The Virtual Composites Factory

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Abstract: *The Virtual Factory (VF) can put composites manufacturing simulations in the hands of those who need them to invent new and innovative ways to capture the extraordinary benefits of these high performance products at an acceptable manufactured cost. "Crowd-sourcing" is the new way to drive innovation where contributions from organizations, large and small, are joined in the development of new products. The VF provides the user with simple browser access to powerful tools that simulate the actual steps and outcome conditions of a complex manufacturing process without the need to download and maintain software in the conventional manner. Learning to use uncertainty quantification (UQ) with manufacturing simulation tools will also be accomplished on the VF in order to allow for continuous learning and growth of the human talent required in composites manufacturing.*

Keywords*: Composites, Manufacturing*

1. Introduction and Background

1.1 Motivation

During the next quarter century, composite materials' unique properties will benefit the civil aviation, defense, alternative energy, leisure and automotive sectors. Yet this growing demand for composite materials and technology is not consistent with the existing twelve-year cycle for material and product development, certification and market delivery described by Tom Brand, CEO of Fiberite (retired), in his presentation at Carbon Fiber 2011 [1]. Brand stated that the typical prepreg product took five years to develop and certify, followed by a typical market life of seven years; hence, a twelve-year cycle. Unlike many modern industries such as electronics, the concept of "just-in-time" products is largely absent from the composites field for this reason.

The significant impact of composites upon the world is evidenced many ways, including the National Academy of Engineering's selection of composites as one of the greatest achievements of the 20th Century [2]. Another measure is the extraordinary growth of the composites industry; carbon fiber production increased from 26 million pounds in 1998 to 49 million pounds in 2007. Current estimates project that 100 million pounds of carbon fiber will be required in the 787 program alone over the next ten years.

There have been extraordinary advances in composites technology such as: ultra-high strength carbon fibers, prepregs, toughened polymer matrices, thermoplastics, automated fiber placement, out-of-autoclave systems, infusion molding, advanced textile preforms, computer-aided design tools, optimum design through part consolidation and adhesives technology.

All of these advances pale in comparison, however, to the growth in computing power. Since 1970, computing power has grown from 0.001 to 100,000 million instructions per second (Mips) [3] and the cost of computing hardware to achieve a billion floating-point operations has dropped precipitously from $1.1 trillion in 1961 to $1.80 in 2011 [4]. Figure 1 shows the extraordinary growth in computer power since the turn of the century and projects computers with human intelligence by 2040. The potential to utilize the current 1,000,000,000,000 fold increase in computing power and efficiency is the most potent path to accelerating product and material certification, replacing the current "test and more tests" approach with an economic and effective mix of test and simulation. Using simulation to replace some fraction of experimental testing can accelerate the development of new materials, manufacturing processes and their certification by reducing both the cost and time necessary for new product development. Of course, there is a clear need for government, industry, academia and the certification agencies to rally around this idea, each with clearly articulated roles to make simulation-based certification a reality.

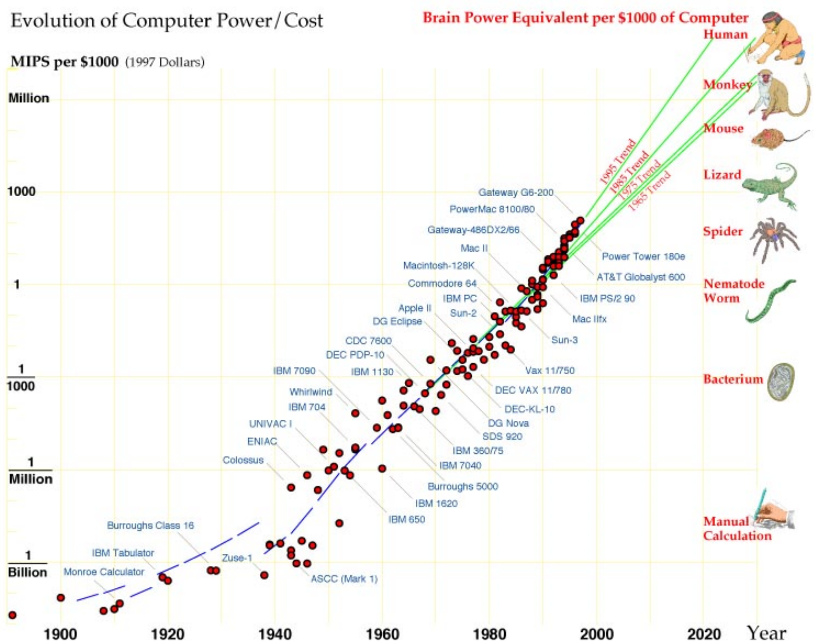

Figure 1. Evolution of Computer Power/Cost Ratio [3]

