

OBJECT-ORIENTED IMPLEMENTATION OF AN INTEGRATED DESIGN AND ANALYSIS TOOL FOR FIBER PLACED STRUCTURES

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Abstract

With the expanding use of fiber placement technology to control fiber orientations in composite parts, a need exists for an integrated system allowing concurrent design, modeling and analysis. Currently, the capability of designing fiber placed parts resides with the offline programming systems of the fiber placement machines themselves. This design capability exists independently of modeling and analysis capabilities. This paper presents the design and implementation of an integrated design and analysis system for use in preliminary through detailed design phases of a fiber placed structure. The described system is unique in that it controls the design of tows rather than plies, and as such enables an evaluation of manufacturability during preliminary design. Implementation includes the development of self-positioning tow representations, simulating the manufactured part, using specified fiber angle control methods; validation of these representations; integration of self-positioning tow representations with a pre-existing analysis tool; and integration with finite element analysis tools accepting the NASTRAN file format. This system allows for the generation and evaluation of multiple solutions in the preliminary design phase without the use of proprietary machine programming systems.

Introduction

Developmental efforts in composites technology include a wide variety of primary and secondary structures in industries ranging from sporting goods to civil structures to high performance aircraft. In addition to potentially significant weight savings, composites offer the benefits of increased fatigue life, corrosion resistance, and life cycle cost savings.

Improved design tools are critical, because current capabilities of existing fiber placement hardware far

exceed the capabilities of design engineering tools, particularly with respect to the ability to fabricate structures with controlled curvilinear fiber paths. Steered fiber architecture has the potential to offer significant weight savings by improving tailoring of local fiber orientation to the specific internal load path of the structure. However, the lack of robust analytical tools and design environments capable of modeling the complexity of steered fibers in the preliminary design phase are prohibiting optimal design solutions. The goal of work presented in this paper is to develop a system capable of modeling and analyzing traditional linear or optimized curvilinear design solutions in the preliminary design phase, and to mature these in a common environment through detailed design. Systems similar to that addressed in this paper have been developed for cloth-layup composite manufacturing^{1,2,3} and for as-woven textile composites^{4,5}. When deployed in industry, one such system has demonstrated 60% or greater cost and cycle time reduction on multiple production and prototype development programs⁶.

This paper addresses a tool currently in development at the University of Kansas. The Steered Composite Analysis and Design System (SCADS) represents an integrated design for manufacturing/fiber steering system for the fiber placement process. Preliminary through detailed design simulation is enabled by producing theoretical paths of individual tows for a set of user-defined manufacturing criteria, to include input tool geometry, tow material and desired path parameters. This detailed tow information historically has resided with the manufacturer of the fiber placement hardware, and thus is not available throughout the design phase. As such, fiber placed components are generally designed as hand lay-up components, preventing a consideration of curvilinear fiber reinforcement and neglecting the requirements of the actual manufacturing process. SCADS allows visualization of actual tow geometry, to include quantifiable computational assessments of common geometric flaws such as tow gaps and overlaps. In addition, SCADS is capable of extracting actual fiber orientations within each layer of a composite structure at discrete locations, providing true local laminate definition for detailed analysis. Additional analytical tool development includes solution methods for

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materials with continuously varying mechanical properties, to enable optimal curvilinear fiber paths.

Knowledge Representation by Objects

The fiber placement manufacturing process discussed in this paper can be represented by decreasing levels of abstraction. At the highest level is the part itself. The part is a collection of plies. A ply of a fiber placed part is a collection of courses (one or more parallel tows placed by the machine head in a single pass), which are themselves collections of individual tows. The tows are technically a collection of individual fibers, but since the tow is the lowest level of abstraction required for the manufacturing technique, this is the lowest level of physical abstraction considered within design and analysis.

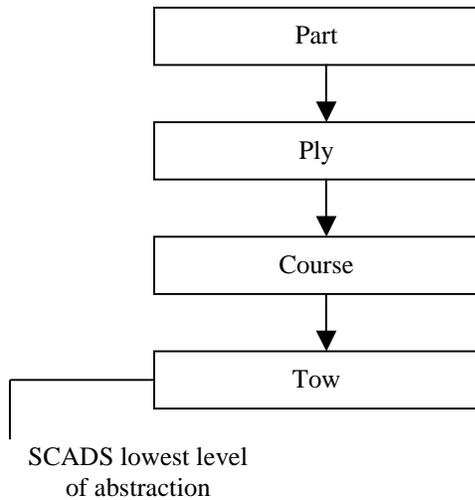


Figure 1. Levels of Abstraction in SCADS

Relationships of the type shown in Figure 1 represent knowledge of the structure of the composite part. This type of structured knowledge of a physical object or system is captured by the IS-A and HAS-A relationships. The IS-A relationship describes inheritance (e.g. a horse is a mammal), while the HAS-A relationship describes structure (e.g. a horse has a tail). Knowledge of this type can be represented by a semantic network⁷. A semantic network is a directed graph representing relationships between objects (Figure 2).

An extension of the semantic network concept is the ‘object’ of the object-oriented paradigm. Object-oriented knowledge representation lends itself to problem domains representing knowledge where reasoning is based on structure and inheritance⁸. Where the semantic network represents relationships, object

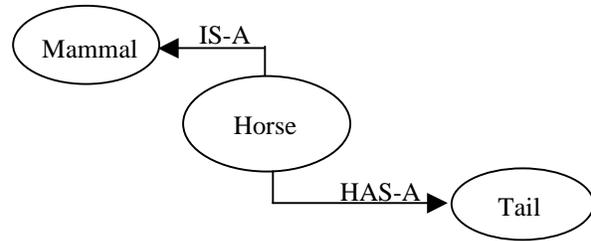


Figure 2. IS-A Represents Inheritance while HAS-A Represents Structure

oriented knowledge representation adds the following features:

- Abstraction: Only the relationships that are relevant to the problem domain need be represented.
- Encapsulation: The object acts as a ‘black box’. The object has a clearly defined interface for its use, while implementation details are hidden.
- Inheritance: For the IS-A relationships, all attributes and methods (functions) of an ancestor are automatically implemented for a descendant. Attributes and methods written expressly for a descendant override those inherited from the ancestor.
- Polymorphism: Abstractly similar methods with differing implementations (e.g. fixed wings and rotary wings both generate lift), can be given the same name. The correct method will be executed based on its context (e.g. airplane or helicopter).

