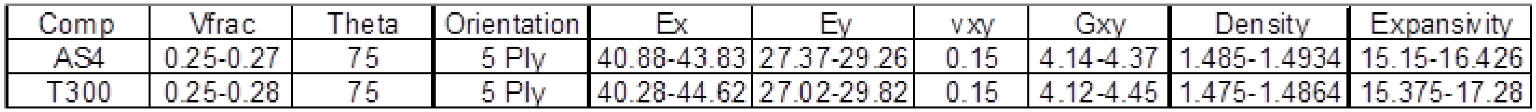


Comp	Vfrac	RMS	theta	Orientation type
AS4	0.25	0	75	5 Ply orientation
AS4	0.26	0	75	5 Ply orientation
AS4	0.27	0	75	5 Ply orientation
T300	0.25	0	75	5 Ply orientation
T300	0.26	0	75	5 Ply orientation
T300	0.27	0	75	5 Ply orientation
T300	0.28	0	75	5 Ply orientation
AS4	0.28	0.004031	75	5 Ply orientation
T300	0.29	0.013925	75	5 Ply orientation

… … … …

T300	0.26	0.317369	0	3 Ply orientation
Kevlar 49	0.33	0.317663	15	5 Ply orientation
Kevlar 49	0.3	0.318516	60	5 Ply orientation
T300	0.26	0.320773	75	3 Ply orientation
Kevlar 49	0.32	0.321415	15	5 Ply orientation
AS4	0.25	0.321711	75	3 Ply orientation
AS4	0.26	0.321784	75	3 Ply orientation
Kevlar 49	0.31	0.321925	15	5 Ply orientation

Table 4-9: Selected composite and the properties chart



Comp	Vfrac	Theta	Orientation	Ex	Ey	vxy	Gxy	Density	Expansivity
AS4	0.25-0.27	75	5 Ply	40.88-43.83	27.37-29.26	0.15	4.14-4.37	1.485-1.4934	15.15-16.426
T300	0.25-0.28	75	5 Ply	40.28-44.62	27.02-29.82	0.15	4.12-4.45	1.475-1.4864	15.375-17.28

Step 8: Applying other constraints

For this example presented we do not have any additional requirements of property Category 3. So, we skip this step for this example and make the selection according to the RMS index only. Additional constraints will require several iterations to calculate the properties attained by these composite combinations and then comparing them with each other to meet the “cost”, “manufacturing processes” and other requirements as appropriate.

4.6 Summary of Chapter 4

In this chapter, a Fiber/Matrix selection approach is presented that can be used to determine the best Fiber/Matrix and their orientation in a composite material in such a way that any property range can be achieved in the selected combination. In the next chapters, this composite material selection approach will be used while demonstrating integrated material and shape design approach for the selection of Fiber/Matrix combinations, and Laminated Composite materials.

CHAPTER 5

SELECTION OF FIBER / MATRIX COMBINATION SIMULTANEOUSLY CONSIDERING MATERIAL AND SHAPE

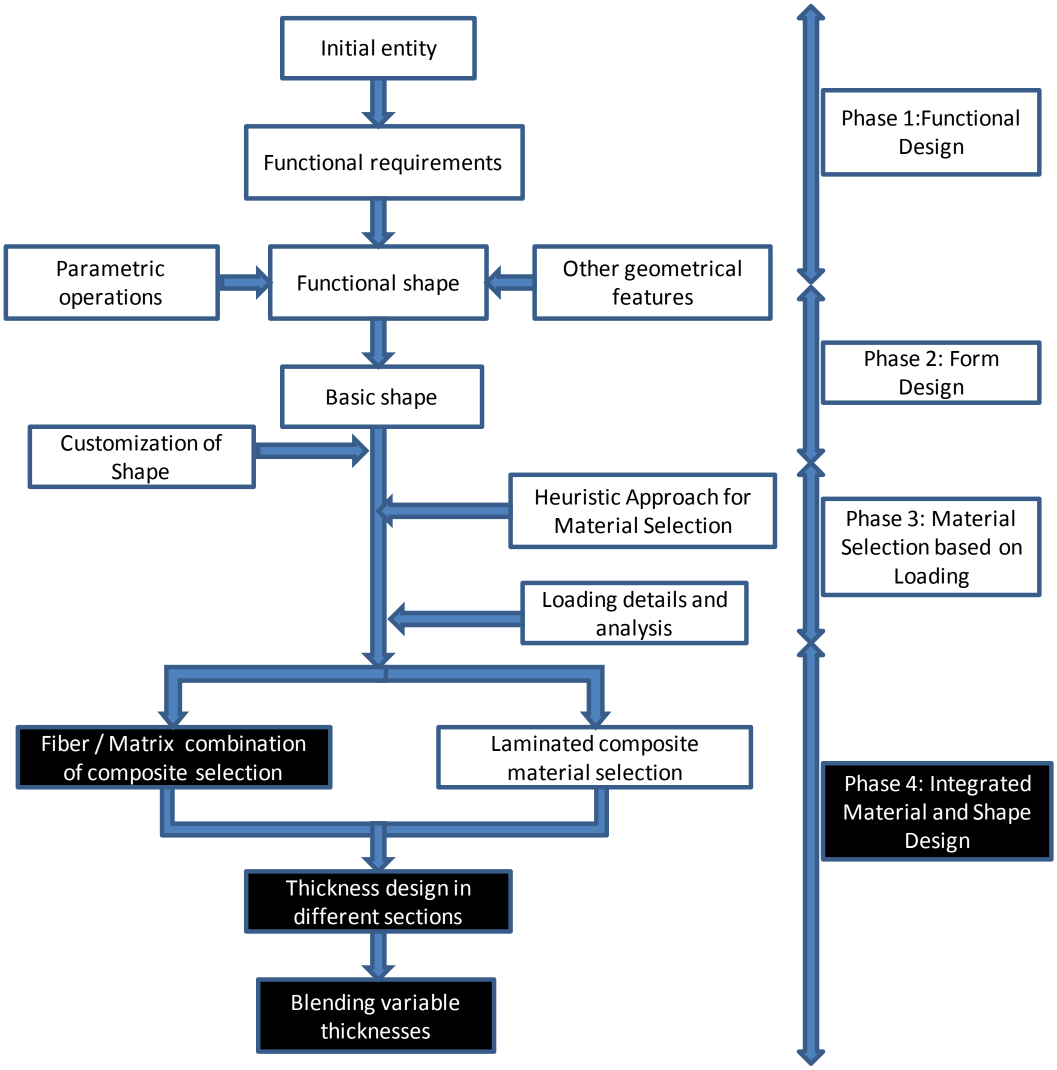


Figure 5-1: Fiber/matrix selection in Grammatical Approach

5.1 Introduction

The previous approach is extended in this section to design a load bearing component using composite material. This section presents a grammatical approach to simultaneously consider the shape and selection composite materials for a load-bearing component. Selection of composites involve determining the fiber and matrix, their volume fraction, and number of layers in different location of the component. A Hip-replacement joint is designed using composite material to illustrate the approach.

In this work, the shape grammatical approach is combined with mechanics (structure and load analysis), and composite material selection (that uses semi-empirical models with lamination theory) in order to generate diversified shape models, with careful steps of blending variable layer thicknesses to ensure manufacturability of any designed product.

Load bearing components usually perform more than one function. They may require carrying bending moments, withstand very high or very low pressure, transmitting heat and electricity or providing resistance to corrosion, etc. On the other hand, the designer has one or more goals to achieve during the design, such as to make the engineering component as cheap, light, or safe, as possible. Selection of appropriate material is the first step to achieve all these functions and goals. In the traditional approach (Ashby, 2005; Edwards, Abel et al., 1994; Ashby, 1995) material selection involves choosing material with a single and specific property limit. This approach is not appropriate for composite material selection. In the work presented in this section, the selection of material is performed using the “Composite material selection tool” (Nandi and Siddique 2009). Once the material is selected, analysis needs to be performed to determine the shape based on loading constraints.

5.2 Integrated Approach to Design Shape and Selection of Fiber/Matrix Combination for Load Bearing Components

The work presented in this section incorporates shape grammar in a composite material customization approach. There are four phases carried out by the grammar: functional design, form design, material selection, and integrated material and shape design (Figure 5-1). The generation of the initial shape takes place in functional design grammar. It begins with a simple geometric entity. This phase addresses the functional requirements, such as types and location of design loads. The form design is performed using a number of additions or subtractions of different geometric features to the initial entity to generate the basic shape. The basic shape may be the inner shape or the outer shape of the component body, which is assumed to be specified by the design requirements. In the material selection phase, the loading details are added in the generated shape grammar to create a simple design chart that can calculate the directional property requirements at different critical cross sections of the body. General mechanics is used at this step to determine the possible critical sections of the loaded component.

Depending on the goals of the design, the composite material is specified. The integrated material and shape design can be done in one of three different sub-approaches. All these sub-approaches use the composite material selection tool (Nandi and Siddique 2009) to select appropriate composite material for different sections of the component. The method of selection used in the tool is explained in Chapter 4 of this chapter. The layer design phase is interrelated with the above mentioned sub-approaches, explained in following sub sections.

5.2.1 Sub-Approach 1: Weight Efficient Method

The first sub-approach is based on a view to reduce the weight of the component as much as possible. Basic steps are shown in Figure 5-2. It is probable that this approach would provide most efficient design in most cases, as the goal of this approach is to avoid over-designing in any direction. Starting from a single ply, minimum thickness of laminate is determined for which at least one property-goal reaches an attainable value. Composite material is selected for the attainable goal(s) and initial layers are designed using the minimum thickness. The thickness is then increased and minimum thickness is determined to meet the next goal(s). Composite material is selected for current goal and corresponding layers are designed with the selected materials.

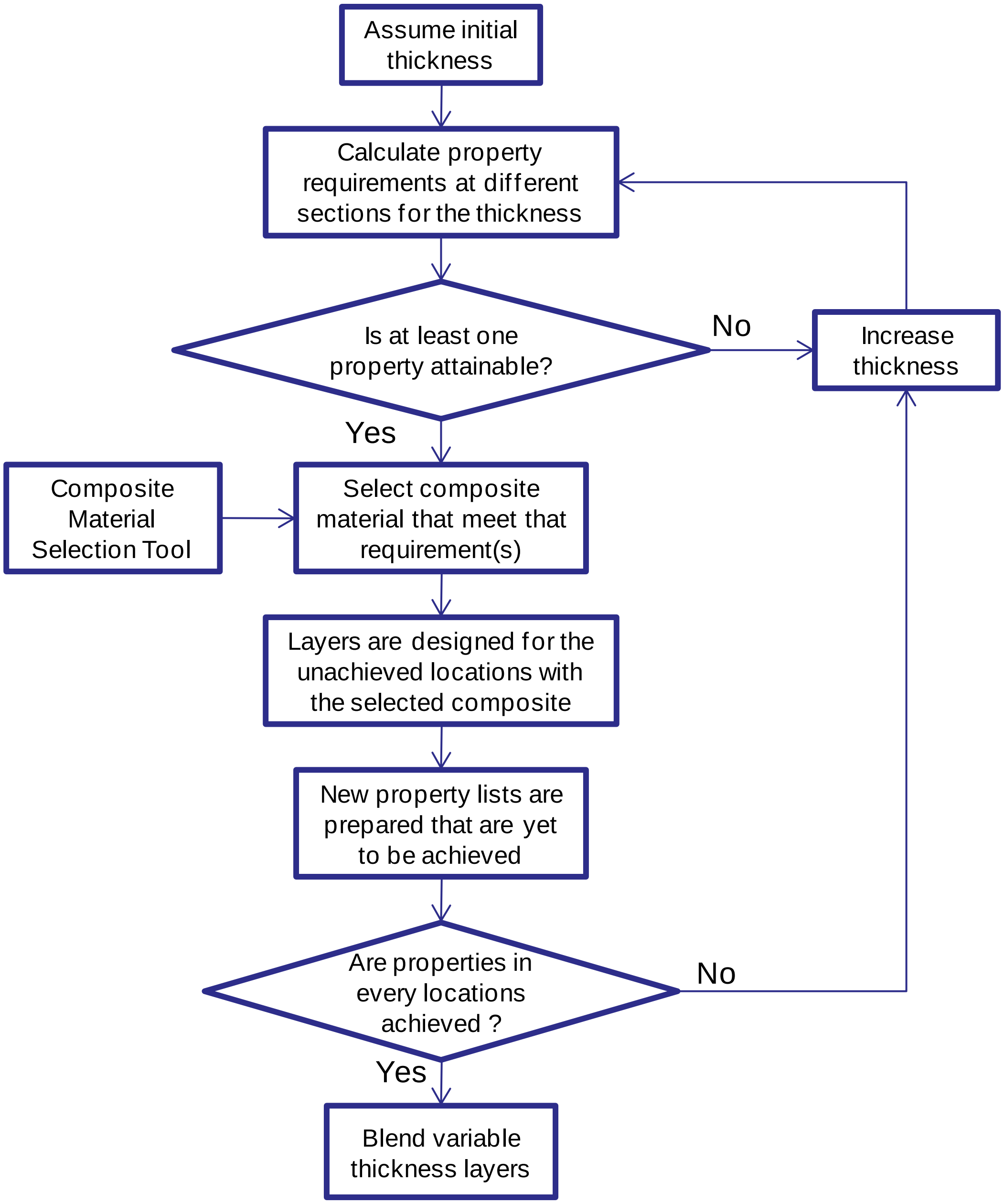


Figure 5-2: Sub-Approach 1 (Weight efficient method)

The same procedure is repeated until all properties (goals) in different locations are achieved. Thus design goals are met for all locations of the component, before the thickness variations are blended to reduce stress concentration.

5.2.2 Sub-Approach 2: Manufacturing Efficient Method

The second sub-approach provides a way to design a component that will be efficient to manufacture. The steps in this sub-approach are shown in Figure 5-3. It is based on the assumption that manufacturing is simple and easily attainable when same fiber-matrix composite is used for the entire product. The calculation begins with increasing the thickness until the property requirements in every section becomes obtainable. The design of layers takes place with the selected composite, based on the design loading conditions at different sections of the body.