Simulation in the design of composite structure has developed during the past four decades to a level of sophistication that allows for the successful design of complex integrated structural geometries consisting of multi-axial composite laminates of curvilinear geometry, sandwich construction, adhesive and mechanical joints, as well as, monocot constructions that possess significantly less sub-assemblies over their metallic counterparts. The Boeing 787 Dreamliner is one example of success this simulation capability has achieved to date. Here the forward fuselage shown in Figure 2 (40-ft. in length and 20-ft. in diameter) is designed and constructed as a single assembly. Simulation of the complex geometry and performance characteristics of this composite structure were enabled through geometric modeling, multi-axial laminate analysis of the material architecture and structural analysis of the forward fuselage structure. Sophisticated computer simulation codes now offer simulation tool sets that address these design issues.

Figure 2. Boeing 787 Dreamliner forward fuselage manufactured by Spirit Aerosystems [3]

1.2 Simulation in Composite Materials

Simulation of the manufacturing of composite structure is not at the same level of development as that of design simulation. VISTAGY Inc. (Waltham, Mass.) recently announced the results of its composites engineering benchmarking survey entitled, "How does your Composite Design Processes Compare to Industry Best Practices?"[5]. The results of the study revealed that only 56 percent of the composite design companies surveyed considered themselves knowledgeable in composites manufacturing practices and were able to apply that knowledge during design. This suggests that 44 percent of companies need to enhance their knowledge of the manufacturing process if they are to improve their competitiveness.

The process for developing new manufacturing simulation tools remains in its infancy. Unlike design simulation software, the manufacturing of polymer composite materials and structures involves multi-physics phenomena such as the curing reactions of thermoset polymers, melting and solidification of thermoplastic polymers, flow and impregnation of viscous polymers in fibrous preforms and tows, consolidation of fiber preforms, conduction and convective heat transfer, geometric conformation of fiber preforms to curvilinear surfaces, residual deformations due to anisotropy in thermal expansion and tooling-composite thermal interactions. These phenomena span the disciplines of polymer science, rheology, reaction kinetics, fluid mechanics of non-Newtonian liquids, heat and mass transfer, mathematical topology, anisotropic thermoelasticity and viscoelasticity. While multi-physics analysis tools have recently been introduced, their use in composites manufacturing simulation is still quite early. Commercial tools now offer a broad range of physical modeling capabilities to model flow, turbulence, heat transfer and curing reactions for industrial applications.

1.3 Uncertainty Quantification as the Foundation of Certification

Uncertainty Quantification (UQ) is an established methodology to predict the range in expected outcomes through simulation. As such, it can combine simulation and experimental test results to reflect the actual range in expected performance and thereby assure confidence in performance with fewer tests. Furthermore, recent advances in optimization techniques can account for these uncertainties, producing robust designs relatively impervious to manufacturing variability. Today, the production of composites design variables, such as “A” and “B” allowables, is an entirely experimental task [6]. The science of UQ is currently utilized by the National Nuclear Security Administration to certify weapons performance in the absence of testing as governed by global treaties. This body of knowledge can be transferred to the composites industry to guide the development of the new certification paradigm for composite materials and structures. Combining UQ with composites simulation tools can provide the foundation for certification of composite products with fewer physical tests [4].

One example of the UQ approach in determining composite performance variability is illustrated by examining if the variability in the microstructure can be related to failure variability in fiber-reinforced composite materials such as the open hole tensile strength. Consider the variation in volume fraction of a typical high performance carbon fiber composite prepreg, IM7/8552 as shown in Figure 3.