Object oriented knowledge representation used in the SCADS package is implemented in the Adaptive Modeling Language (AML) development environment⁹. The AML environment implements an object-oriented knowledge framework that includes a powerful geometry engine to represent physical objects. As an object-oriented language, AML emphasizes decomposing engineering problems into classified objects. It strongly supports the most powerful feature of object-oriented modeling: the ability to construct a class hierarchy in which complex classes inherit properties from simpler classes. This is the same mechanism that powers human understanding: the ability to make abstractions and then build upon them to create more complex concepts. In addition, AML implements the feature of dependencies between objects. The developer is able to define any object, subobject or object attribute in terms of another object, subobject or attribute. The AML environment establishes a corresponding network that automatically enforces the propagation of changes throughout the network.

AML was chosen because it is a mature, commercially available architecture that already contains many of the objects necessary for developing integrated structural design, analysis and manufacturing tools (e.g. geometric solid modeling, mesh generation, machining analysis, manufacturing process planning, etc.). Another powerful feature of AML is that it automatically builds and manages networks of dependencies between objects, and supports "demand-driven" computation. If, for example, the dimensions of a wing spar are dependent on the particular aerodynamic shape of the wing and the selected substructure arrangement, they will become undefined ("smashed") if the wing geometry changes. They would then be re-computed only when they are referenced ("demanded") by another object (for example, if stress data depended on output of finite element analyses (FEA) of a model of the wing).

Because AML is tailored specifically for engineering modeling, it contains robust class libraries of engineering objects. This includes classes for geometric modeling, geometry discretization (meshing), and Finite Element Analysis. AML applications can therefore build upon these fundamental elements, add new ones to model other physical phenomena, and address complex tasks of analysis and simulation. The knowledge of structure, inheritance and interdependencies of fiber placed composite parts are implemented in an object-oriented manner in the SCADS design package.

Software Design

The Steered Composite Analysis and Design System (SCADS) represents an integrated design for manufacturing/fiber steering system for the fiber placement process. Preliminary through detailed design simulation is enabled by producing theoretical paths of individual tows for a set of user-defined manufacturing criteria, to include input tool geometry, tow material and desired path parameters. This detailed information historically has resided with the manufacturer of the fiber placement hardware, and thus is not available throughout the design phase.

Development of SCADS has focused on two areas. The first is the development of software components that simulate the positioning of tow path curves in a fiber placed part based on specific fiber angle control methods⁶. Simulation of tow placement consists of defining curves that, in turn, define the position of tows. Required parameters include user defined tool surface and fiber orientation parameters. The development has utilized object-oriented knowledge representation implemented via the object oriented and knowledge based language and development environment,

Adaptive Modeling Language (AML). Object classes for three fiber angle control methods are implemented and are presented in this paper.

A second focus of SCADS development is the integration of self positioning tow paths with existing Fiber Placement Analysis software. Previously developed Fiber Placement Analysis (FPA) software⁸ has the capability of analyzing properties, to the tow level, of a fiber-placed part. Analysis capabilities include area analyses, orientation and radius of curvature analyses, quantification of drops, adds, gaps and overlaps, and automated geometric analyses at points defined by finite element meshes. The previously developed FPA software requires an input file of tow definitions, and thus is useful only as a parallel tool to be used with machine programming tools provided by the fiber placement machine manufacturer. Integration of self positioning tow curve objects now allows the integrated software to act as a stand-alone design and analysis package

Object Structure of Self Positioning Tows

As described in the Knowledge Representation Section, SCADS utilizes an object-oriented paradigm to represent knowledge of the fiber placed part. The object relationship structure of Figure 1 is repeated here with the added objects of tow-curve and points which are purely geometric abstractions used to represent the position of the physical tow (see Figure 3).

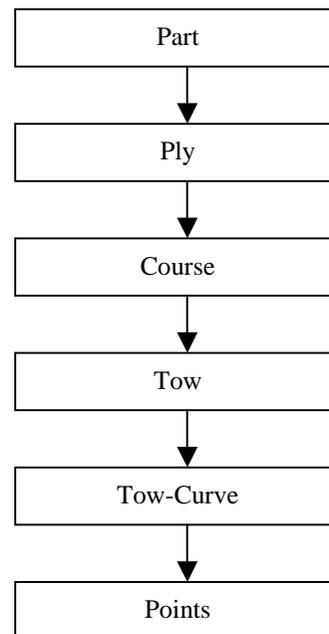


Figure 3 Levels of Abstraction Represent the Structure of a Fiber Placed Part

The inheritance structures shown in Figure 4 depict parent classes to the left of child classes. The data structure and methods of the parent class are automatically implemented in its child classes. Any method inherited from a parent class may be overridden by redefining the method for the child class. Polymorphism allows the system to choose, based on class, the correct implementation of a method. Therefore, different fiber orientation control methods are implemented by defining new classes. By inheriting from a parent class and redefining commonly named tow generation methods, a fiber orientation control method can be implemented completely independent of previously implemented methods.