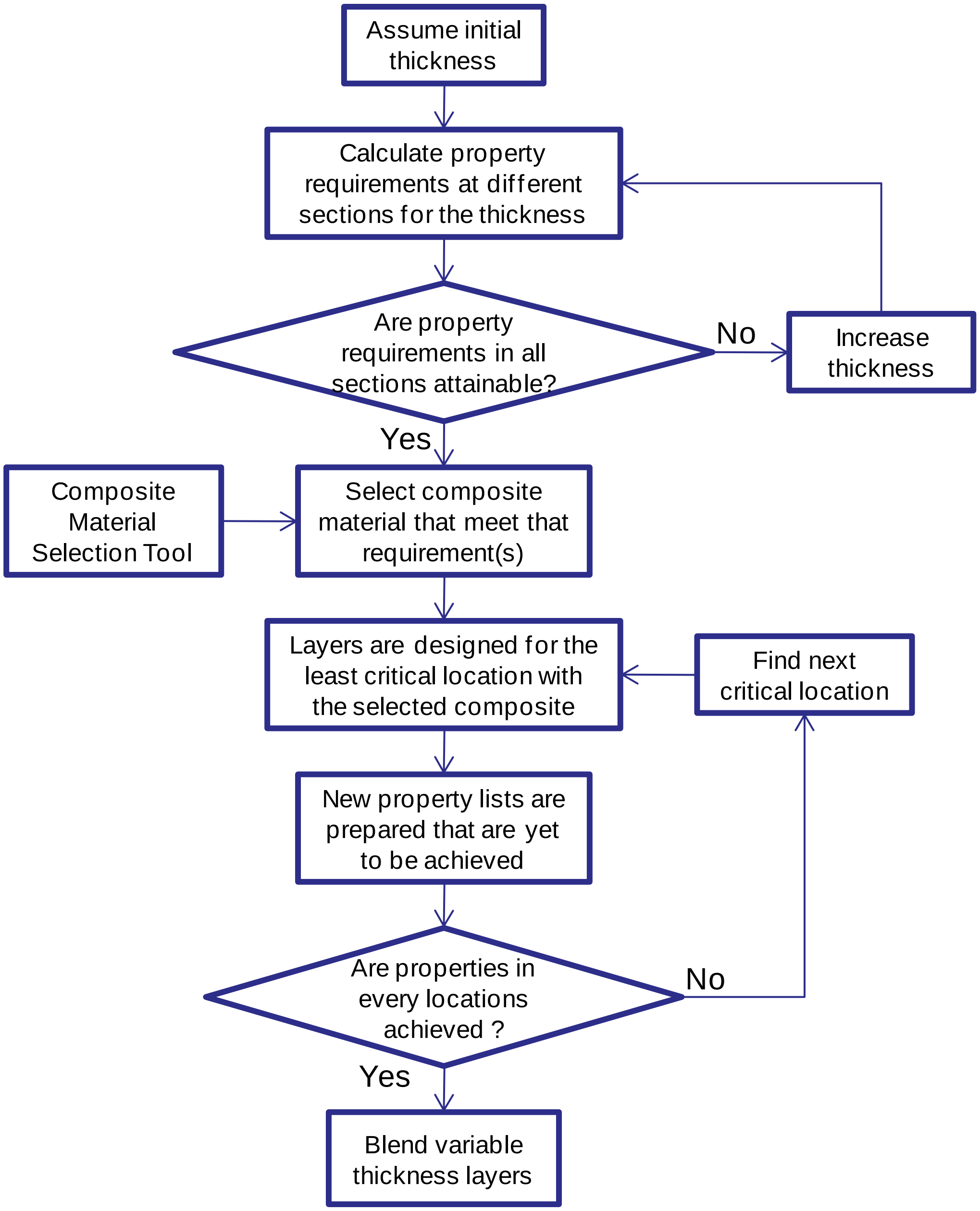


Figure 5-3: Sub-Approach 2 (Manufacturing efficient method)

5.2.3 Sub-Approach 3: Cost Efficient Method

The third approach is based on the assumption that a maximum thickness is allowed for different locations in a body. This is expected to be the least expensive approach as by designing for maximum possible thickness in every section (design flexibility is maximum), it can select the least expensive materials that provide least allowable quality of materials that will meet all desired property requirements. The design of layers may take place similar to any of the first two sub-approaches or in a combination of both. The detailed steps in this sub-approach are shown in Figure 5-4.

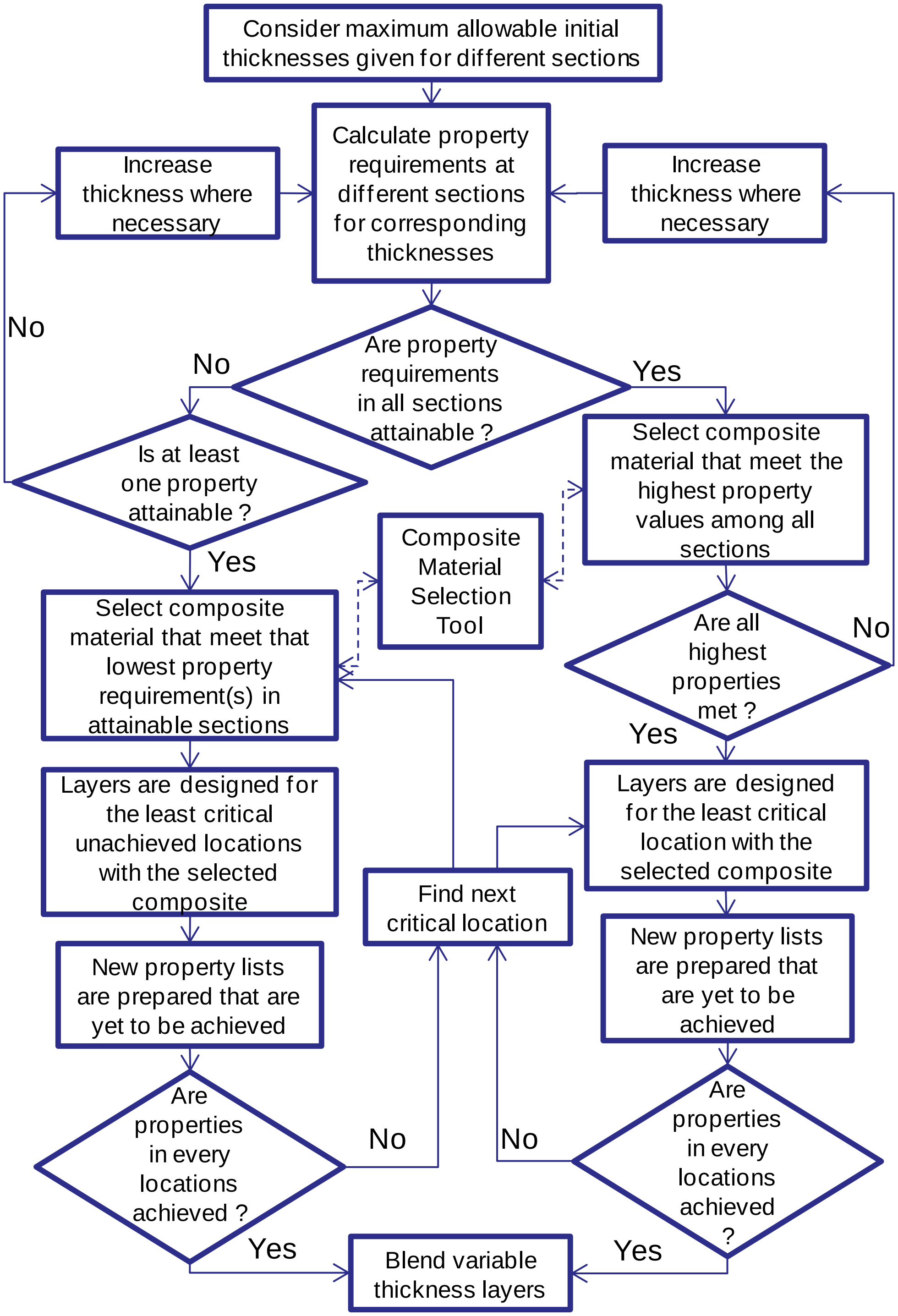


Figure 5-4: Sub-Approach 3 (Cost efficient method)

Blending the Layers

Now that different locations of the body are designed with different numbers of composite layers (different thicknesses) a proper blending method is used in the last step of all the sub-approaches to achieve a continuous inner (or, external) surface.

Designing composite panels with specified local loads could result in manufacturing incompatibilities between adjacent panel designs. A guide based optimization was employed by Adams (Adams, Watson, and Gürdal, 2003; Adams, Watson, Gürdal, and Anderson-Cook, 2004) to select composite panels to overcome this incompatibilities and the inner or outer surface was blended for utilizing a simple master-slave parallel implementation. This master-slave blending method is implemented in the final part of this approach to ensure a design that would be feasible to manufacture.

Different phases in this approach though seem in a sequence, are generally more interconnected. While designing a load bearing component using composite material if the choice of initial shape is kept flexible, a further optimization method is warranted in the functional and form design phase to determine the best shape among the infinite possibilities. For simplicity of explanation, the case presented in this section will represent an example with given outer shape, thus only an ordered sequence of phases will be used to solve this problem.

5.3 Designing a Hip-replacement Joint Considering Shape and Fiber/Matrix Simultaneously - Example

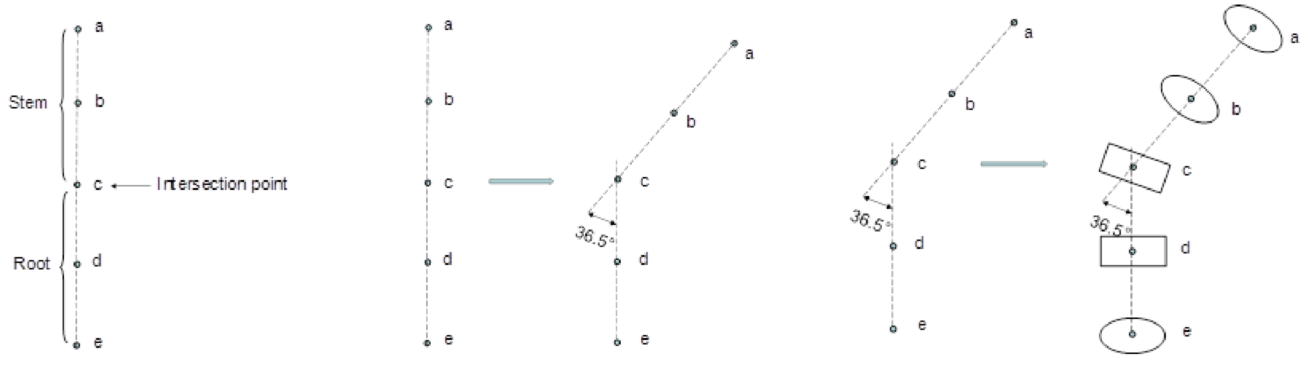
5.3.1 Problem Description

To demonstrate the proposed approach a hip joint is designed using the shape grammar approach. The loading condition is illustrated by Hamrock (Hamrock et al., 2005). Figure 5-5 shows a total hip replacement inserted into a human femur and hip. Such devices are commonly used to treat painful arthritic conditions that result in loss of mobility. The operation consists of sawing off portions of the femur, reaming the femoral cavity to allow for implant insertion, and hammering the implant into the femur. The hip portion of the implant is similarly installed, often with screws. The femur portion of the implant includes a stem onto which the highly polished ball is attached. Mass customization of total hip replacement joint will satisfy size constraints more accurately for individual patients.

Shape and size constraints are provided by the designer, and are described in Section 2.3.1. An additional constraint for this problem is related to the bone strain. Which states that it has been found that due to tensile loading in the longitudinal direction, human bone yields at a strain of 6.7×10^{-3} and fractures at a strain of 0.03 (Park and Lakes, 1986). In this case study, the design strain is considered as 6.7×10^{-3}.

Figure 5-5: A total hip replacement inserted into a human femur and hip (Hamrock et al., 2005)

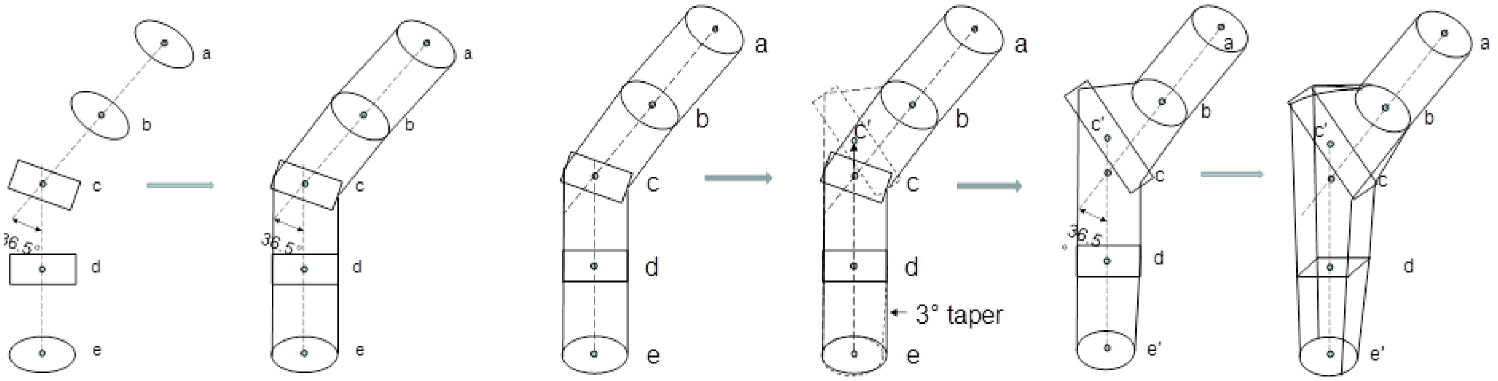
One of the assumptions made in this example is that commonly used implant materials are cast cobalt chromium, forged stainless steel, and Ti-6Al-4V (titanium alloy). For this example case, we intend to design the implant using composite material. While designing for commercial use, the selection of material must consider compatibility with human body as this implant will be in direct contact to the inner parts of the human body. However, the example case presented in this section is prepared with a purpose to explain the design approach only, and for this design, the compatibility is not considered at all. We assume all the composite materials are compatible with human body.



(a) Defining initial shape

(b) Defining angle

(c) Defining cross section



(d) Sweep shape

(e) Outer shell

Figure 5-6: Generating outer shell of the Hip-replacement joint using common shape rules (Repeated from Figure 3-2)

5.3.2 Phases 1 and 2: Function and Form Design

Functional and Form Design phases are illustrated in Chapter 2 and 3 in order to generate a shape grammar for the customized Hip-replacement joint design. Figure 5-6 shows the generation of shape using the grammar. In this chapter the shape generated from the grammar will be used directly in order to demonstrate the composite material selection and loading analysis phase of the approach.

5.3.3 Phase 3: Material Selection based on Loading

Defining Critical sections

There are some commercial computer tools available to analyze the loadings for any complicated structures. The operation of these tools require highly skilled designer and consume plenty of time for solving. Finite Element Method has been tried in determining the properties of composite materials as well (Barbero and Tomblin, 1993; Barbero and Tomblin, 1996; Barbero and Trovillion, 1998; Barbero, 2008). Using FEA at the initial design stages to explore alternatives can be resource intensive. Simplified Solid Mechanics can be used to determine the critical locations and to calculate loading conditions of a load bearing component.

As explained by Bernard (Hamrock et al., 2005) in page 255, using general knowledge of Solid Mechanics, it can be said that the critical sections for this examples are A_1-A_2, B_1-B_2, and C_1-C_2 as shown in the Figure 5-7. These sections were selected because they have geometric features that act as stress raisers and because their locations maximize the stresses associated with the applied loads.