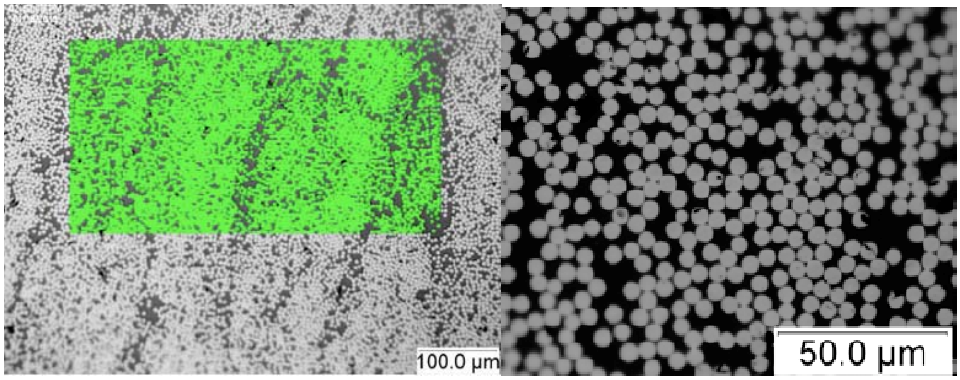

Figure 3. Carbon Fiber Distribution for IM7/8552 Prepreg Tape

There are clearly resin and fiber rich areas even though the mean fiber volume fraction is that specified by the manufacturer of 0.56. Figure 4 shows the resulting variability in volume fraction after a careful and thorough microscopic analysis varies from 0.3 to 0.8. This "uncertainty" in the fiber-volume fraction can be propagated through simulation models to determine the uncertainty in the failure location and stress or magnitude at the onset of damage as shown in Figure 5, where the experimental results are shown in black while the simulation results are in green. The results in Figure 6 show that the variability of the microstructure, in particular of the fiber-volume fraction, determines variability in failure location and load magnitude. As can be seen, the experimental and simulation results complement one another so that a smaller number of experimental results can be combined with analytical predictions of variability to achieve knowledge appropriate for certification. Other material defects, such as surface imperfections and debonded or broken fibers may be incorporated with a similar approach. Further, this framework can be used to establish variability in both performance and manufacturing results such as macro/micro geometry and resin cure variability, and clarify the origins of structural performance variability.

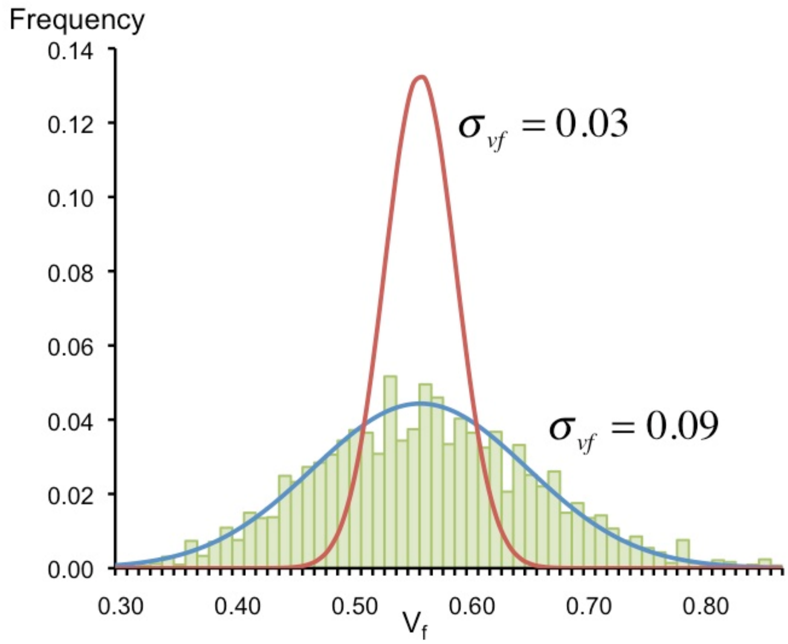

Figure 4. Carbon Fiber Volume Fraction Variation

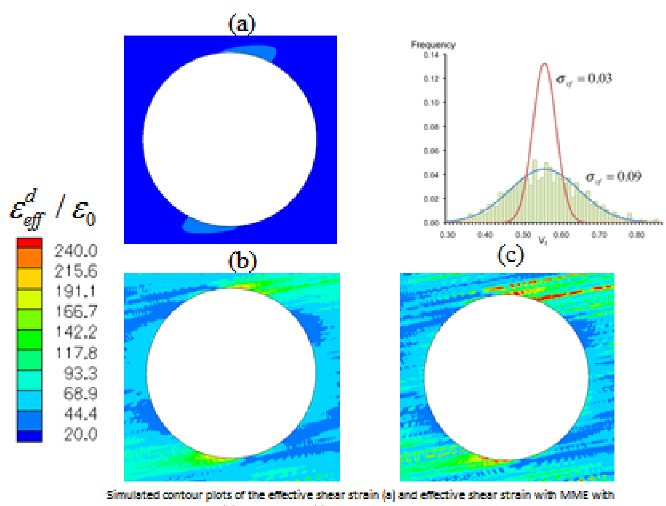

Figure 5. Simulated contour plots of the effective shear strain (a) and effective shear strain with MME with vf=0.56 and σ_{vf} = 0.03 (b) and σ_{vf} = 0.09 (c)