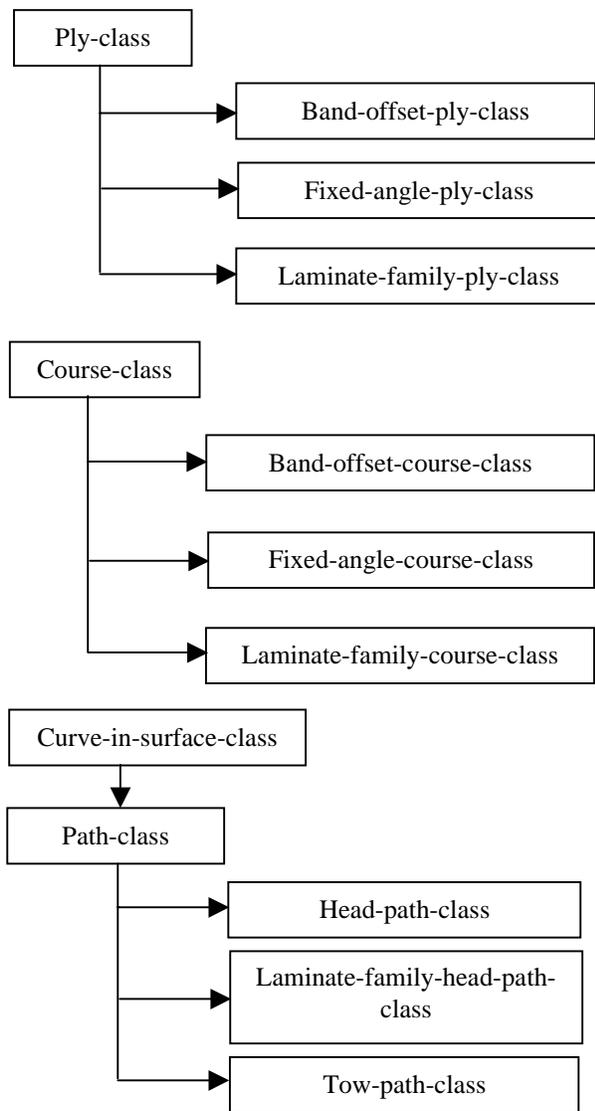


Figure 4 Class Inheritance at Ply, Course and Tow Levels

Figure 4 shows that the following fiber orientation methods have been implemented:

Band Offset: an initial fiber path is specified. This fiber-path serves as a path for the initial course. Subsequent courses are generated such that no gaps or overlaps occur between courses. On a curved surface, significant variation from the initial fiber path can occur as courses are positioned farther from the initial fiber path.

Laminate Family: given a guiding ply (0° ply) to which to map, course paths are generated such that the angle between the course path and the closest tow in the map-to-ply is a constant. This method is used to generate laminate family plies (e.g. 45° ply, 90° ply, etc).

Fixed Angle: an initial fiber angle (vector) is specified. Course paths are generated such that, at any point on the course path, a plane can be defined at that point by the vector normal to the placement surface, and the fiber angle vector. The next point on the course path is found on the intersection of that plane and the placement surface.

Self positioning tow classes and their inheritance structure, described above, are designed so that they can be inherited into other class definitions, adding self positioning capabilities to those other classes. Development of the Fiber Placement Analysis (FPA) software, mentioned previously, also utilized an object oriented knowledge representation. A drawback of previously developed FPA software is its requirement of an input file describing the tow-by-tow structure of a fiber-placed-part. By integrating self positioning tow classes, the FPA software becomes an integrated design and analysis package.

Because both systems are object oriented, the self-positioning classes described here can be directly inherited into the FPA classes, which have already implemented analysis methods. Other than an inheritance statement, very few changes are required in the FPA software classes. In addition to inheriting self positioning classes, additions to the FPA software are required to differentiate fiber angle control methods. Also, user interface components are added to the software to support design.

Software Implementation

Ply Design Process

This section presents screen shots and descriptions of the process of designing two plies of a fiber placed part: one is a band offset ply, and the other is a laminate

family ply mapped to the band offset ply. The part is a simple panel with the primary fiber path combining an arc portion and two straight line portions extending both sides of the arc (Figure 5).

Figure 5 shows the mandrel surface, ply boundary and fiber axis definition for the flat panel part. The outer closed boundary represents the boundary of the mandrel surface. The inner closed boundary represents the ply boundary. Tows will not be placed outside of the boundary. The single, non-closed curve represents the fiber axis. All tows in the band offset ply will be created parallel to the fiber axis curve.

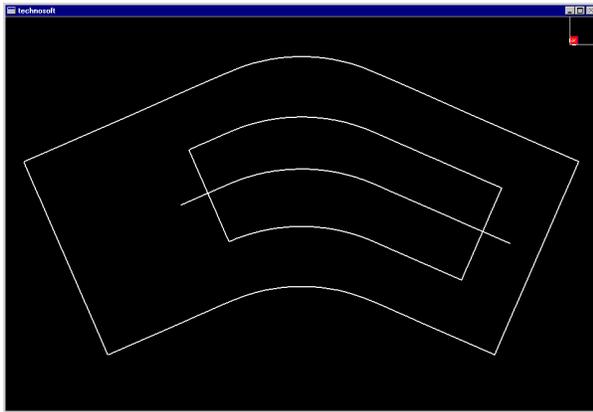


Figure 5 Mandrel Surface, Ply Boundary and Fiber-Axis are Initially Defined

After specifying the required input for a band offset ply, the system generates tows and courses such that the ply boundary is completely covered by tows (see Figure 6). Figure 6 shows the band offset ply before tows are trimmed to the ply boundary. Individual courses are colored and can be seen as the 11 bands in Figure 6. Each course consists of 12 tow paths. Individual tow paths are not clearly visible in the figure.

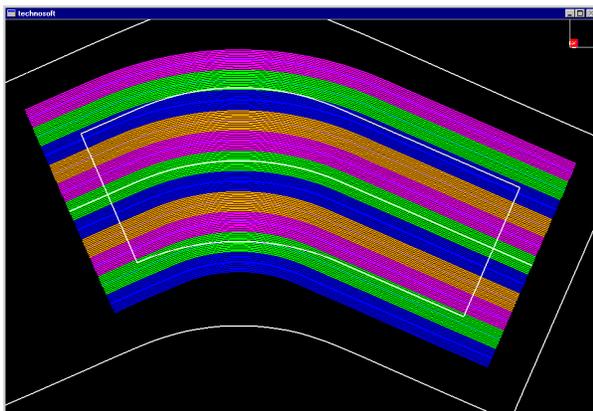


Figure 6 Initial Ply Generation Creates Enough Courses to Completely Cover Ply Boundary

After the initial generation of courses, which completely cover the ply boundary, the system divides

each tow path into segments lying inside (undropped) or outside (dropped) of the boundary. This is called trimming and corresponds to the fiber placement machine's ability to drop and add individual tows in a course. Figure 7 shows courses remaining inside the ply boundary after trimming. It can be seen in Figure 6 that two courses lie completely outside of the ply boundary. These courses are completely trimmed away and ignored by any operations involving undropped tows.