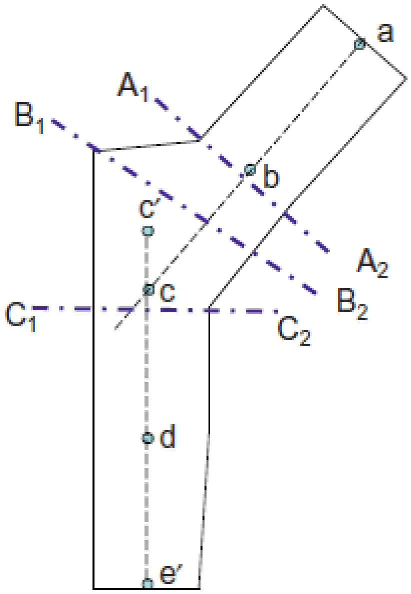


Figure 5-7: Critical sections (Hamrock et al., 2005, p-256)

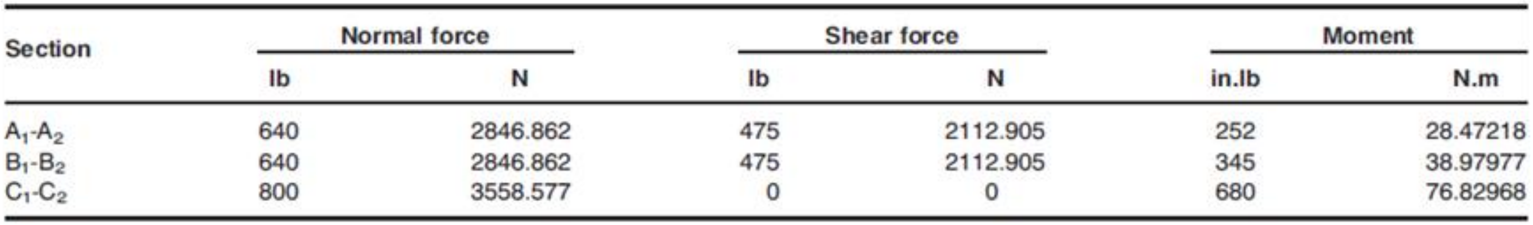
Material Selection Using the Heuristic Approach

The challenge of the problem lies in obtaining the stresses. The actual load applied to a hip joint is extremely complicated and varies from person to person. Given that the loading can be complex, the load was taken 4 times the user’s body weight, a peak force measured during a walking step. It is assumed that the most implant recipients are elderly or have a less active lifestyle, thus running is not considered for the design. Thus considering a 200 lb (90.72 Kg weight, i.e., 890 N) user, the design weight on the implant is found to be 800 lb (362.88 Kg weight, i.e., 3560 N).

Table 5-1 is determined directly by using methods of Statics that shows how the design weight leads to a normal force, a shear force, and a bending moment at each section.

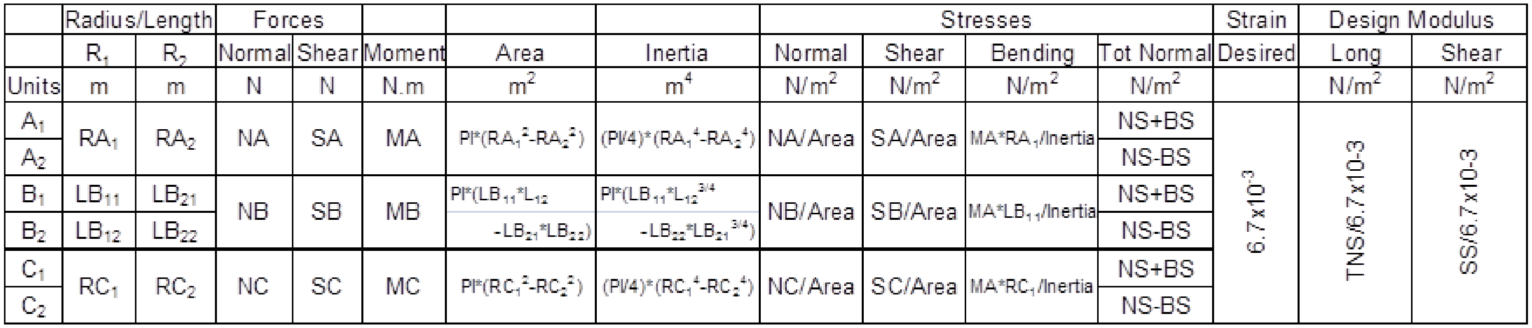
As this component is to be made using composite materials, there will be three main design requirements: the longitudinal modulus, the transverse modulus, and the shear modulus. Since, the presence of weight of the person is the only load applied vertically to the component and does not involve torsion, no transverse modulus requirements need to be satisfied during design. The unidirectional composite layers can be used to achieve all the design goals by placing them in vertical planes, without any angular orientation. Table 5-2 is prepared to calculate required modulus, while varying thicknesses for different loading sections. As the same maximum allowable (design) strain is considered throughout the component body, an incremental increase in thickness will improve the stiffness of the part, thus reduce the resulting maximum strain under the design loading. Once the maximum strain under the design load is below the allowed limit, longitudinal and shear modulus for different sections will be accepted as designed. The equations used for such calculations are provided in each cells of the chart.

Table 5-1: Applied loads (Hamrock et al., 2005)



Section	Normal force		Shear force		Moment	
	lb	N	lb	N	in.lb	N.m
A_1-A_2	640	2846.862	475	2112.905	252	28.47218
B_1-B_2	640	2846.862	475	2112.905	345	38.97977
C_1-C_2	800	3558.577	0	0	680	76.82968

Table 5-2: Chart to determine property requirements



	Radius/Length		Forces					Stresses				Strain	Design Modulus	
	R_1	R_2	Normal	Shear	Moment	Area	Inertia	Normal	Shear	Bending	Tot Normal	Desired	Long	Shear
Units	m	m	N	N	N.m	m^2	m^4	N/m^2	N/m^2	N/m^2	N/m^2		N/m^2	N/m^2
A_1	RA_1	RA_2	NA	SA	MA	PI*(RA_1^2-RA_2^2)	(PI/4)*(RA_1^4-RA_2^4)	NA/Area	SA/Area	MA*RA_1/Inertia	NS+BS	$6.7x10^{-3}$	TNS/6.7x10-3	SS/6.7x10-3
A_2											NS-BS			
B_1	LB_{11}	LB_{21}	NB	SB	MB	PI*(LB_{11}*L_{12} -LB_{21}*LB_{22})	PI*(LB_{11}*$L_{12}^{3/4}$ -LB_{22}*$LB_{21}^{3/4}$)	NB/Area	SB/Area	MA*LB_{11}/Inertia	NS+BS			
B_2	LB_{12}	LB_{22}									NS-BS			
C_1	RC_1	RC_2	NC	SC	MC	PI*(RC_1^2-RC_2^2)	(PI/4)*(RC_1^4-RC_2^4)	NC/Area	SC/Area	MA*RC_1/Inertia	NS+BS			
C_2											NS-BS			

RA1, RA2, RC1, RC2: Radius at section A-A and C-C
LB11, LB21, LB12, LB22: Lengths at section B-B
NA, NB, NC: Normal forces at different sections
SA, SB, SC: Shear forces at different sections
MA, NB, NC: Moments at different sections
NS, BS: Normal and shear stresses

5.3.4 Phase 4: Integrated Fiber / Matrix Combination Selection and Shape Design

The three sub-approaches mentioned in Section 5.2 are used to select fiber/matrix combination, while simultaneously designing the shape.

Sub-Approach 1 (Weight efficient method)

The first sub-approach is expected to ensure maximum weight reduction by avoiding overdesigning in any direction. As mentioned before, the calculation begins with a trial and error method to find a minimum initial thickness for which at least one property goal reaches a value that can be achieved by available composite material options.

In this case study, while designing the initial layers, a thickness of 0.095 mm is found that brings required longitudinal modulus at point B_2 (at Section B_1-B_2) an achievable value of 70 GPa. Table 5-3 shows this condition (highlighted cell shows the design requirement).

Table 5-3: Design properties for thickness 0.095 mm and achieved properties for thickness 0.1 mm

Section	Design Properties		Achieved Properties	
	Long Mod (GPa)	Shear Mod (GPa)	Long Mod (GPa)	Shear Mod (GPa)
A_1	248	84	236	79
A_2	474	84	450	79
B_1	213	104	206	99
B_2	70	104	62	99
C_1	2511	N/A	2390	N/A
C_2	2984	N/A	2840	N/A

Using the composite material selection tool, the selected composite material for this goal is AS4 as fiber and Epoxy as matrix material, the theoretical fiber-volume fraction to achieve the property is 35%. Thus the initial laminate is designed to be composed of only one layer using the selected composite. Considering a typical thickness for AS4-Epoxy unidirectional laminate to be 0.1 mm, the thickness for the designed laminate is also found 0.1 mm. Since, the allowable strain is considered constant (6.7×10^{-3}), this updated thickness reduces the design requirement for longitudinal modulus at section B_2 to 62 GPa as shown in Table 4. Achieved modulus for this initial layer is 86 GPa, which is above the requirement for this thickness. The selected composite for this run meets the requirement for B2 location only.

Increasing previous thickness of 0.1 mm the next attainable goal(s) are determined using the chart shown in Table 5-2. Longitudinal modulus of 99 GPa at point A_1 is the next achievable location. Thus, the increase in thickness brings us to an additional thickness of 0.12 mm (a total of 0.22 mm) for which the design properties are shown in Table 5-4. It should be noted that the achieved property cell is removed from this table and is not considered for future calculations.

Table 5-4: Design properties for thickness 0.22 mm and achieved properties for thickness 0.091 mm

Section	Design Properties		Achieved Properties	
	Long Mod (GPa)	Shear Mod (GPa)	Long Mod (GPa)	Shear Mod (GPa)
A_1	99	32	102	33
A_2	185	32	193	33
B_1	121	40	124	42
B_2	Achieved	40	Achieved	42
C_1	1018	N/A	1056	N/A
C_2	1202	N/A	1247	N/A

The next laminate, that will be adjacent to the previous selected laminate from inside, is designed by selecting Boron-Epoxy composite with 40% volume fraction (1 layer, i.e., 0.0.14 mm), that posses longitudinal modulus of 128 GPa and shear modulus of 3.67 GPa. In addition to meeting the design requirement for Location A_1, this selection achieves longitudinal modulus requirements for Location B_1 as well (Table 5). In the same manner, next laminates and their materials are designed; the details of these layers for this case study are shown in Table 5-5.

As shown in Table 5-5, both the longitudinal and shear modulus requirements are achieved after the fourth laminate. Thus the thinnest Sections (A_1-A_2 and C_1-C_2) of the component will consist of first four laminates. Section B_1-B_2, will be comprised of all five laminates according to this method.

Table 5-5: Results for Sub-Approach 1 (Weight Efficient Method)

Layer	Fiber	Num of plies	Thickness (mm)	Vf (%)	Section	Design property	Required	Achieved
1	AS4	1	0.1	35	B_2	Long Mod	63 GPa	86 GPa
2	Boron	1	0.14	40	A_1	Long Mod	102 GPa	128 GPa
					B_1	Long Mod	124 GPa	128 GPa
3	Boron	1	0.14	35	A_2	Long Mod	126 GPa	132 GPa
4	P 100S	3	0.9	65	A_1	Sh Mod	6.9 GPa	7.61 GPa
					A_2	Sh Mod	6.9 GPa	7.61 GPa
					C_1	Long Mod	307 GPa	374 GPa
					C_2	Long Mod	349 GPa	374 GPa
5	P 100S	2	0.6	45	B_1	Sh Mod	6.5 GPa	6.59 GPa
					B_2	Sh Mod	6.5 GPa	6.59 GPa

Sub-Approach 2 (Production efficient method)

As mentioned before, this method is based on the assumption that composite material manufacturing is most efficient when the designed fiber-matrix combination remains same for the whole product. Equations given in Table 5-2 are used to determine the minimum thickness for which properties in each and every location in the body becomes obtainable.

For this case study, total thicknesses of 2.2mm bring attainable values of longitudinal and shear modulus requirements for every location. Using the ‘Composite Material Customization Tool’, Sapphire fiber is selected with Epoxy matrix material to meet design goal of longitudinal modulus of 287 GPa and shear modulus of 5.7 GPa (Table 5-6), which are the most critical loads for any location. A typical thickness of 0.11mm for each Sapphire-Epoxy layers will accommodate 20 layers with 65% volume fraction to meet these requirements. This composite material, selected for the most critical section, is used to design thicknesses for other locations starting from the least critical section using steps similar to Weight Efficient Method (Sub-Approach 1). Table 5-6 shows the selected materials and the thicknesses of the design performed using this method.

Table 5-6: Results for Sub-Approach 2 (Production Efficient Method)

Layer	Fiber	Num of plies	Thickness (mm)	Vf (%)	Section	Design property	Required	Achieved
1	Sapphire	1	0.11	65	B_2	Long Mod	51 GPa	289 GPa
2	Sapphire	1	0.11	65	A_1	Long Mod	111 GPa	289 GPa
					B_1	Long Mod	130 GPa	289 GPa
3	Sapphire	1		65	A_2	Long Mod	143 GPa	289 GPa
4	Sapphire	8	0.88	65	A_1	Sh Mod	7.2 GPa	9.08 GPa
					A_2	Sh Mod	7.2 GPa	9.08 GPa
5	Sapphire	3	0.33	65	B_1	Sh Mod	7.5 GPa	9.08 GPa
					B_2	Sh Mod	7.5 GPa	9.08 GPa
6	Sapphire	1	0.11	65	C_1	Long Mod	263 GPa	289 GPa
7	Sapphire	1	0.11	65	C_2	Long Mod	287 GPa	289 GPa

Sub-Approach 3 (Cost efficient method)

The Cost Efficient Method is based on the assumption that greater range of design thickness provides greater freedom to the selection of material. Thus, if maximum thickness is allowed for each different location of a component, the cheapest materials can be selected to design it. To demonstrate the approach in this case study, a maximum thickness of 2.00 mm for Section A_1-A_2, 1.00 mm for Section B_1-B_2, and 2.5 mm for Section C_1-C_2 is assumed. If the property requirements at all sections are attainable by the cheapest material, the design follows Production Efficient Method (Sub-Approach 2) with that material. Otherwise, all attainable sections are designed using the cheaper selection(s) and the remaining sections are designed with costlier composites to ensure that the design requirements are achieved. To demonstrate the approach with comparison of prices, we will design the component using three types of composites: (i) the comparatively cheaper option made of Glass fiber with a typical layer thickness of 0.18 mm. (ii) AS4 Graphite fiber, which is costlier than Glass fiber, with typical layer thickness about 0.1 mm and (iii) The more expensive P 100S fiber with layer thickness of 0.3 mm. Thus the goal is to use Glass fiber more and AS4 and P 100S fiber as less as possible in this design.

For maximum allowable thickness at each location, it was determined that shear modulus at Section B_1-B_2 and longitudinal modulus at Section C_1-C_2 cannot be achieved using only Glass-Epoxy composites. So, for these sections, design is carried out with a combination of Glass, AS4 and P100S, while ensuring that minimum possible AS4 is used, and maximum allowable thicknesses are not exceeded. The design requirements at remaining sections are achieved adding Glass-Epoxy layers only so that cheapest design is obtained. The result of the selection is given in Table 5-7.

Table 5-7: Results for Sub-Approach 3 (Cost Efficient Method)

Layer	Fiber	Num of plies	Thickness (mm)	Vf (%)	Section	Design property	Required	Achieved
1	Glass	1	0.18	65	B_2	Long Mod	6.1 GPa	59.74 GPa
2	Glass	2	0.36	65	A_1	Long Mod	50 GPa	59.74 GPa
3	Glass	2	0.36	65	A_2	Long Mod	58.9 GPa	59.74 GPa
4	AS4	2	0.2	65	B_1	Long Mod	67 GPa	77.27 GPa
					A_1	Sh Mod	7.8 GPa	7.59 GPa
					A_2	Sh Mod	7.8 GPa	7.59 GPa
5	Glass	3	0.54	65	B_1	Sh Mod	7.2 GPa	7.51 GPa
					B_2	Sh Mod	7.2 GPa	7.51 GPa
6	P 100S	5	1.5	65	C_1	Long Mod	252 GPa	263 GPa
7	P 100S	1	0.3	65	C_2	Long Mod	276 GPa	282 GPa

5.3.5 Phase 4 (Continued): Blending the Layers

Designing and selection of composite materials for different layers as explained in previously, are done in such a way that the same layer contains same fiber-reinforced composite of same orientation. Thus blending of inner surface for this case is primarily concerned with this continuation of same fiber-reinforced layers and of the same orientation. The initially selected layers and composite creates the outer shell and is constant throughout the body. The next layers are attached to the outer shell from the inner side and are distributed everywhere inside the outer shell; they are discontinued only where the design goals are met by previous layers. The cross-section of the hip-joint after the laminates design should look like Figure 5-8, Figure 5-9, and Figure 5-10.