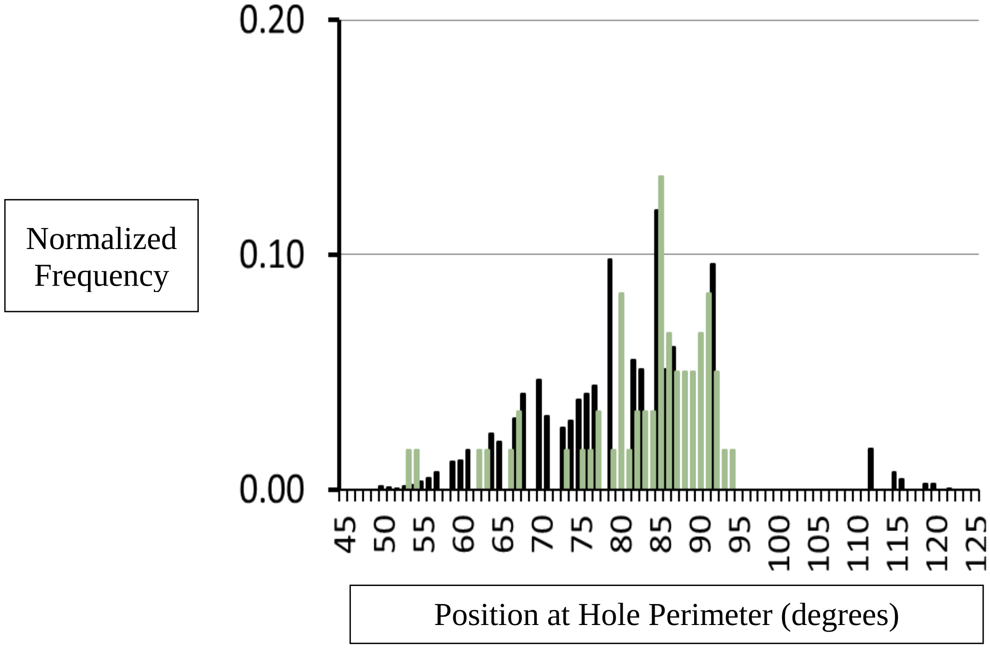

Figure 6. Combining Experimental Data and Simulation Predictions for Failure Location for Composite Materials and Structures Certification through Uncertainty Quantification

1.4 Composites Manufacturing HUB Characteristics and Functionality

The Composites Manufacturing HUB is a cloud-based cooperative platform that can host composites manufacturing simulation tools that may be accessed with a web browser from the Internet. The National Science Foundation provided the funding to develop the original nanoHUB concept at Purdue University. Figure 7 illustrates the extraordinary success of this new innovation in the delivery and discovery of knowledge in global communities. Today there are 20 types of HUB organizations using the same platform and software (HUBZero). To date nanoHUB boasts 10,000 users worldwide. It has over 350,000 simulations with over 210 engineering tools to simulate important nano phenomena important in nanoelectronics, materials science, thermal science, physics and chemistry. Over 2,500 content items such as tutorials seminars and full classes drive the overall community to over 175,000 users annually. The user community connects students at all levels, research professionals, faculty and industrial users. Tools range from molecular modeling and simulation to photonics.