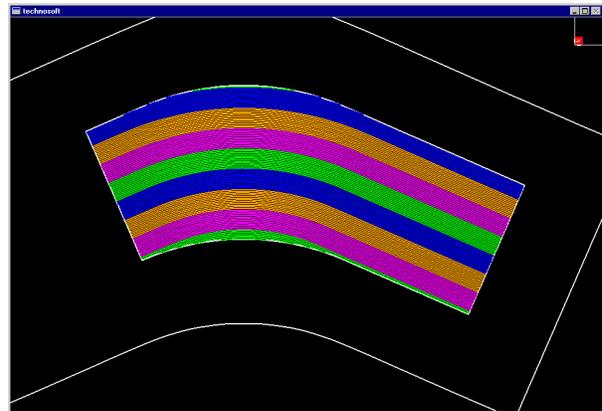


Figure 7 Tow Paths are Trimmed (only undropped segments are shown here)

Figure 7 shows the band offset ply after trimming of tows to the ply boundary. The differently shaded bands in Figure 7 represent individual courses in the ply. Figure 8 shows a zoomed view of the detail of the lower left corner of the band offset ply. In Figure 8, individual tow paths can be discerned. The curves shown in Figure 8 represent the centerline of each tow, from which a surface or solid (given a tow cross section) can be constructed and displayed by the design program.

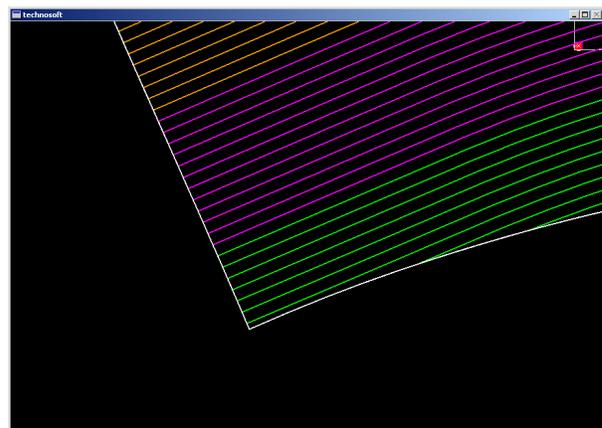


Figure 8 Magnified View of Band Offset Ply Showing Individual Tow Path Representations

After a band offset ply has been generated, a laminate family ply, mapped to the band offset ply, can be

generated. The laminate-family ply is created by mapping course paths to the band offset ply (the map-to-ply) of Figure 7. Each course path is generated such that the angle of intersection with every tow in the map-to-ply is constant, in this case 45° . Figure 9 shows the laminate family ply created so that courses completely cover the ply boundary. The tows are not trimmed to the ply boundary, and courses converge onto one another as they are steered towards the center of curvature of the map-to-ply. This convergence of the courses requires that tows be dropped to avoid additional material thickness.

The differently shaded bands of Figure 9 represent individual courses in the laminate family ply. It can be seen that the courses converge upon one another as they are mapped toward the center of curvature of the band offset ply. Figure 10 shows a zoomed in view of the converging courses, where it can be seen that individual tows from neighboring courses are overlapping.

Finally, the full tow paths of Figures 9 and 10 are trimmed to the surface boundary, and tows are dropped as the courses converge.

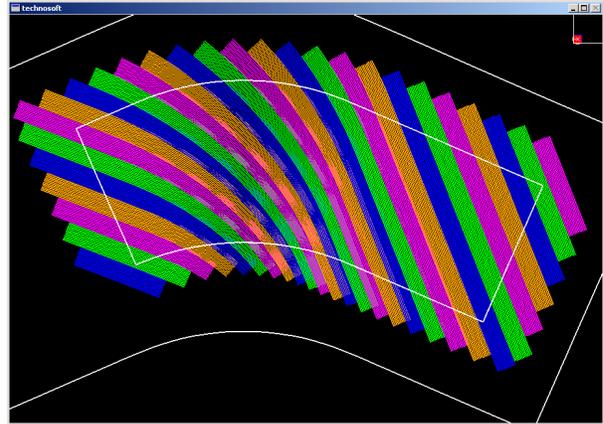


Figure 9 Laminate Family Ply Generation with Full Paths

Figure 11 shows the tow paths of Figure 10 after trimming of tow paths to the ply boundary and to overlapping courses.

The differently shaded bands of Figure 11 represent individual courses. It can be seen that the courses have been trimmed to the ply boundary. As courses converge towards one another, tows are trimmed