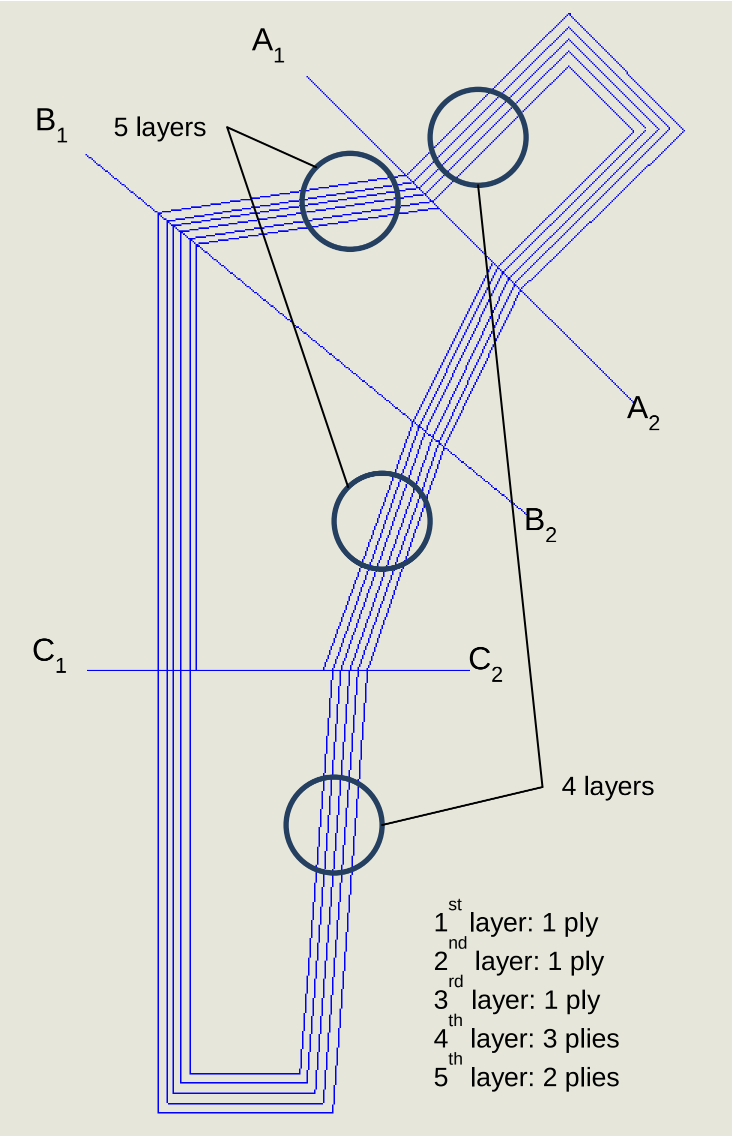


Figure 5-8: Layer design in Sub-Approach 1

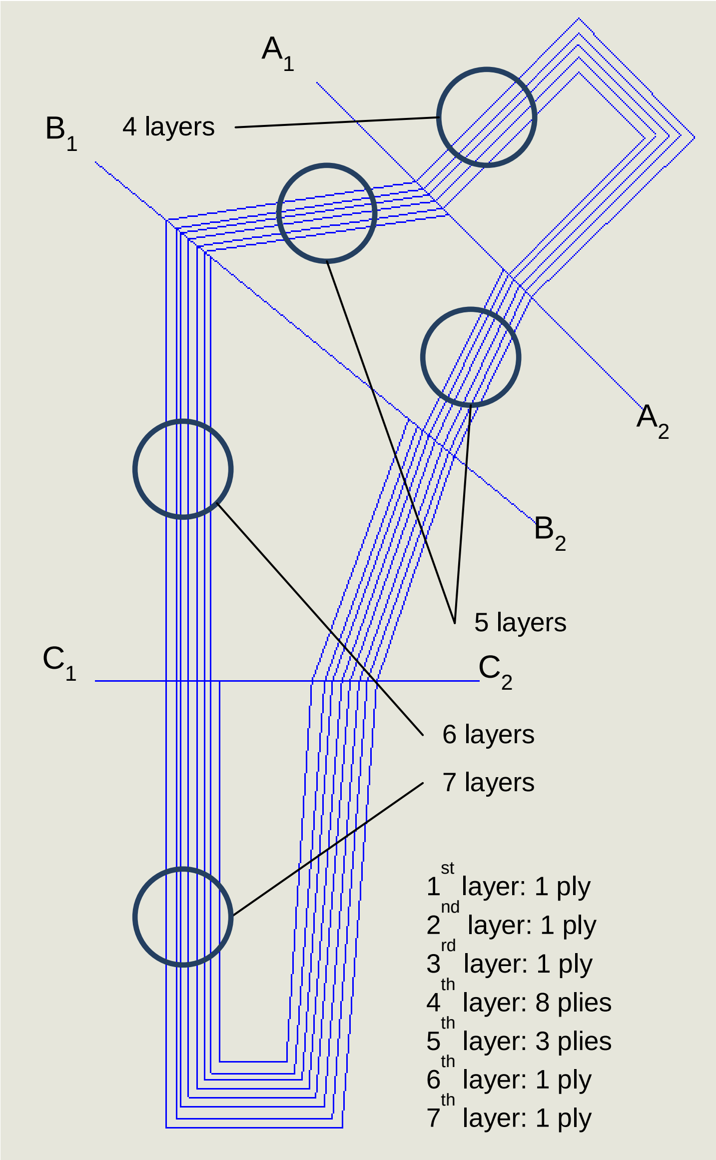


Figure 5-9: Layer design in Sub-Approach 2

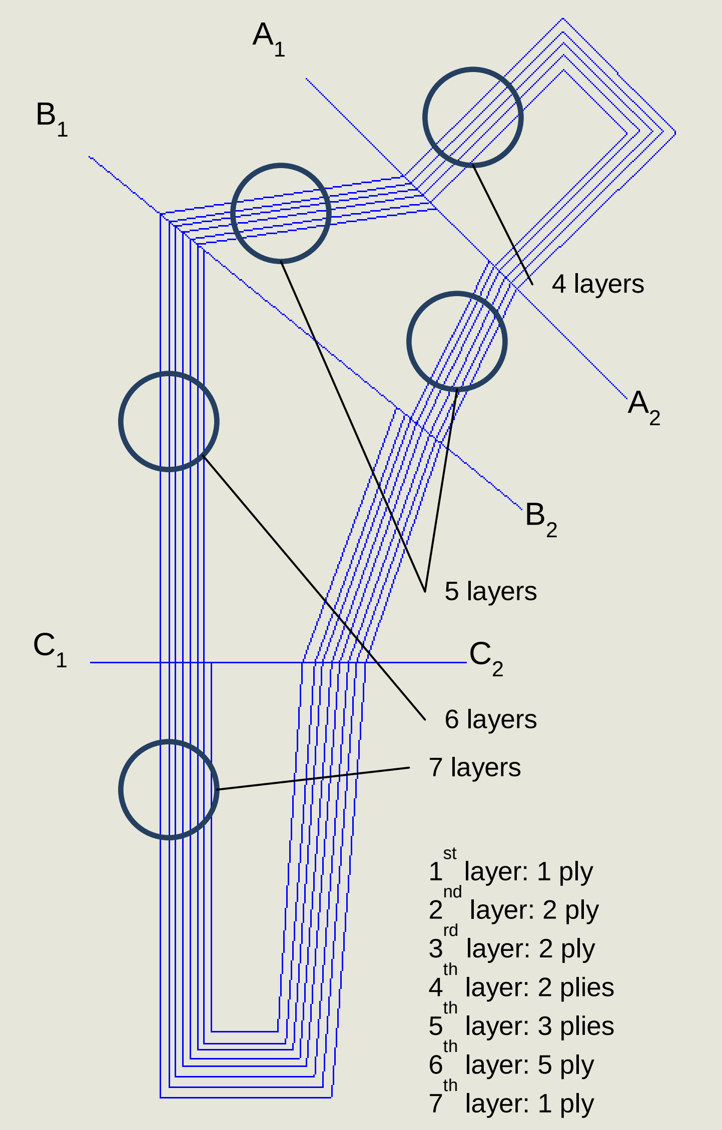
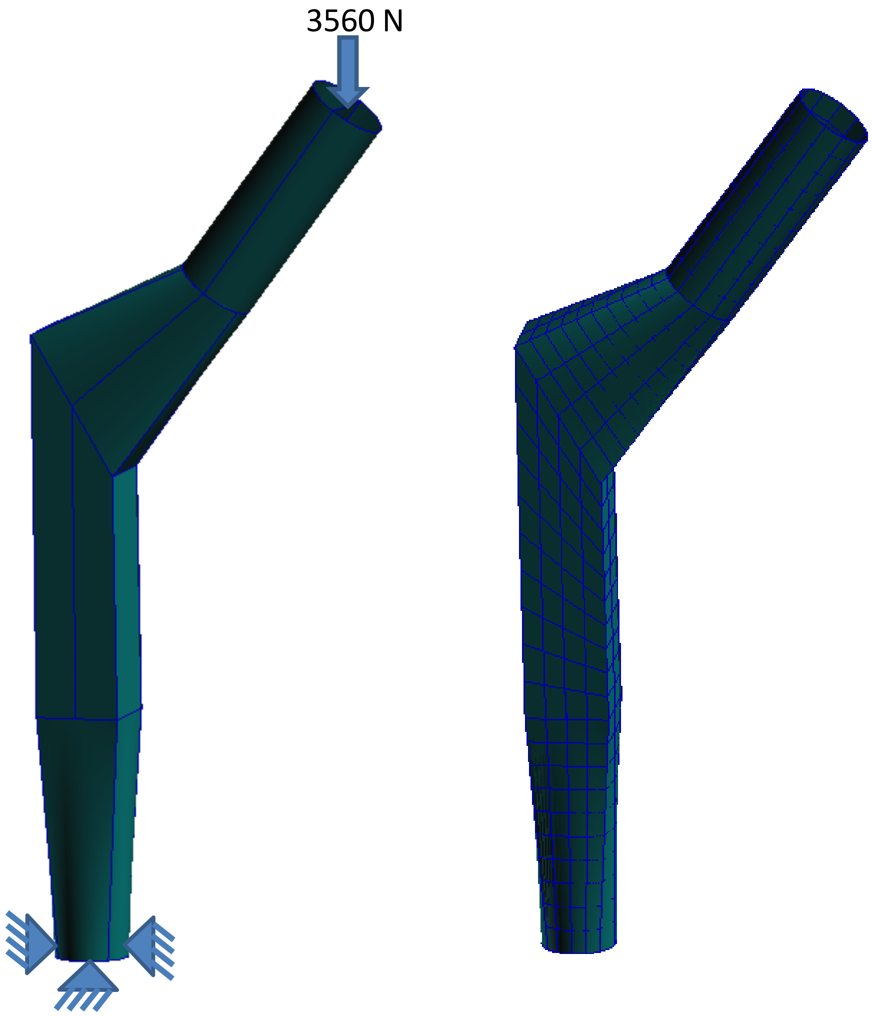


Figure 5-10: Layer design in Sub-Approach 3

5.4. Finite Element Analysis of the Hip-replacement Example

A finite element analysis is performed to verify the results achieved in this method. The result of Weight Efficient Approach is plotted with the given dimensions using a

CAD tool. A vertical load of 3560 N is applied to run a finite element analysis. Figure 5-11 (a) shows the component with fixed bottom edge as the root end of the component is assumed to be constrained inside the femur bone to have zero displacement. This figure also shows that a vertical load of 3560 N is applied at the top edge. Figure 5-11 (b) shows the mesh elements created for the component in order to perform the finite element analysis. 2D Shell element is used to calculate Laminate properties using standard formulation. 2D Orthotropic, Linear Elastic model is considered for defining each plies, and the plies are stacked in layers of 0˚ fiber orientations to determine laminated composite properties. Quadratic mesh element is created using IsoMesh Quad4 topology. Every cross section is divided into 12 elements and the corresponding nodes are placed on the same fiber orientation in order to obtain proper deformation under vertical loadings.



(a) (b)

Figure 5-11: (a) Loaded component with fixed edge; (a) Mesh elements prepared for finite element analysis

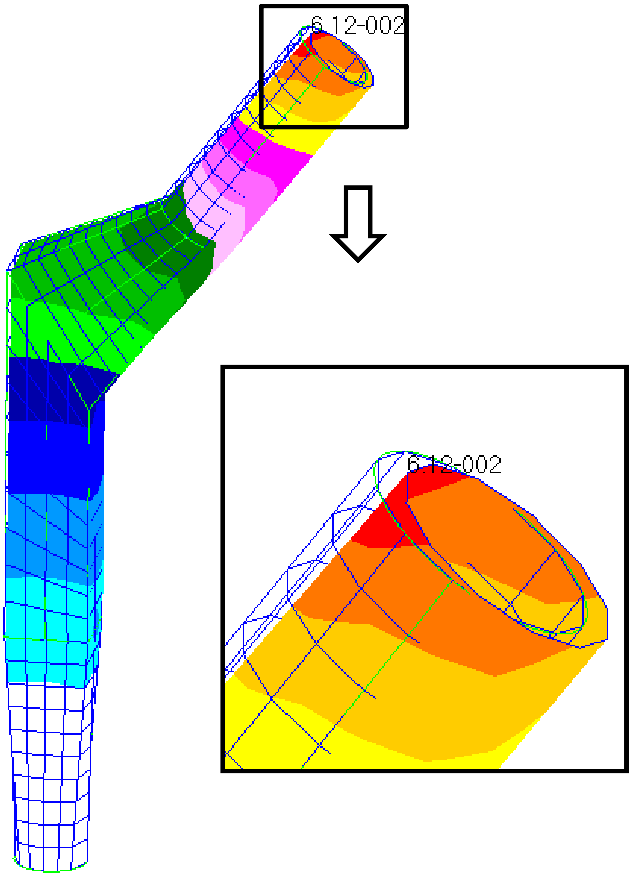


Figure 5-12: Deformation under vertical load

Figure 5-12 shows the true scale deformed shape under design loading. From this figure, it can be seen that the maximum deflection is at the tip of the stem as expected. For convenience of understanding the deformation, Figure 5-13 is provided that shows magnified deformed shape at model scale.