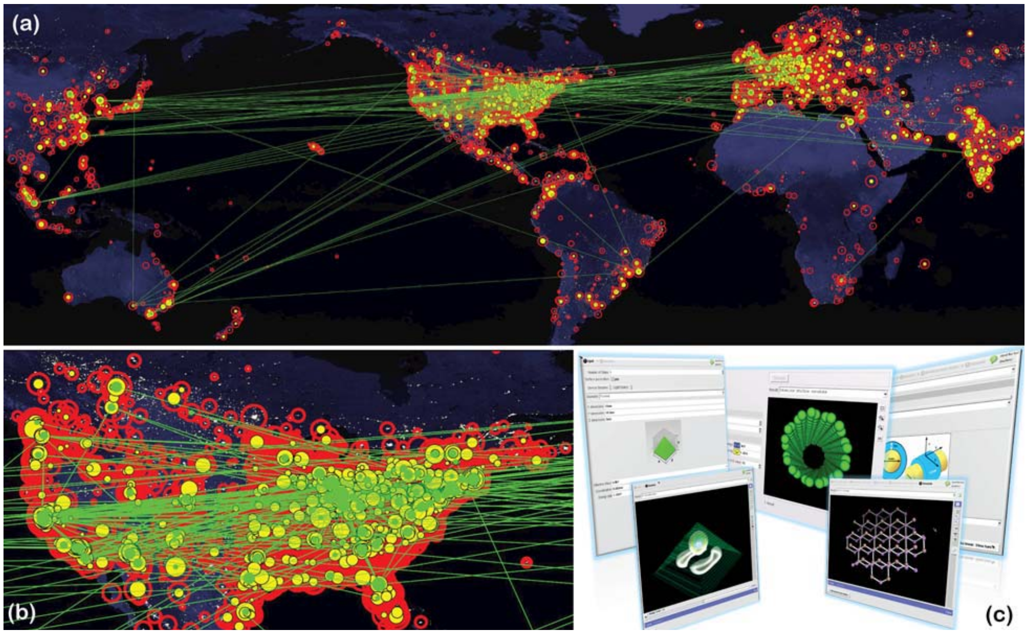

Figure 7. (a) nanoHUB user map in the year 2011 superposed on NASA's world at night. Red circles designate users viewing lectures, tutorials, or homework assignments. Yellow dots are users of simulation. Green dots indicate authors of over 720 scientific publications citing nanoHUB. Dot size corresponds to the number of users, and lines show author-to-author connections proving intense research collaboration networks. (b) U.S. enlarged. (c) collage of typical nanoHUB interactive tool sessions and 3D-rendered interactive explorable results (quantum dots, carbon nanotubes, nanowires)

The Composites Manufacturing HUB has adopted the HUBZero platform functionality, which allows users to access tools via web browser. Tools hosted on the Composites Manufacturing HUB can range from simple tools that require only small amounts to computational cycles and those that require the power super computing systems. The HUB provides access to the appropriate level of computing cycles for each tool and user problem. Further, the platform hosts learning tools that teach the underlying principles upon which the tool is based and demonstrate the correct use and limitations of the tool. Examples of tools include simple engineering mechanics formulations and models of heat and mass transfer essential to simulate composites manufacturing processes. Molecular modeling simulation and uncertainty quantification will inform all the manufacturing process simulations to provide guidance from first principles and to account for process variability.

The HUB can also provide a forum for evaluation of tool performance by the user community through hosted discussions and rating systems. The HUB community can post "Wish lists" on the HUB for discussion. Tool developers are rewarded for both tool use levels and the development of new tools through funding developed by the HUB. Tools developed and placed on the HUB are subjected to a financial analysis to determine their worth to the HUB and the developer is rewarded accordingly.

Specific composites manufacturing processes are the focus of the Composites Manufacturing HUB. While the choice of manufacturing processes is initially limited by the tools currently available, the number of process simulations will be expanded by new tool development during the program. Indeed, it is likely that the available tools on the HUB will be continuously changing as tools are invented, developed and matured. Over time mature tools will likely be migrated to commercial support enterprises. As such, the HUB embraces technology readiness levels (TRL) of TRL 2 through TRL 6 and fosters rapid deployment of manufacturing processes poised for commercialization.

The HUB simultaneously embraces technology readiness levels of TRL 2 through TRL 6. At the TRL 6 level, existing simulation software is provided to the user community with the goal of educating the user community in tool use and establishing gaps in functionality required for complex composites manufacturing process simulations. The TRL 2 level work is the research necessary to address the scientific foundation of the simulation tools identified to fill the missing gaps. In this way, the Composites Manufacturing HUB provides a “food chain” for development of the comprehensive portfolio of manufacturing simulation tools needed to meet the expanding need for composites manufacturing simulation.

This technical approach, of hosting existing simulation tools, exposing them to a relevant user community, and supporting the development of new/better tools, is based on solid experience in both the hosting and development elements of the project. Approximately half the effort supports the Composites Manufacturing HUB infrastructure to provide access of tools to the user community, while support for research and development of new simulation tools is the second major goal of the CM HUB.