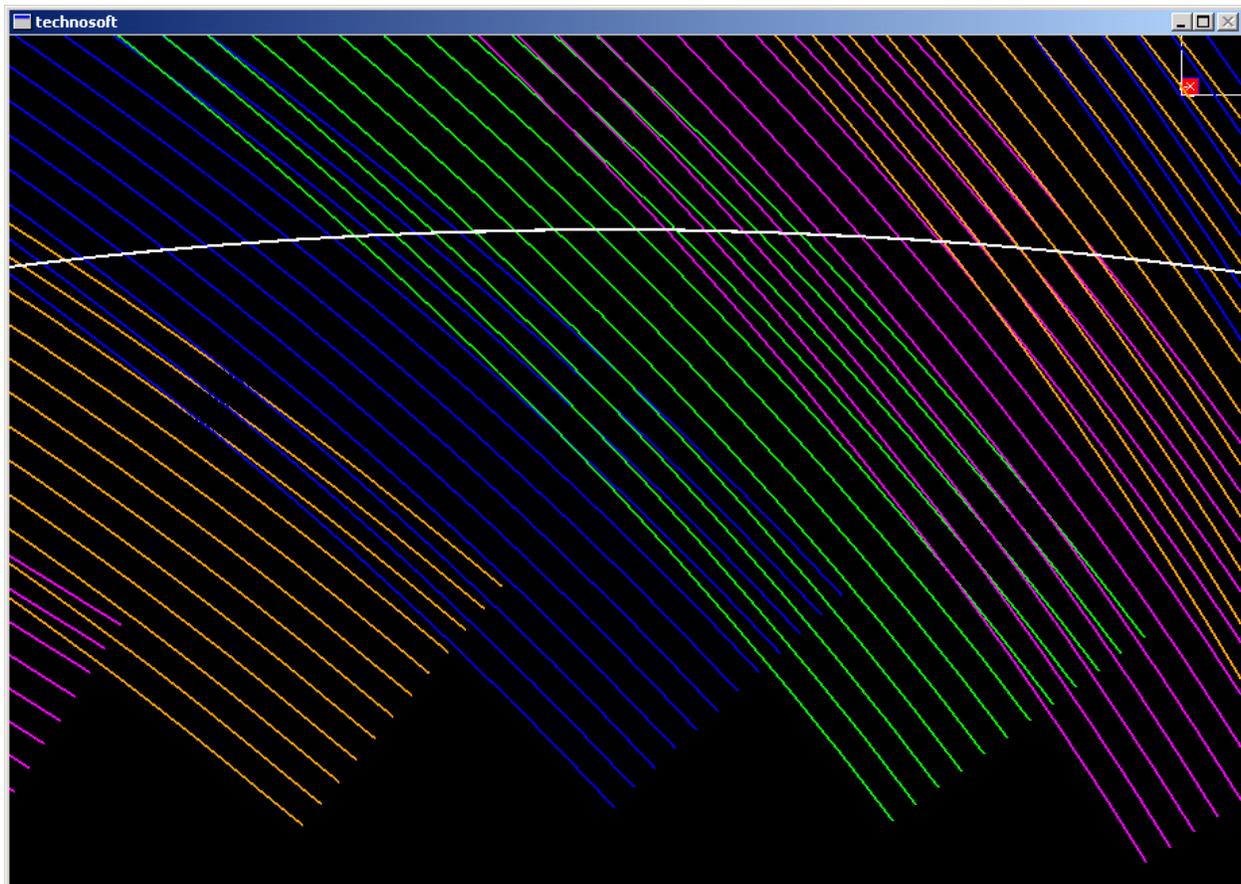


Figure 10 Magnified View of Laminate Family Ply Showing Tow Overlaps

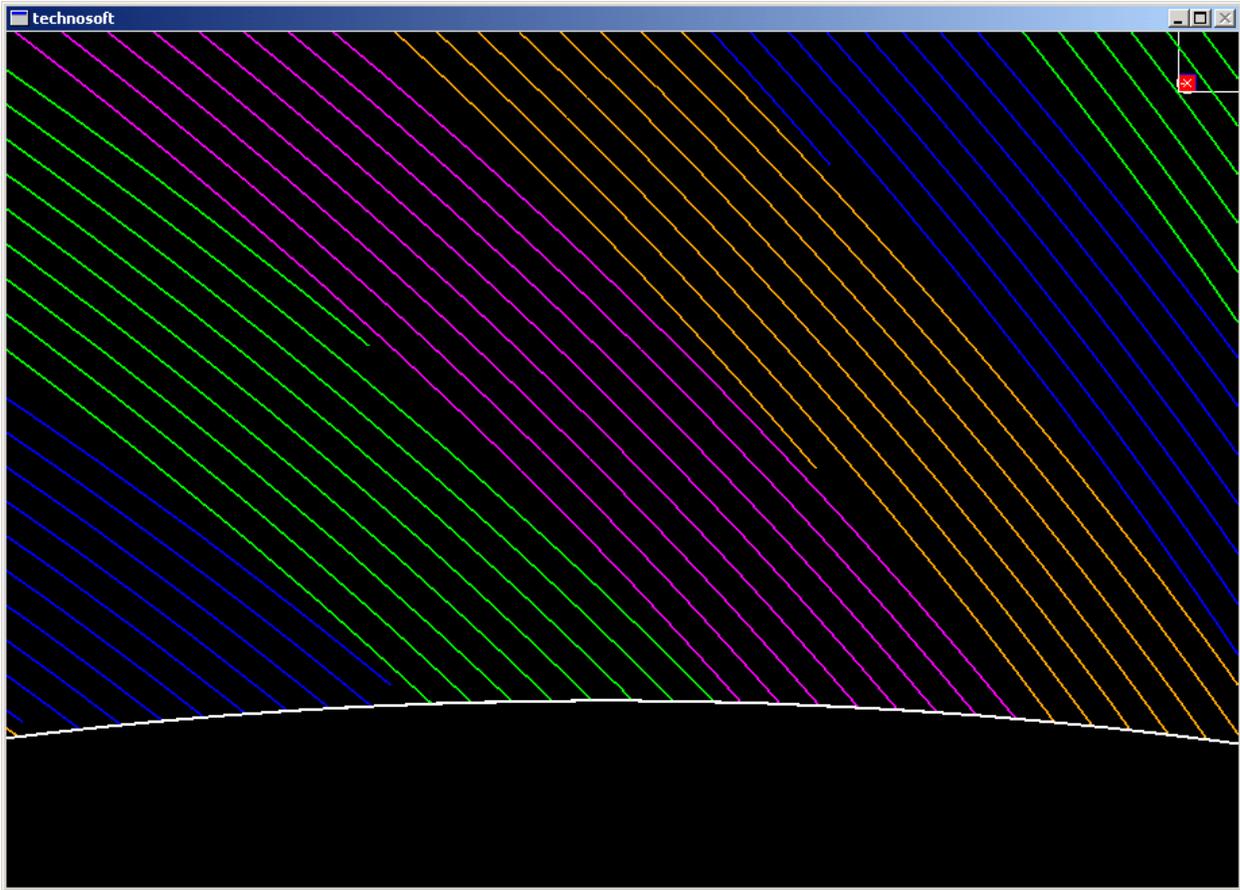


Figure 11 Magnified View of Laminate Family Ply After Trimming of Tows

(dropped) from alternating courses. The amount of overlap that can occur before a tow is dropped is specified by the user. In Figure 11, overlap of 50% is specified. In this case, when the distance between two tow paths becomes less than one half of one tow width, one of the tows is dropped. If less than 100% overlap is specified, gaps in tow material develop from the point where a tow is dropped until the overlapping tow completely takes its place. The specification of allowed overlap results in a controllable ratio of overlap to gap regions. Figure 11 shows a depiction of tow overlaps with the 50% overlap specification, resulting in equal overlap and gap areas.