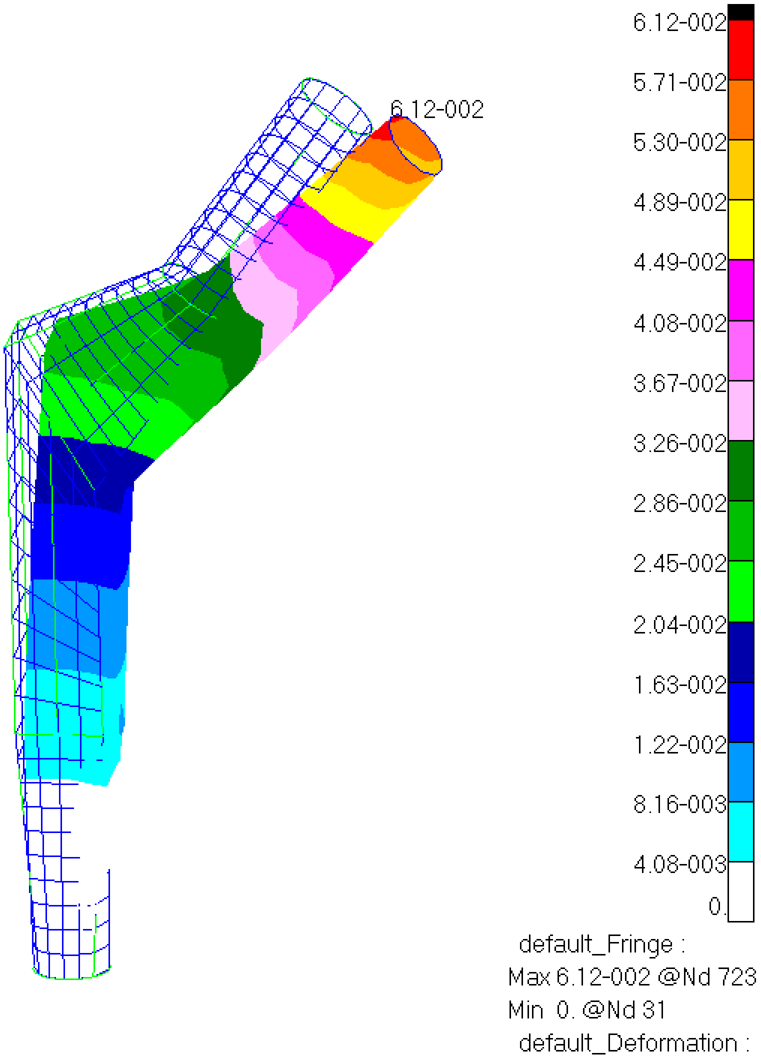


Figure 5-13: Magnified deformed shape at model scale

Figure 5-14 (I) shows the maximum stress distribution in fiber direction for different layers and plies and Figure 5-14 (II) shows the maximum stress distribution in transverse direction to fiber. The stresses seem to have tendency to increase at Section A_1-A_2, B_1-B_2, and C_1-C_2, as defined previously. This agrees with our initial assumption of critical sections for the component.

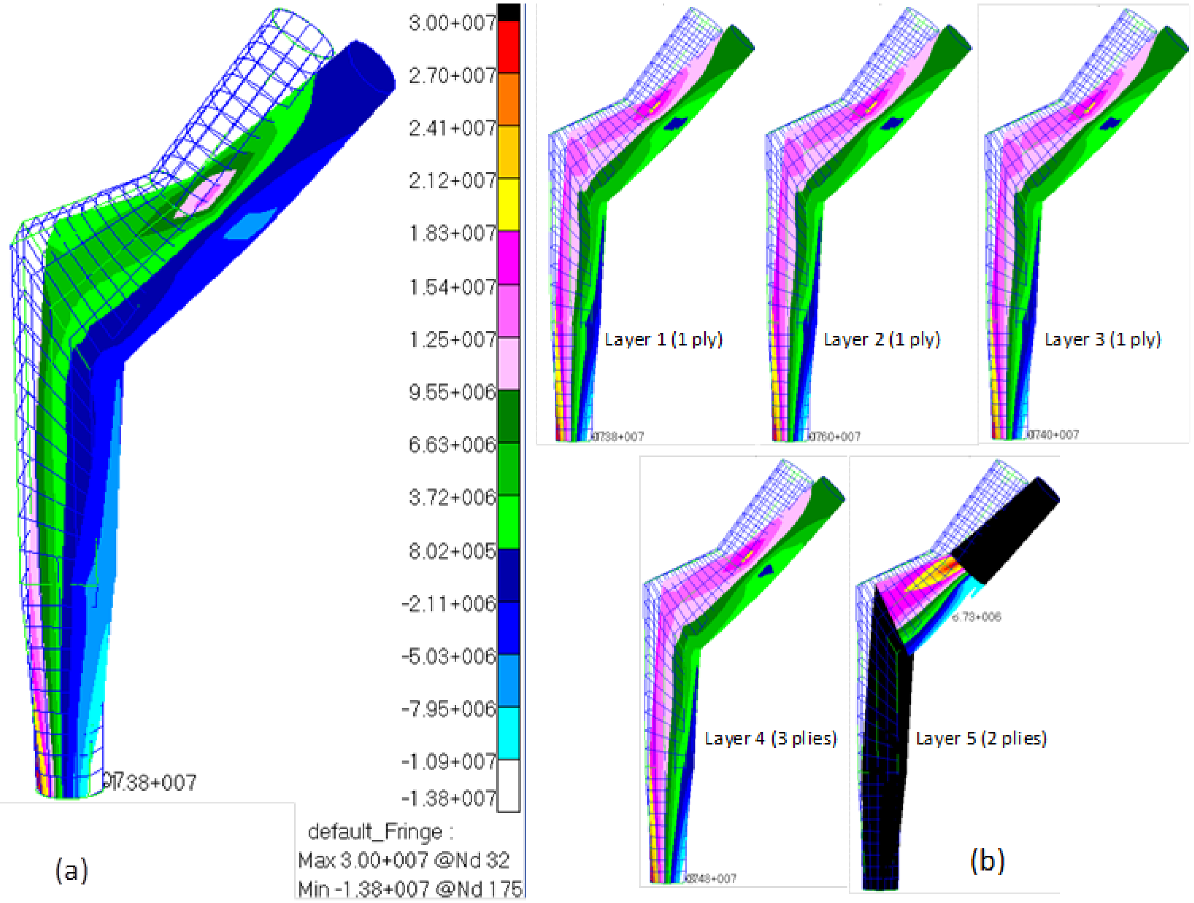


Figure 5-14 (I): Stress distribution for the component at fiber direction (vertical plane): (a) maximum stress distribution combining all layer, (b) stress distribution at different layers and plies

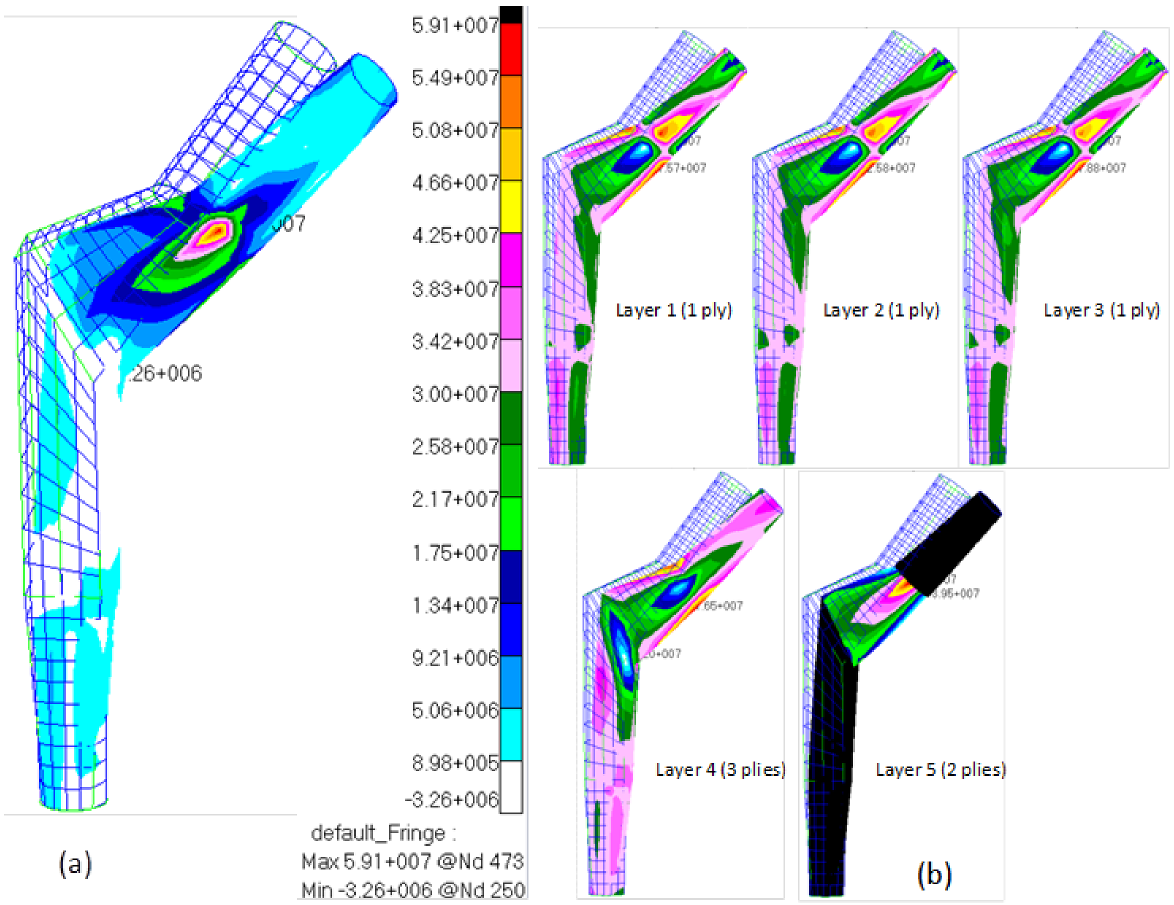


Figure 5-14 (II): Stress distribution for the component at transverse direction to fiber (horizontal plane): (a) maximum stress distribution combining all layer, (b) stress distribution at different layers and plies

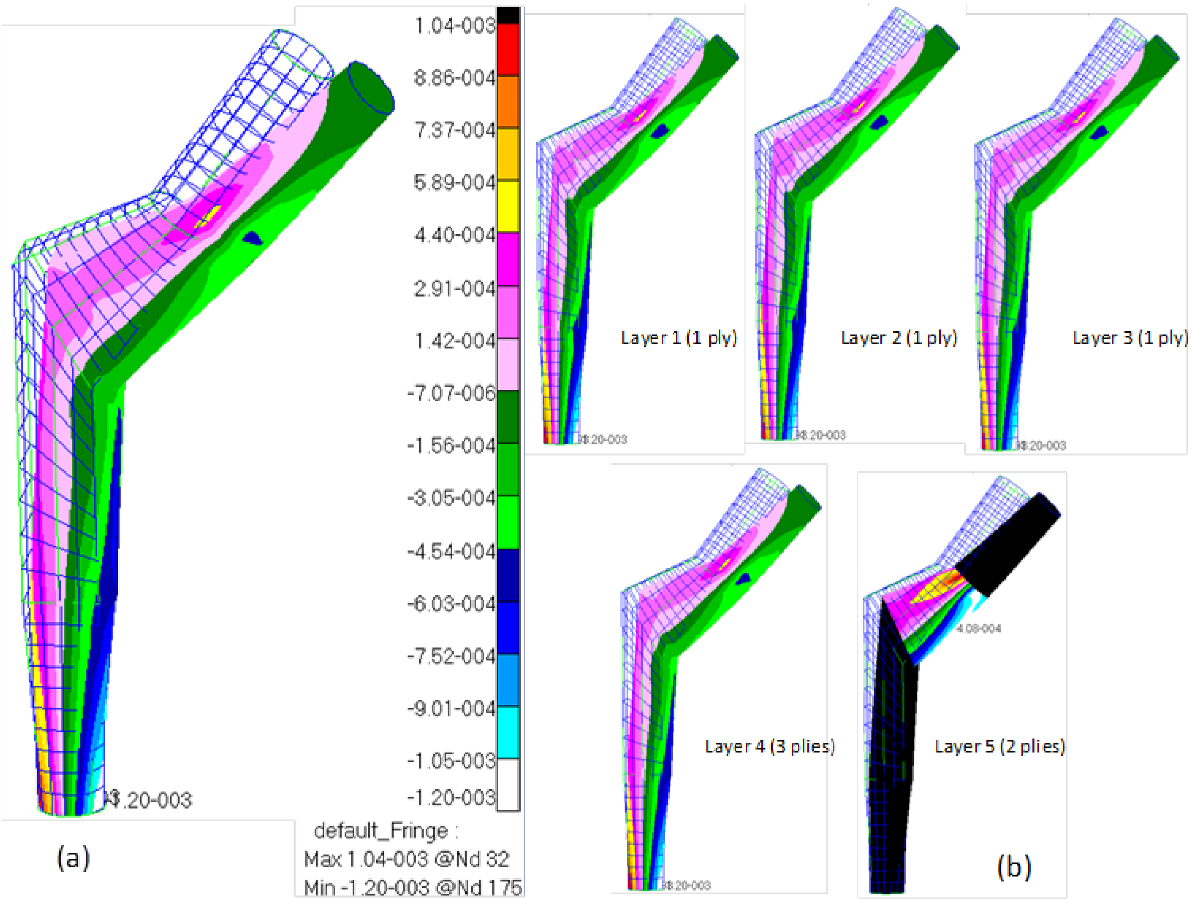


Figure 5-15 (I): Strain distribution of the component at fiber direction: (a) maximum strain combining all layers, (b) strain distribution at different layers and plies

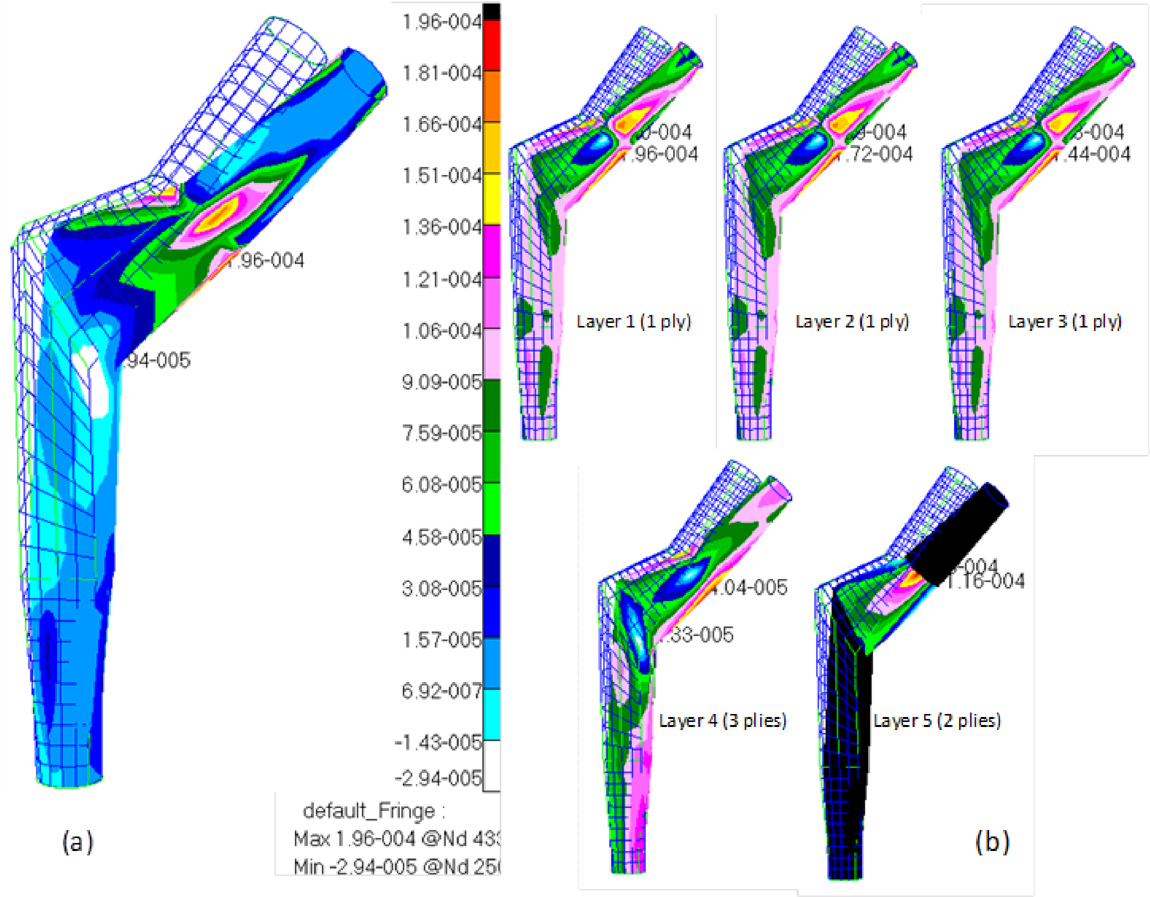


Figure 5-15 (II): Strain distribution of the component at transverse direction to fiber: (a) maximum strain combining all layers, (b) strain distribution at different layers and plies