2. Hub Operating Principles

The Composites Manufacturing Hub provides all the functionality of the nanoHub.org and more. The Hub user community promotes broad-based innovation across all sectors of composites manufacturing. An organization or person, who develops an idea for manufacturing of composite structure, accesses the simulation tools and data to evaluate the concepts through a virtual design and manufacturing process. The economics of the manufactured products can be evaluated and numerous scenarios studied to achieve near optimum conditions prior to development of the actual prototype system. This avoids the expensive trial and error approach now so prevalent in much of manufacturing, and it would allow a much larger design space to be explored by the user.

The Hub is a clearinghouse for tools developed for composites design and manufacturing. The simulation tools are hosted on the Hub with all its allied support mechanisms. In the development stage, corporate sponsors jointly support the Hub in order to view the tools as they are developed and to assess their relative benefits and characteristics. A tool builder places the tool on the Hub, supports its use and retains ownership. The ultimate goal is to host all the composites manufacturing simulation tools (in the world) currently available. Commercial simulation organizations can use the HUB to expose their products to the user community and to provide education in tool use. Hub tool evaluations allow users to judge the relative strengths and weaknesses of the tools in their applications. Access to tools is governed by a use policy wherein the small user is subsidized. The users would provide ongoing support of the Hub in use fees. Much of the nanoHub sociology is adopted for the Composites Manufacturing Hub, so that there can be a composites skunk works in every manufacturing organization!

2.1 Manufacturing Design Examples

Two examples will serve to illustrate the power of these composites manufacturing simulation tools. In the first case, it is desired to determine the final shape of a component fabricated of carbon fiber/epoxy unidirectional prepreg tape. In this case a simple angle structural element is desired, but the well-known "shrinkage deformation" phenomenon resulting from thermal and chemical shrinkage of the epoxy during cure can produce a final geometry after cure significantly different from the designed shape. The first step in the process is to design the geometry of the structural element including the laminate lay-up that is optimum to meet the geometric constraints of the desired element. Use of software modeling provides the necessary functionality. Next a finite-element analysis (FEA) of the structural element is carried out to ensure that stiffness and strength performance requirements are satisfied. This process involves creation of a FEA model using a software program. When the geometry of the structural element involves curvilinear surfaces, the conformation of the unidirectional prepreg tape to the tool surface is determined form a simulation tool. In other cases such as textile preforms and prepreg, the transformation of the planar sheet material to the curvilinear geometry requires that an analysis of the sheet forming process be carried out with simulation tools. In order to determine the contribution of chemical and thermal shrinkage on final shape and to specify the appropriate cure cycle for the specific polymer system, an analysis of the curing kinetics and resulting shrinkage is required. The output of this analysis can then be fed into the original FEA tool in order to determine the final part geometry after cure. By iterating the process, it is possible to choose an initial tool geometry that will yield the desired structural part geometry after the thermal and chemical shrinkage have occurred. This process is summarized in Figure 8.

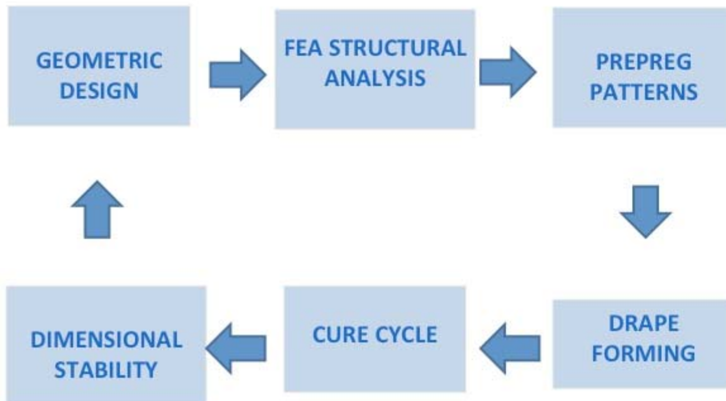

Figure 8. Carbon Fiber Prepreg Manufacturing Simulation

The second example is for the molding of discontinuous fiber composite materials where the flow of the polymer and fiber during molding determine the *in situ* fiber orientation geometry and thereby the performance characteristics of the molded part. The complex interaction between mold geometry and flow pattern within the mold act on the fiber ensemble as it enters the injection mold or as the compression mold closes around the preform. Flow of the system is influenced by the local temperature and viscosity of the system, as well as, the character and extent of the deformation. For example, shearing deformation very near the mold surfaces tends to align fibers in the flow direction, as does converging flows. It is not uncommon for fibers to be highly aligned near mold surfaces while interior regions exhibit more nearly random states of orientation. The Simulation of molding with discontinuous fiber/polymers is illustrated in Figure 9.