Figure 12 shows detail of tows in a laminate family ply after tow trimming has taken place. The step boundary occurs when a tow is dropped. The figure shows that a tow is dropped when it overlaps a neighboring tow by 50%. Gaps in tow material are represented by black shaded regions in Figure 12, and result from the point of tow drop until the next tow meets the neighboring course. Note also that the full tow outline is displayed, as opposed to the tow path (centerline) of previous figures. Such display parameters for level of

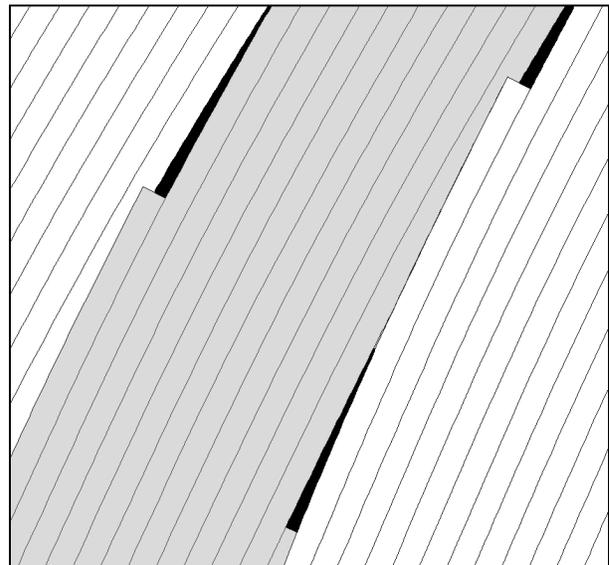


Figure 12 View of Overlap and Gap Regions (gap regions are shaded black)

visualization abstraction and features such as color or shading may be specified by the user.

Figures 5-12 show the design sequence for a band offset ply and a laminate family ply mapped to the band offset ply. In the design of a fiber placed part, multiple plies would be specified in the same manner to create the desired stacking sequence for a thickness region.

After generation of the plies, the analysis tools of the software can be used. Analysis capabilities include area analyses, orientation and radius of curvature analyses, quantification of drops, adds, gaps and overlaps, and automated geometric analyses at points defined by finite element meshes.

Analysis Capabilities

Figure 13 shows an example of gap, overlap, and ply-level analyses in the FPA software. Gaps and overlaps in three plies of a fiber placed part are depicted visually on the left of Figure 13. In the system, gaps and overlaps are differentiated by color, gaps are white and overlaps are yellow in Figure 13. The two dialog boxes at the center of the figure depict a query of gaps and overlaps in a 6 inch by 6 inch area of the part. The right side of the figure shows a dialog box depicting

area analyses of a 45° laminate family ply.

An additional analysis capability is implemented by finite element node and mesh generation and export to FEA analysis packages. Classes are implemented for simple parallelogram quad meshes. The previously implemented Fiber Placement Analysis (FPA) software¹⁰ implemented geometric queries at node points as specified by an input file. The FPA software required two input files- one of nodes, and one of the mesh (consisting of node identifiers for each mesh elements) generated by a finite element analysis package such as NASTRAN¹¹. The update to the FEA capabilities of the FPA software allows generation of nodes and meshes without input files. The self generating nodes and meshes are then used to generate finite element analysis (e.g. NASTRAN) files for coupon type elements located anywhere on the part (see Figure 14).

Currently, FEA files are generated according to MSC Software's NASTRAN file format¹¹. Files include sections denoting:

- layered composite element properties (PCOMP)
- material property definitions (MAT8)
- grid points (GRID)
- quadrilateral plate element connection (CQUAD4)