Figure 5-15 (I) and (II) provides a glance of strain distribution at different layers for the design in fiber direction and in transverse direction. The layer 5, having two plies is discontinuous at the stem and root (indicated by dark space at Figure 5-15 (I) and (II), (b)). To verify the design, another assumption can be satisfied by the obtained results. While defining the case problem, the design strain was considered to be limited to 6.7×10^{-3}. From the finite element analysis results, the maximum strain is found to be 1.20×10^{-3}, as shown in Figure 5-15 (I) (a), which is inside the allowable range. From Barbero (1998, p. 8), typical properties of unidirectional composites are found, which shows that Carbon/Epoxy (T800/3900-2) can carry smallest Longitudinal Tensile Strain compared to other composites, and is 1.29%. Since, the maximum strain for the Hip-replacement joint example is found to be 1.20×10^{-3} (= 0.12%), which is much less than 1.29%, the designed component will not fail under given load.

5.5 Summary of Chapter 5

Based on the widely used micro-mechanical models and incorporating lamination theory with these models, this approach selects appropriate composite materials that meet the properties locally and then the laminates are blended throughout the body. The illustrative case study describes the three different approaches for designing the laminates.

The grammatical approach defined in this work combines mechanics (structure and load analysis), composite material selection technique, and shape grammar (that captures design shape from a wide range of shapes), with careful steps of blending variable layer thicknesses to ensure manufacturability of any designed product.

The designs obtained in the case study presented in this paper are validated using finite element analysis. MSC Patran is used for pre-processing and MSC Nastran is used for post-processing the finite element analysis. The results of the analysis completely agree with the assumptions made for the problem, and validate the reliability of the design under appropriate loading.

CHAPTER 6

SELECTION OF LAMINATED COMPOSITES SIMULTANEOUSLY CONSIDERING MATERIAL AND SHAPE

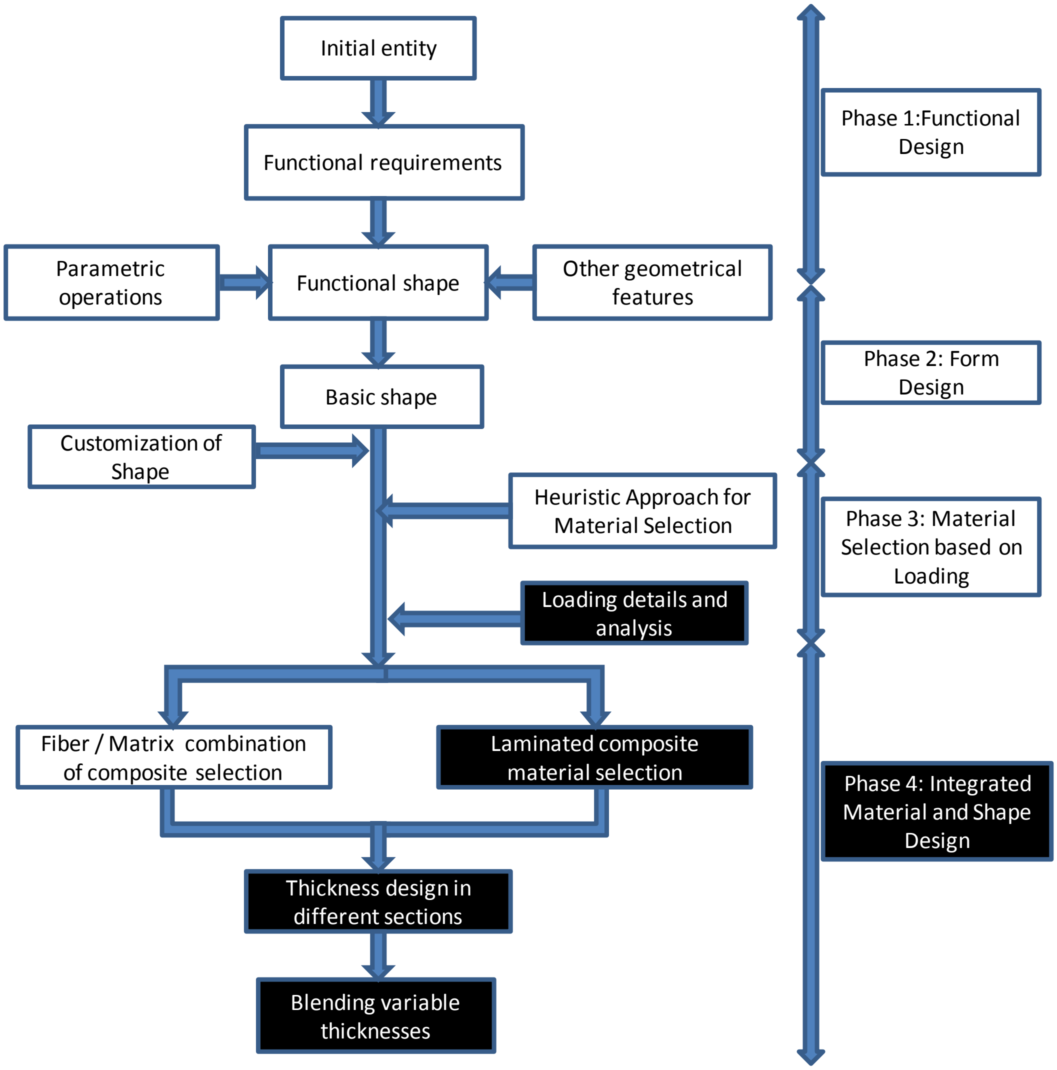


Figure 6-1: Composite laminate selection using Grammatical Approach

6.1 Introduction

In Chapter 5 a grammatical approach was presented that incorporates shape grammar with composite material selection tool to design any load bearing components. The composite material selection tool was used to select appropriate fiber-matrix combination with proper fiber volume fraction and orientation to meet multiple property goals for the design. However, it may not be economical or commercially viable for the manufacturer to fabricate composite laminates of any fiber-matrix combination that a designer may wish. Hence, instead of selecting fiber-matrix combinations, the selection of commercially available unidirectional laminates is performed in this chapter with the customization taking place while designing load bearing components using selected laminates in appropriate orientation to satisfy the properties.

In this chapter, an updated grammatical approach is presented that incorporates shape grammar (Figure 6-1), (that combines mechanics - structure and load analysis) with composite laminate selection (that uses lamination theory), to generate diversified shape models, with careful steps of blending variable layer thicknesses, to ensure manufacturability of any designed product. The Hip-replacement joint is re-designed using commercially available composite laminates with pre-defined mechanical properties in order to illustrate the approach. Thus, in this chapter an effort is made to answer Research Question 4:

How to design a load bearing component using commercially available laminated composite materials with limited property range in order to satisfy directional properties and design requirements?

6.2 Integrated Approach to Design Shape and Selection of Commercially Available Laminated Composite Materials for Load Bearing Components

The work presented in this chapter demonstrates a composite laminate customization approach that incorporates with the shape grammar approach presented in Chapter 2 to 3, to design a load bearing component using composite laminate. The first three phases of the grammatical approach has been explained in previous chapters. In this chapter integrated material and shape design phase, which is an alternative approach to Phases 3 and 4, will be further explored in order to design the component using off-the-shelf laminated composite materials.

Usually the composite laminates produced by a manufacturer have limitations in achieving too high and too low properties. The manufacturers may be renowned for producing laminates of certain property range, and may have limited or no production of some extreme quality laminates. So, it is necessary to design the shape of the load-bearing component in such a way that the design properties at any section of the shape will be achievable by the available laminates. In this chapter Phase 3 is used to explore the optimization approach to determine the shape based on loading details and analysis.

After designing the outer shape, the design goals can be calculated for any minimum number of composite laminates (Phase 4). Depending on the goals of the design, the composite laminate is then designed. In Chapter 5 it was shown that the composite material selection and shape design can be done in one of three different sub-approaches. The same sub-approaches can be used in the integrated composite laminate and shape design as well. All these sub-approaches use the lamination theory to determine the appropriate composite laminates needed to satisfy the design requirements.

6.2.1 General Shape Optimization Formulation (Phase 3)

A simple shape optimization can help designing such a shape. Considering maximum allowable thickness throughout the component, this technique determines the optimum dimensions for various sections with minimum property gaps between different sections.

A general optimization formulation is as follows:

Considering S(i) = {Set of dimensional parameters at different critical sections of the component, i = 1, 2, … n}; where, n is the number of critical sections,

t(i) = {set of thicknesses at i’th section}

Pj(i) = {Property/stress concentration at i’th section}; where j is the number of properties to be considered

D(j) = {Goal for j’th property}

The optimization problem in this approach can be defined as follows:

Determine S; $\{S$ € $S(i)\}$

Minimize $S(i)$

Minimize $t(i)$

Such that,

maximum $(Dj) > Pj >$ mininum (Dj)

and, maximum $S(i) > S(i) >$ minimum $S(i)$

Figure 6-2 shows the optimization flow chart as a part of the Phase 3.

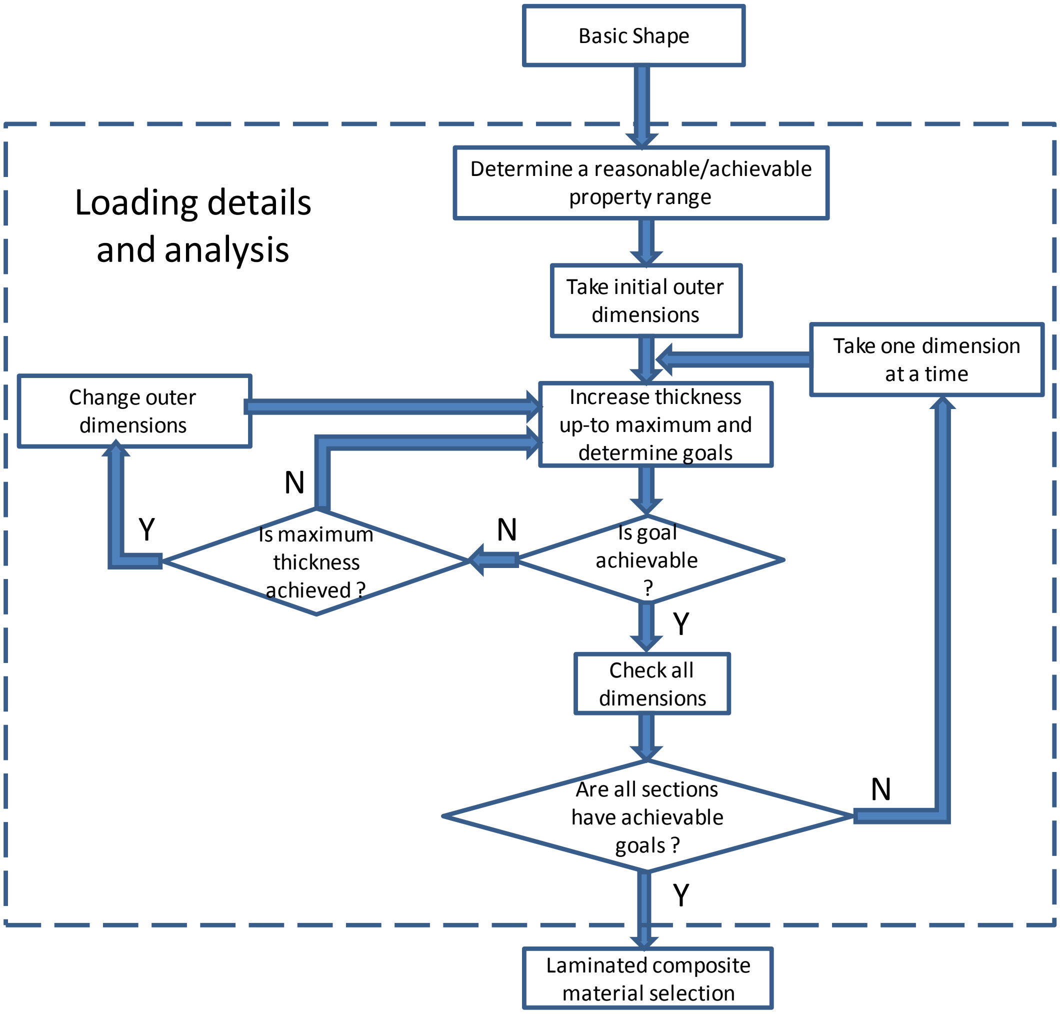


Figure 6-2: Optimization flow chart in order to determine optimized shape based on loading

6.2.2 Laminated Composite Material Selection (Phase 4)

With the shape of the critical cross sections determined from the shape optimization (Section 6.2.1), the laminated composite material can now be selected for different critical sections from the list of commercially available laminates produced with limited property ranges. After designing different locations of the component with different numbers of selected laminated composite materials (different thicknesses) a proper blending method is used in the last step of all the sub-approaches to achieve a continuous inner (or, external) surface. Composite laminate selection takes place in Phase 4 in three simple steps:

Step 1: Creating chart to determine property requirements

Step 2: Selecting appropriate material(s) and Designing thicknesses for different locations

Step 3: Blending inner shell for different thicknesses

6.3 Designing a Hip-replacement Considering Shape and Composite Laminates - Example

To demonstrate the approach the design of hip joint is performed again using the grammatical method that incorporates the proposed laminate design approach. The loading condition is illustrated by Hamrock (Hamrock et al., 2005) and the problem definition is elaborated in Chapter 5. For completeness, Figure 6-3 is repeated to show a total hip replacement inserted into a human femur and acetabulum (hip socket).