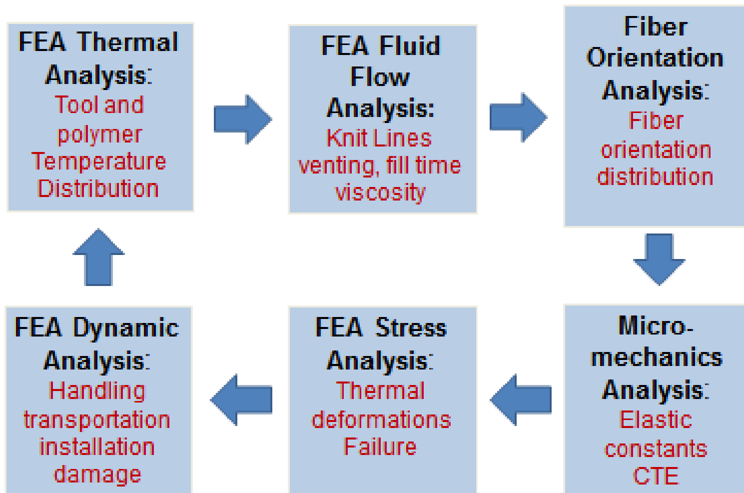

Figure 9. Composites Molding Simulation

The first step in this analysis is to determine the temperature of the mold and composite during the molding process. This is accomplished with a thermal analysis of the tool in order to establish the conditions for the flow analysis carried out in the second step. In the third step the kinematics of fiber orientation is modeled so that the final state of fiber orientation can be determined at each material point within the molded part. Simulation tools provide the FEA computational capability to carry out each of the first three analyses. Given that the effective thermo-mechanical properties of the composite material are uniquely determined by the volume fractions of its constituents and the local fiber orientation distribution, a micromechanical analysis is necessary to predict the local properties of the material. Here it should be noted that the concept of a material with uniform material properties throughout the part is never achieved in molded products. Rather, each molded part consists of a family of material microstructures and resulting thermo-mechanical properties. These properties must then be reflected in the solid FEA model constructed in the next step. Micromechanical analyses of the material in the region of each element provide the input element properties for the FEA simulation. The solid FEA analyses provides the deformed geometry of the molded part that is often quite different from the mold shape due to the anisotropy of the coefficients of thermal expansion of the composite. The same FEA analysis is then utilized to predict the performance of the molded part to the service-loading environment for which it was designed.

These two examples show how manufacturing simulation is essential for rapid design, development and certification of composite materials and structures. With a robust array of simulation tools, the heuristic character of manufacturing of composites can be transformed into and engineering and science-based process where significant economy can be realized.

3. Summary

In summary, the Composites Manufacturing HUB offers the potential to significantly accelerate the development and lower the cost of composites manufacturing and certification by making simulation tools available through the browser of a personal computer. Further, it provides a platform for the integration of simulation tools so that the complete manufacturing process can be modeled to yield trade study functionality that should significantly reduce the cost of developing manufacturing methods to meet specific needs. In addition, the hosting of simulation tools on the HUB provides opportunities to assess performance and become familiar with commercial and emerging tools as they evolve. In this manner, the HUB is a vehicle to determine unmet simulation tool needs and to become a platform for evaluation of new tools as they are developed. Finally, the HUB assists tool developers in the integration and connection of tools to provide broader functionality and applications.

The examples discussed show how design and manufacturing simulation can provide for rapid and robust design and manufacture of composite materials and structures. With a broad array of simulation tools augmented by the science of UQ, the heuristic character of the manufacturing and certification of composites and the "test only" approach can be transformed into an engineering and science-based process where significant economy can be realized. The economic benefits of rapid certification of composite materials and process technologies provide the incentive for the initiation of an innovative and comprehensive industry, government and academia partnership to establish this new paradigm. This vital step forward is essential if our industry is to continue to pave the way for new developments in the field of composites as well as meeting society's rapidly growing demand for high-performance materials. The time is now for the industry and profession to join hands and take the steps to create this new paradigm.

4. References

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