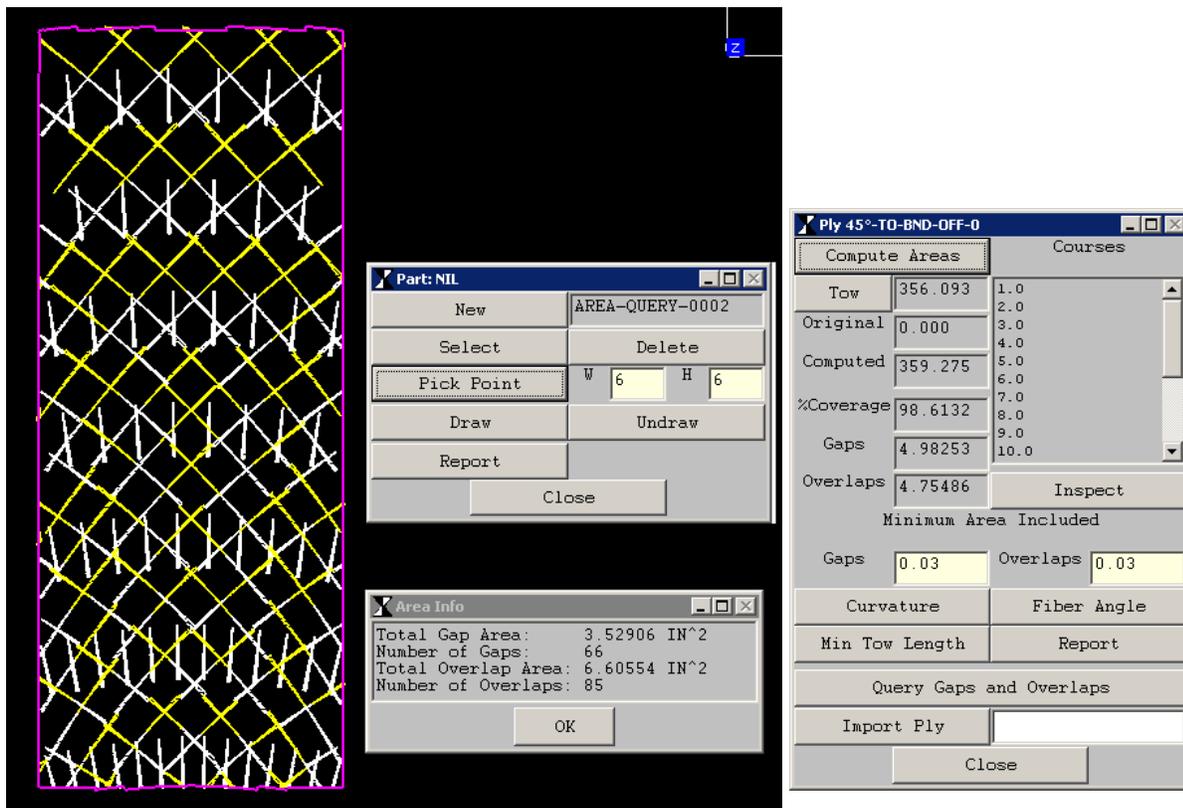


Figure 13 Analysis Examples (tow gap and overlap regions of three laminate family plies are shown)

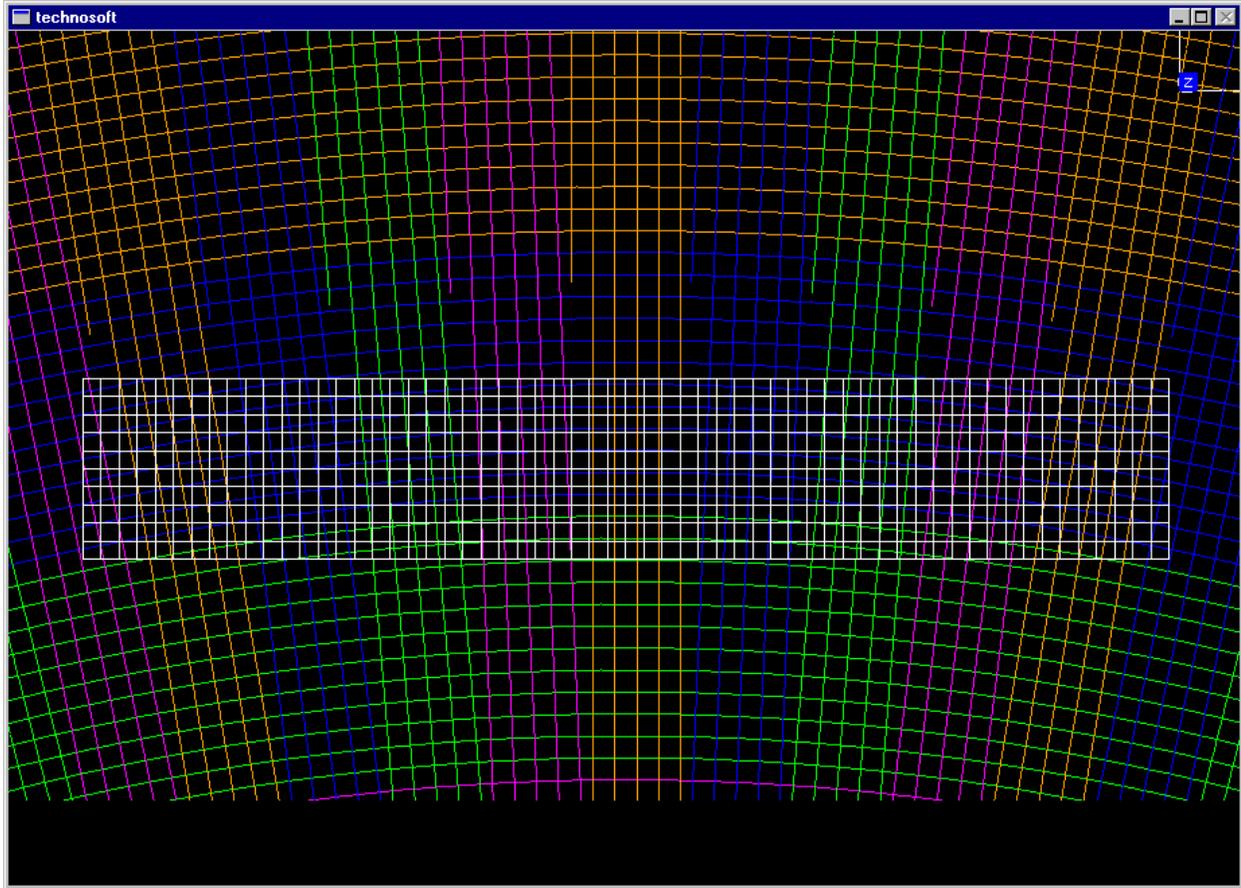


Figure 14 Finite Element Mesh (60 x 10 elements) of Test Coupon on Fiber Placed Part

Figure 15 (next page) shows a material orientation map for the coupon of Figure 14, as visualized by MSC Patran¹² using a NASTRAN file format created by the fiber placement design and analysis tool. The figure demonstrates integration of the fiber placement design and analysis tool with an existing FEA analysis package.

Figure 15 shows a material orientation map generated by MSC Patran using an FEA file generated by the fiber placement analysis and design package. The figure shows vectors in the 0°, 90°, 45° and -45° plies of a fiber placed part with steering of the 0° ply. The 90°, 45° and -45° plies are laminate family plies mapped to the 0° ply, and thus also exhibit steering. The individual layers and orientations within each layer are calculated within the fiber placement analysis tool and exported as layered composite element properties (PCOMP) entries in a NASTRAN compatible file.

Layered composite element properties (laminates) are calculated for every element. The current implementation calculates the geometric average of the node points making up an element (a calculation for element center), and then ‘drills’ through the part at that point,

recording all courses that are intersected. If two courses of a common ply are intersected, an overlap is registered for that ply. If no courses are intersected for a given ply, a gap is registered. Fiber orientation parameters are calculated for each ply when drilling at the element center intersects one or more courses in that ply. When a course is intersected, the tangent direction and thickness of the closest tow to the intersection point is recorded and added to the laminate at that element.