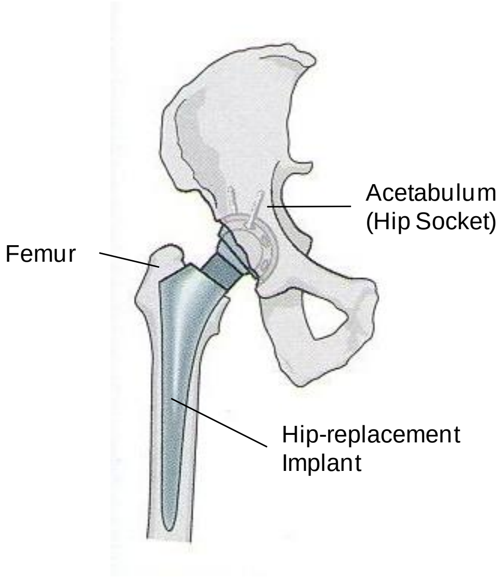


Figure 6-3: A total Hip-replacement implant inserted into a human femur and hip socket (Hamrock et al., 2005, p-255)

Preferable shape and size constraints are captured using Shape Grammar that is defined based on functional requirements (Phase 1) and form requirements (Phase 2). Phases 1 and 2 for this example are same as that presented in Chapter 2 and Section 5.3.2.

6.3.1 Phase 3: Optimization Model for Shape Design

Depending on the size and shape ranges of the hip and femur of the receiver, where the component is to be placed, a shape optimization can be formulated as follows:

Defining objective of optimization

The irregularity of shape can result in high and low stress concentration for a particular load on that component. A same composite laminate with limited property range may not be able to satisfy the property requirements for all cross-sections of a component if the load concentration varies too much. The same situation can happen to some manufacturers who produce a number of laminates with limited property range, and want to design component with irregular shapes. This issue can be addressed by allowing some flexibility in the shape, and selecting shape parameters inside the range in such a way that the differences between the load concentrations due to irregularities would be minimum.

Hence, the objective of the shape optimization is to minimize the difference between the load concentration, and thus minimizing differences between property requirements of different sections. An RMS value of the differences is introduced that is used in order to solve the multi-objective problem as a single objective problem.

Representing Longitudinal Modulus of the Hip-replacement joint at section A_1-A_2, B_1-B_2, and C_1-C_2 (Figure 6-4) as LongMod, and Shear Modulus for different sections as ShearMod,

f(x) = RMS of property gaps or differences

$$= \surd\Sigma(LongMod_{i,j} - LongMod_{i,(j+1)} + (ShearMod_{i,j} - ShearMod_{i,(j+1)})^{2}))^{2}/(i\times j);$$

Where, $i = A, B,$ and C, and $j = 1$, and 2

Identification of constraints

Constraints for the problem are on performance of the structure, material properties, and dimensions of the critical sections. The constraints for the Hip-replacement joint design example are considered as:

Longitudinal Modulus: $120 < LongMod < 200$

Shear Modulus: $60 < ShearMod < 80$

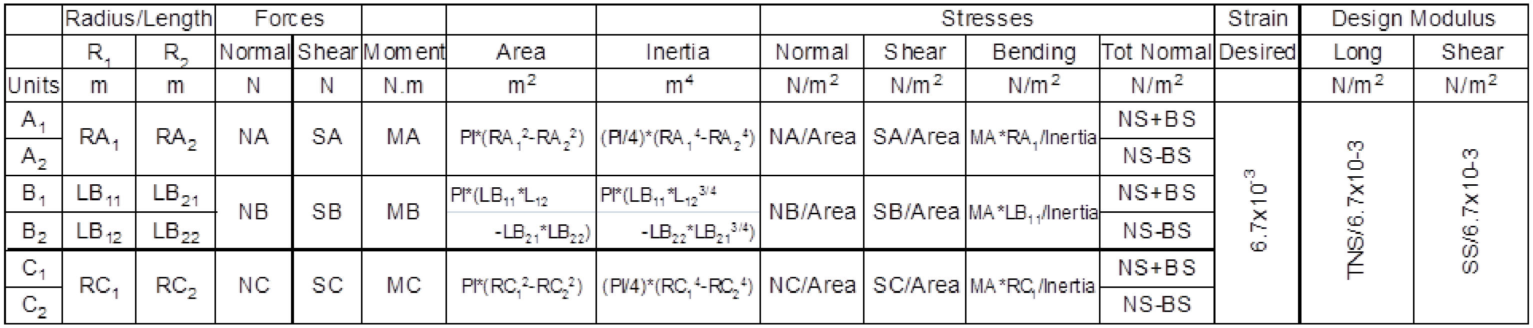
Radius of circular sections: $0.03 < r < 0.05$

Size of rectangular sides: $0.03 < l < 0.05$

Angle between stem and root: $30 < theta < 45$

Table 6-1 shows the formulations of the property calculations for these sections.

Table 6-1: Chart to determine property requirements (Repeated from Table 5-2)



	Radius/Length		Forces					Stresses				Strain	Design Modulus	
	R_1	R_2	Normal	Shear	Moment	Area	Inertia	Normal	Shear	Bending	Tot Normal	Desired	Long	Shear
Units	m	m	N	N	N.m	m^2	m^4	N/m^2	N/m^2	N/m^2	N/m^2		N/m^2	N/m^2
A_1	RA_1	RA_2	NA	SA	MA	$PI*(RA_1^2-RA_2^2)$	$(PI/4)*(RA_1^4-RA_2^4)$	NA/Area	SA/Area	$MA*RA_1/Inertia$	NS+BS	$6.7x10^{-3}$	TNS/6.7x10-3	SS/6.7x10-3
A_2											NS-BS			
B_1	LB_{11}	LB_{21}	NB	SB	MB	$PI*(LB_{11}*L_{12}$	$PI*(LB_{11}*L_{12}^{3/4}$	NB/Area	SB/Area	$MA*LB_{11}/Inertia$	NS+BS			
B_2	LB_{12}	LB_{22}				$-LB_{21}*LB_{22})$	$-LB_{22}*LB_{21}^{3/4})$				NS-BS			
C_1	RC_1	RC_2	NC	SC	MC	$PI*(RC_1^2-RC_2^2)$	$(PI/4)*(RC_1^4-RC_2^4)$	NC/Area	SC/Area	$MA*RC_1/Inertia$	NS+BS			
C_2											NS-BS			

RA1, RA2, RC1, RC2: Radius at section A-A and C-C
LB11, LB21, LB12, LB22: Lengths at section B-B
NA, NB, NC: Normal forces at different sections
SA, SB, SC: Shear forces at different sections
MA, NB, NC: Moments at different sections
NS, BS: Normal and shear stresses

Solving the problem

The optimization problem is stated in the standard form as follows:

Minimize $f(x)$

Subject to,

$$G_{i,j}(x) = 120 - LongMod_{i,j}$$

$$G_{i,j}(x) = LongMod_{i,j} - 200$$

$$G_{i+1,j+1}(x) = 60 - \mathrm{Shear}Mod_{i,}$$

$$G_{i+1,j+1}(x) = ShearMod_{i,} - 80$$

The problem is solved using the fmincon function in the MATLAB Optimization Toolbox. Optimizing the shape parameters at the critical cross sections of the Hip-replacement joint, the assumed ranges are found feasible to design using the property range of available laminated composite. So, the shape constraint for the Hip-replacement design at the Chapter 5 will also be used in this chapter.

6.3.2 Phase 4 – Laminated Composite Material Selection

Step 1: Creating chart to determine property requirements

For a 200 lb (90.72 Kg weight, i.e., 890 N) receiver of the implant, the design weight is considered to be 800 lb (362.88 Kg weight, i.e., 3560 N)(Safety factor is equal to 4). The following chart (Table 6-2) is determined directly by using methods of Statics that shows how the design weight leads to a normal force, a shear force, and a bending moment at each section.

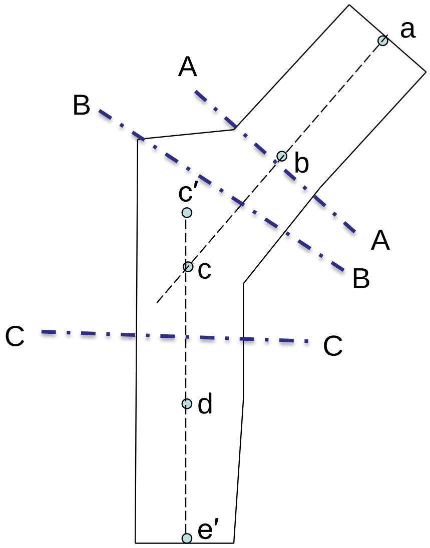


Figure 6-4: Critical Sections of the Hip-replacement Joint

Table 6-2: Applied loads (Hamrock et al., 2005)

Section	Normal Force		Shear Force		Moment	
	lb	N	lb	N	in.lb	N.m
A_1-A_2	640	2846.862	475	2112.905	252	28.47218
B_1-B_2	640	2846.862	475	2112.905	345	38.97977
C_1-C_2	800	3558.577	0	0	680	76.82968

As this component is to be made using composite laminates, there will be three main design requirements: the longitudinal modulus, the transverse modulus, and the shear modulus. However, the presence of weight as the only load, applied vertically to the component, involves no torsion to it, thus requiring no transverse modulus to meet during design. The unidirectional composite layers can be used to achieve all the design goals by placing them in vertical planes, and no angular orientation is required. Table 6-1 is prepared to calculate required modulus while varying thicknesses for different loading sections. As the maximum allowable (design) strain is considered constant throughout the component body, increase in thickness will reduce the requirements of both longitudinal and shear modulus for different sections. The equations used for such calculations are provided in each cells of the chart.

Step 2: Selecting appropriate material(s) & Designing thicknesses for different locations

Selecting appropriate laminates for different section and designing thicknesses are interconnected to each other. Available composite laminates are not tested for bio-compatibility, and hence, not recommended to design human implants. So, just for the demonstration, laminates and their properties are assumed imitating some widely used commercial laminates. The properties of the assumed laminates are provided inside the demonstration. The selections made in this example should not be considered for commercial use. Composite laminate design following the sub-approaches presented in Chapter 5 for this case will be as follows.

Sub-Approach 1 (Weight efficient method)

The weight efficient method is expected to ensure maximum weight reduction by avoiding overdesigning in any direction. As mentioned before, the calculation begins with finding minimum number of layers, for which at least one property goal reaches a value that can be achieved by available composite material options.

In this example case, from different company guidelines minimum thickness for each ply is considered to be 0.09 mm. It is calculated that a single ply can meet the design requirements for longitudinal modulus at point B_2 (at section B_1-B_2) which is an achievable value of 77 GPa. Table 6-3 shows this condition (yellow cell shows the design requirement).

Table 6-3: Design properties requirements for thickness 0.09 mm

Section	Design Properties	
	Long Mod (Gpa)	Shear Mod (Gpa)
A_1	261	88
A_2	499	88
B_1	221	111
B_2	77	111
C_1	2645	N/A
C_2	3144	N/A

An appropriate laminate is selected minimizing the weight from the set of laminates. SA110 (assumed name for the imitated laminate) unidirectional laminate with longitudinal modulus of 134 GPa and Shear modulus of 4.3 GPa. Thus the initial laminate is designed to be composed of only one layer using the selected composite. This layer can satisfy the longitudinal modulus requirements at B2. Rightmost column of Table 6-4 shows the name of the achieved section and the type of satisfied property (“L” for “Longitudinal”, and “S” for “Shear”).

Table 6-4: Results for Sub-Approach 1

Layer	Laminate	Num of plies	Thickness	Total thickness achieved	Section satisfied
1	SA 110	1	0.09	0.09	B_2 (L)
2	SA 110	1	0.09	0.18	A_1, B_1 (L)
3	SA 120	1	0.09	0.27	A_2 (L)
4	SA 120	7	0.63	0.9	A_1, A_2 (S)
5	SA 120	1	0.09	0.99	C_1 (L)
6	SA 120	1	0.09	1.08	B_1, B_2 (S)
7	SA 120	1	0.09	1.17	C_2 (L)

Thus the next closest property goal at B_1 requires an additional laminate to meet 87 GPa. The next layer is selected minimizing the weight so that longitudinal modulus is just higher than 87 GPa, SA110 is again selected for this layer; this layer satisfied both properties at location A_1 and B_1.

For the next attainable goal longitudinal modulus of 231 GPa at section A2 a layer of SA120 (assumed name for the imitated laminate) is selected that has longitudinal modulus of 265 GPa and shear modulus of 10.34 GPa. Thus different layers are selected until all sections are satisfied. Table 6-4 lists the selection for this weight efficient method.

Sub-Approach 2 (Production efficient method)

As mentioned before, the production efficient method is based on the assumption that composite material manufacturing is most efficient when the designed fiber-matrix combination remains same for the whole product. Equations given in Table 6-1 are used to determine the minimum thickness for which properties in each and every location in the body becomes obtainable.

For the example in this paper, such a laminate is selected for the design that alone can meet the property requirements at all sections, and in the same time is less costly and less in weight. SA200 (assumed name for the imitated laminate) laminate with longitudinal modulus of 224 GPa and shear modulus of 7.52 GPa is known for its moderate high modulus, having medical, aerospace, and industrial applications. This laminate is selected for this example case and all the longitudinal and shear modulus requirements for this example is selected. The optimized selection is given by Table 6-5 below.

Table 6-5: Results for Sub-Approach 2

Layer	Laminate	Num of plies	Thickness	Total thickness achieved	Section satisfied
1	SA 200	1	0.09	0.09	B_1, B_2 (L)
2	SA 200	1	0.09	0.18	A_1 (L)
3	SA 200	1	0.09	0.27	A_2 (L)
4	SA 200	9	0.81	1.08	A_1, A_2 (S), C_1 (L)
5	SA 200	3	0.27	1.26	B_1, B_2 (S), C_2 (L)

This should be noted from the table that this method required more plies than the weight efficient method. Thus this method provides less weight efficient design, but it can avoid mixing of multiple type laminates.

Sub-Approach 3 (Cost efficient method)

The cost efficient method is based on the assumption that a maximum thickness is allowed for each different location in a body. To demonstrate the approach in this example, a maximum thickness of 2.00 mm for section A_1-A_2, 1.00 mm for section B_1-B_2, and 2.5 mm for section C_1-C_2 is assumed. Now, if the property requirements at all sections are attainable by the cheapest material, the design follows sub-approach 2 with that material. Otherwise, all the attainable sections are designed using the cheaper selections and the remaining sections are designed with costlier composites to ensure achievement of the design requirements. For demonstrating the approach with comparison of prices, the component will be designed using three types of composites with imitated properties and costs. The SA320 series are considered to be cheapest among the different types available, and they provide the lowest mechanical properties. It is assumed that SA320 are preferred over costlier SA315 series that costs slightly more than SA320 series, providing enhanced transference and mechanical properties. Even costlier SA305 to SA310 series are also considered that offer wider property range to meet the goals. Thus the goal is to use SA320 more and SA115, SA310 and SA305 series as less as possible in this design.

For maximum allowable thickness at each location it was found that Shear modulus at section B-B cannot be achieved using only SA320 or SA315 series laminates as higher thickness are required to meet the maximum thickness requirements. Only 11 ply layer of SA310 can hardly satisfy the requirements meeting the constraint. So, all sections are designed using SA310 until properties at B_1-B_2 is achieved. It is possible that property goals at some other sections will be met even before the section B_1-B_2 is met. So, designing have to be started considering the earlier achievable sections, and continue until section B_1-B_2 is met. Afterwards, the remaining sections can be designed with less costlier laminates. The result of the selection is given in Table 6-6.

Table 6-6: Results for Sub-Approach 3

Layer	Laminate	Num of plies	Thickness	Total thickness achieved	Section satisfied
1	SA 310	1	0.09	0.09	A_1, B_1, B_2 (L)
2	SA 310	1	0.09	0.18	A_2 (L)
3	SA 310	7	0.63	0.81	A_1, A_2 (S)
4	SA 310	1	0.09	0.9	C_1 (L)
5	SA 310	1	0.09	0.99	B_1, B_2 (S)
6	SA 320	2	0.18	1.17	C_2 (L)

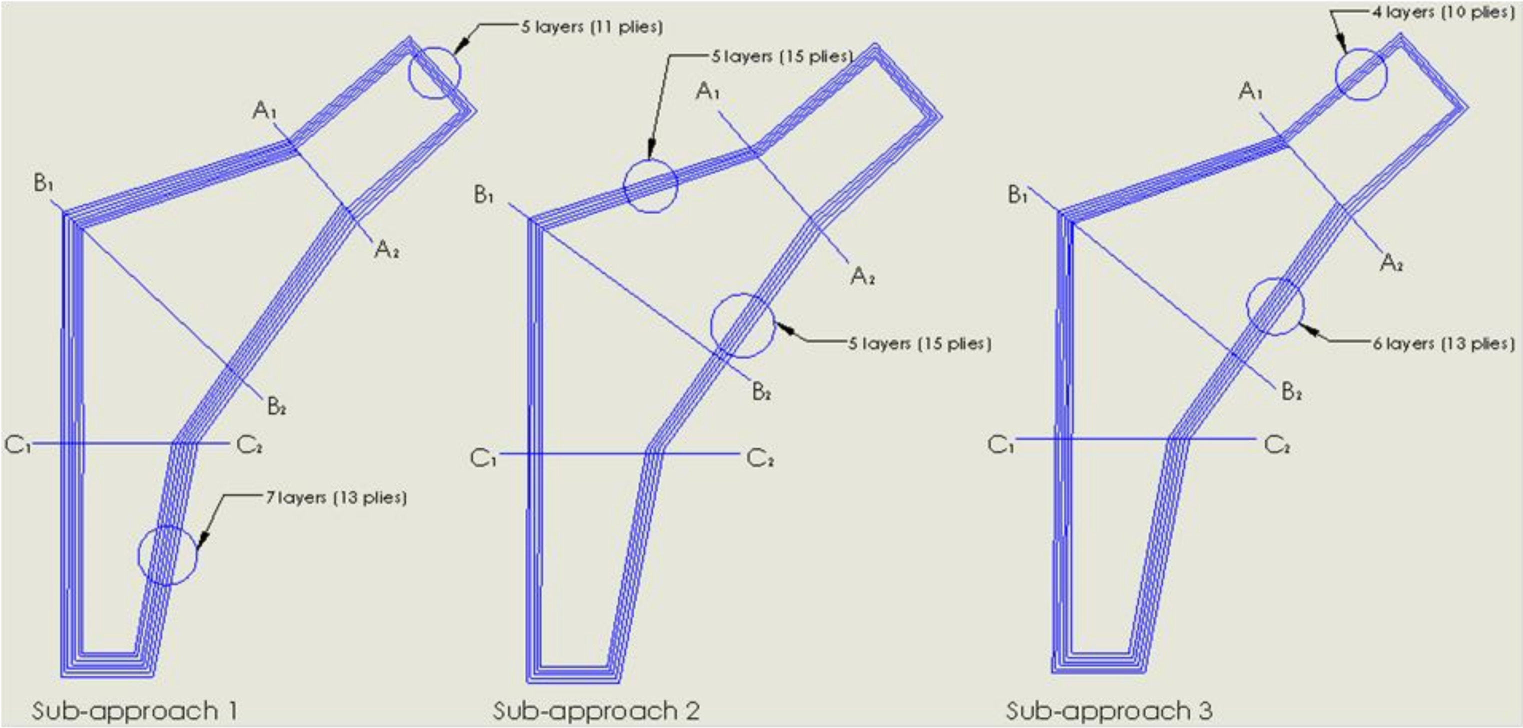


Figure 6- 5: Layer design in three sub-approaches

It can be seen from the table that only section C_2 was left to satisfy while the property requirements at section B-B are met. And the thickness constraint at this section allows use of cheapest SA320 series to satisfy the requirements. Thus the remaining layers at C_2 are designed using SA320 laminates.

Step3: *Blending inner shell for different thicknesses*

Designing composite panels with specified local loads could result in manufacturing incompatibilities between adjacent panel designs. A guide based optimization was employed by Adams (Adams et al, 2004) to select composite panels to overcome this incompatibilities and the inner or outer surface was blended for utilizing a simple master-slave parallel implementation. This master-slave blending method is implemented in the final part of this approach to ensure a design that would be feasible to manufacture.

Designing and selection of laminated composite materials for different layers as explained in previous sections, are done such a way that the same layer contains same laminated composite throughout the component shape. Thus blending of inner surface for this case is primarily concerned with this continuation of same fiber-reinforced layers and of the same orientation. The initially selected layers create the outer shell and remain uniformly distributed throughout the body. The next layers are attached to the outer shell from the inner side and are distributed everywhere inside the outer shell; they are discontinued only where the design goals are met by previous layers. The cross-section of the hip-joint after the laminates design should look like Figures 6-5.

6.4 Summary of Chapter 6

A new approach for design of load-bearing components using laminated composite materials to achieve multiple properties is presented in this chapter. Based on the lamination theory for fiber-reinforced composite materials, this approach selects appropriate composite laminates that can satisfy the design properties locally thus allow avoiding overdesigning at any section of the component. The discontinuities in the laminates are blended throughout the body. The illustrative example describes the three different approaches for designing the laminates.

CHAPTER 7

CONCLUDING REMARKS

A summary will be made of the work presented and the resulting contributions. In addition, further extensions of the grammatical approach in integrating shape and material selections, simultaneous optimization of shape and materials, and the possible applications of the methods capability for design innovation will be discussed.

7.1 Dissertation Summary

The Grammatical Approach, an integrated shape and material design, that combines shape grammar with composite material selection tool in order to design a load bearing component of any shape using composite material. At the first and second phase of the work, a shape grammar is defined in such a way that any shape can be generated from a very basic geometric entity by applying a number of shape rules. The unique advantage of using shape grammar is explained in this work that it can handle a range of shapes. The application of shape grammar in mass-customization of shapes is considered as the input for a shape optimization technique that leads to the selection of shape parameters of a component that will have designable stress-concentrations. The third phase considers the optimized shape selected and designs commercially available laminated composite materials to satisfy the given loading conditions (Chapter 6 explains this scenario). However, in the alternate approach explained in Chapter 5, the shape optimization may not be necessary if fiber and matrix combination are selected from an ideal material list covering wider property range. In the fourth phase, three sub-approaches are introduced based on the ultimate design goals of the designer that can be used to select either fiber-matrix combination with proper orientation (Chapter 5) or suitable laminated composite materials with ply angles (Chapter 6) in order to satisfy directional property requirements at any sections of the component. A heuristic approach for composite material selection is also presented (Chapter 4) that is used by these sub-approaches to determine the best materials for the designs. Thus the grammatical approach provides a unique design style that can enhance the creativity of the designer in design of composite material structures.

7.2 Answering the Research Questions

In this work an effort is made to address the Primary Research Question associated with the challenges of this research. The Primary Research Question is:

How to simultaneously explore shape and composite materials during the design of a product to meet multiple property and functional goals?

In order to address to this Primary Research Question, a general hypothesis is also presented:

The incorporation of mass customization of shape into directional material design enable the design of any load bearing component without compromising any design goals and can avoid overdesign in any direction.

Based on this hypothesis the Primary Research Question was addressed using four intertwined phases. The Primary Research Question was divided into 4 Research Questions. Answers to these 4 research questions, as addressed in this dissertation, are presented next.

Phase 1 and Phase 2 combines Functional and Shape Design Phases that generate the design shape by functional decomposition of the component. Phase 1 and Phase 2 begin with generating shape grammar for any irregular shape component, such as Hip-replacement joint. They together addresses to the following research question:

Research Question 1: How can a shape grammar model be generated in order to represent a component shape that will be used to perform desired functions while meeting space constraints?

This question is addressed by developing a simplified technique to generate shape grammar based on the functions it is going to perform, and approximate shape requirements and space constraints. Chapter 2 addresses this question with two demonstrative examples of generating shape grammar of a Hip-replacement joint, and the airfoil shape of a wind turbine blade. The generated shape grammars are found to have different rules for different shapes, but they all follow the same pattern of generating any shape from a very basic geometric entity.

After the shape is generated, the next challenge becomes how to implement the shape grammar in real-life situations such as optimization and mass customization. The following question is addressed:

Research Question 2: How to implement product family and product platform concepts in shape grammar technique in order to determine the shape ranges that will be used in the shape optimization that will take place?

This research question is addressed in Chapter 3. It was shown that shape grammar, which can handle a range of shapes, can be easily applied in mass-customization. With the introduction of Product Platform and Product Family design technique of mass-customization into shape grammar a number of commercially used Hip-replacement joint shapes are captured in a very efficient way.

Chapter 4 illustrates the Composite Material selection approach that introduces a unique RMS index approach that can be used to select fiber-matrix combination based on directional property requirements. The research question is being addressed is:

Research Question 3: How to select appropriate composite materials in order to satisfy directional property requirements at the critical sections of a component?

In Chapter 4 a composite material selection tool is developed that uses the RMS index approach to perform composite material selection. An example was used to show that multiple property requirements can be satisfied by properly selected fiber-matrix combination with properly determined orientation and ply angle.

Chapter 5 shows a complete design method that considers user requirements in the very basic form, and translates into design requirements and selects direction of the fibers. Thus, Chapter 5 puts an effort to address the remaining part of the research question that Chapter 4 addresses. The grammatical approach presented in Chapter 5 is used to design the Hip-replacement joint as a demonstrative example. Commercial FEA tools validated the design and the assumptions completely agreed with the results of the FE analysis.

Considering the commercial scenario where the composite laminates are to be selected from the available laminates in the market, instead of ideal fiber-matrix combinations, Chapter 6 addresses the following research question:

Research Question 4: How to design a load bearing component using commercially available laminated composite materials with limited property range in order to satisfy directional properties and design requirements?

A shape optimization approach is developed using Matlab optimization tools as a part of the Phase 3. The optimization allows design of shape in such a way that the component can be designed by any available material. Thus the complete work integrates the shape design and composite material selection approaches that resulted in a unique approach to design composite structures.

7.3 Contributions

The work presented has explored the shape grammar and its application in mechanical design, directional properties of fiber-matrix and laminated composite structures, and the integration of shape and materials in order to mass customize load bearing components. The approach developed here for composite material design could provide the foundation for a simultaneous customization approach for composite material and shape. Although optimization was not the primary goal in this work, the work presents a shape optimization formulae in order to facilitate the technique for best material selection inside a given range of shapes. It introduces a complete package of composite structural design that considers the end users requirements and formulates them into a sustainable and efficient design in a very innovative way.

The composite material design methods used by different composite manufacturers and designers are usually manual selection approach, and are thus limited by the designer's experience. Thus the quality of designs performed by the designers cannot be always guaranteed. The grammatical approach presented in this work is designed to make the selection from an established database using a proven heuristic computation. It also ensures that the proper shape is designed that will allow most efficient design. The integration of shape and material design is the key reason of the approach to have numerous applications.

The major contributions of this work are:

a) A grammatical approach to integrate shape and material design
b) A simplified method to generate shape grammar and its application in mass-customization of shapes
c) A heuristic approach to select composite materials to satisfy multiple property requirements
d) An efficient design approach to composite structure in order to meet directional property requirements that can result in minimizing weight and cost, and maximizing thermo-mechanical properties.

7.4 Future Work

The work presented here is not fully automated. Based on functional and space requirements, design of the components are performed manually with the help of partially automated design tools. Hence, the whole approach needs to be automated. Thus a possible future work may include automation of the approach presented in this work.

There is no single database developed yet that can be used to compare and select commercial laminates from various manufacturers. So, a comprehensive database can be developed as in order to help designers use this tool more efficiently.

The grammatical approach is shown to be capable of designing load bearing components of irregular shape using composite materials. Further extensions and improvements can be made to implement simultaneous material and shape optimization techniques in order to automate the design approach.

The potential extension to simultaneous material and shape optimization approach can be defined for the three sub-approaches as follows.

7.4.1 Sub-Approach 1: Weight Efficient Method

The first sub-approach is based on a view to reduce the weight of the designed component as much as possible. It is probable that this approach would provide most efficient design in most cases, as the goal of this approach is to avoid over-designing in any direction. An appropriate multi-objective optimization technique can be employed to determine the ply-laminate combination with proper angular orientation to meet multiple property goals.

Considering S(i) = {Set of laminates available in the market, i = 1, 2, … n}; where n is the type of laminates,

C(i) = {Cost of the i’th layer}

Pj(i) = {Property of i’th layer}; where j is the number of property goals

W(i) = {Weight of i’th layer}

D(j) = {Goal for j’th property}

T(k) = {Allowable thicknesses for k’th section of the compoenent}

R(k) = {dimensional parameters of the k’th section of the component}

t(i) = {set of thicknesses for i’th layer}

The optimization problem in this approach can be defined as follows:

Determine S; {S € S(i)}

Min ΣW(i)

Min C(i)

Min Pj(i)

Max R(k),

Such that, Pj(1) > Pj(2) > … > Pj(i)

maximum (Dj) > Pj > minimum (Dj)

and so on…

So, in this possible extension with Sub-approach 1, the minimum number of layers or plies will be determined for which at least one property or shape goal reaches an attainable value.

7.4.2 Sub-Approach 2: Manufacturing Efficient Method

The second sub-approach is the way to design a component that will be efficient to manufacture. It is based on the assumption that manufacturing is simple when same fiber-matrix composite is used for the entire product. The optimization problem in this approach can be defined as follows:

Determine S(i); where, S(1) = S(2) = … S(i)

Min C(i)

Min Pj(i),

s.t., Pj(1) > Pj(2) > … > Pj(i)

and, maximum (Dj) > Pj > minimum (Dj)

7.4.3 Sub-Approach 3: Cost Efficient Method

The third approach is based on allowing maximum possible thickness for different locations in a component body while designing composite materials and their orientations. This is expected to be the least expensive approach as by designing for maximum possible thickness in every section (design flexibility is maximum), it should be able to select the least expensive materials that provide least allowable quality of materials that will meet all desired property requirements. The design of layers may take place similar to any of the first two sub-approaches or in a combination of both. The optimization problem in this approach can be defined by,

Determine S; {S € S(i)}

Min C(i)

Min ΣW(i)

Min Pj(i),

s.t., Pj(1) > Pj(2) > … > Pj(i),

Σt(i) < T(k),

and, maximum (Dj) > Pj > minimum (Dj)

7.5 Limitations to the Approach

As shown in the future work, a better integration between shape and material could be achieved by implementing a simultaneous shape and material optimization technique. Again shape optimization presented in this work might be difficult to formulate in some cases, because some of the shape grammar rules might be discrete in nature.

In this work, very simple micro-mechanical models are used while predicting the properties of composite materials. Though these models are widely used, they may result in less accuracy for some cases compared to some other customized models. The limitation can be overcome by developing a technique that can use such customized and more detailed models in the grammatical approach to achieve more accurate designs.

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