Another method of calculating laminate properties for mesh elements was implemented in the FPA software for imported FEA meshes. The FPA method performs a drilling operation at each node in the mesh. For every element in the mesh, the laminate properties are taken from a representative node being one of the nodes making up the element. This method can introduce errors in local fiber angle as the element material properties represent those at on extreme corner of the element.

Alternate methods of calculating laminate properties at an element are planned. Two alternate methods are described here. One method will again drill at every node in a mesh, but instead of choosing a representative

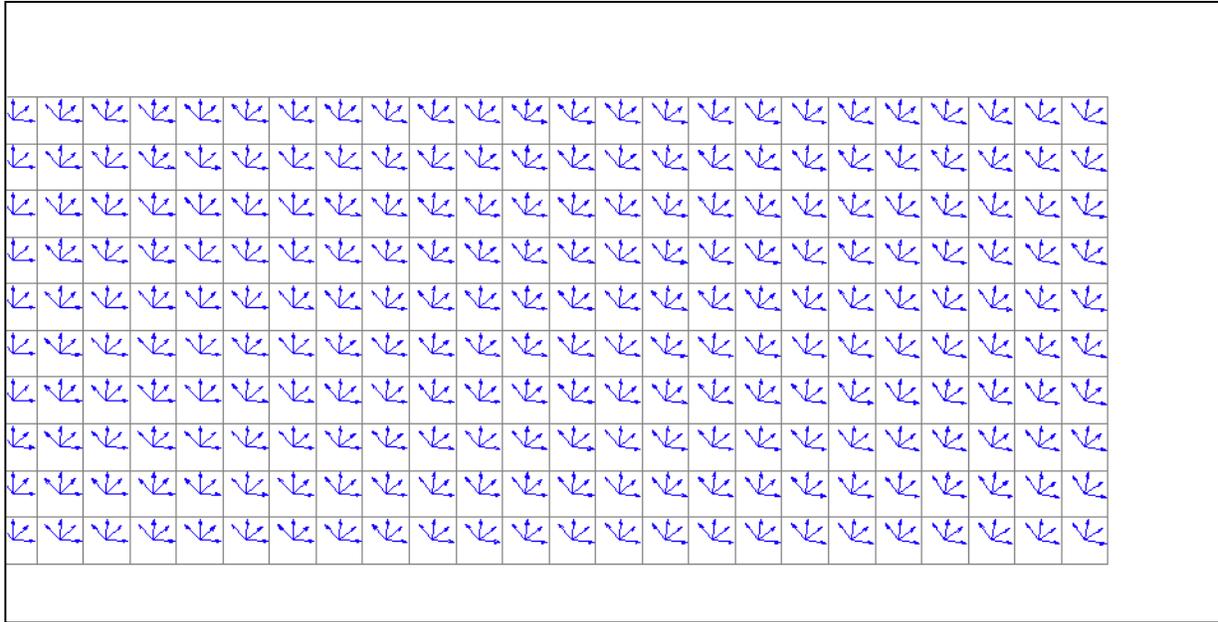


Figure 15 Material Orientation Map Shows Fiber Orientations, at individual elements, for 0°, 90°, 45° and – 45° plies (note fiber steering from left to right)

node, every node in the element will be used to calculate an average laminate. A second method will drill at multiple points within an element and average the laminate results.

As mentioned above, the self generating FEA nodes and meshes allow the integration of the fiber placement design system with standard finite element analysis packages. A generated mesh such as the one shown in Figure 14 can be used to simulate mechanical test coupons which, in turn, can be used for analytic trade studies. Currently planned studies will analyze the sensitivity of coupon strength to:

- misalignment of coupon centerline
- misalignment of coupon orientation angle with respect to fiber axis
- misalignment of coupon radial position
- variations in course (tow waviness)
- asymmetries

Summary - Expected Use and Benefits

INDUSTRIAL - Industrial use and benefits of the SCADS tool and process are apparent. A similar system, developed for hand layup composite manufacturing, is the Parametric Composite Knowledge System, PACKS¹. PACKS has demonstrated the ability to provide design consistency and boasts embedded knowledge capturing the proven processes of a company well-known for manufacturing high performance composite structures¹³. These processes will be effective for any composite structure, aerospace

and non-aerospace, and since the processes are generic they are useful for a wide variety of applications. Savings metrics are directly proportional to part difficulty; the greater the part thickness and complexity, the greater the savings¹⁴.

EDUCATIONAL - The interaction of the enhanced multimedia interface, parametric relationships for composite structural definition, a database of existing research results, and available structural analysis components will provide a powerful educational resource. A wide range of analysis routines and visualization tools will expose new employees, or undergraduate and graduate students, to the latest advances in these areas and will promote the optimum use of the knowledge generated. In academia, models developed by upper-level students can be used in freshmen-level introductory courses to introduce students to the problem solving process. Having an integrated approach to the use of information will allow students to revisit projects at different levels throughout their instruction. Thus, systems such as this can be utilized throughout an integrated curriculum in structural sciences, to increasingly add complexity to the abstraction of student models of physical systems as the students' own grasp of the underlying technical issues expands. More importantly, tools such as this allow a paradigm shift in education. Rather than focusing only on local theoretical calculations or design and analysis specific topics it becomes feasible to introduce broad real-world requirements and multidisciplinary trade studies.

Conclusions

The Steered Composites Analysis and Design System (SCADS) tool for fiber placed composites has been developed and contains robust and complete sets of methods to streamline all aspects of design, analysis and manufacturing of fiber placed composite structures. The implementation uses an object-oriented structure to capture the abstract relationships of a fiber placed structure: part -> ply -> course -> tow. SCADS is unique in that it controls the design of tows rather than plies, and as such enables an evaluation of manufacturability during preliminary design. Simulation of the manufactured part is implemented through the development of self-positioning tow representations using specified fiber angle control methods; validation of these representations; integration with a pre-existing analysis tool; and integration with finite element analysis tools accepting the NASTRAN file format. This system allows for the generation and evaluation of multiple solutions in the preliminary design phase without the use of proprietary machine programming systems. The robust nature of the SCADS tool and the general dependencies inherent in composite structures should allow these tools to be implemented in composite structures for any industry.

Acknowledgments

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