OPTIMAL DESIGN OF HYBRID ELECTRIC-HUMAN POWERED LIGHTWEIGHT TRANSPORTATION

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EXECUTIVE SUMMARY

The goal of this project was to develop a lightweight and efficient hybrid bicycle design. A series approach to design of the hybrid bicycle was used to allow for more technical advances to be made. This approach required the project to be divided into three subsystems. During this reporting period graduate students were assigned to two subsystems, i.e., the drive line design and composite material design with the intent of assigning a third graduate student to the third subsystem frame member design in the future. A double planetary gear drive was developed to couple the power from the electric motor and bicyclist. The drive was mounted on a typical bicycle frame for evaluation. Efficiency and experimental data is currently being collected. A computer program using a genetic algorithm was developed to efficiently determine engineering properties of composite materials. This program was numerically verified with commercially available software and textbook composite examples.

Insights into the development process were gained during the course of this project. Advantages to the series approach to design in the university environment were found. Higher-risk designs, such as the genetic algorithm, were attempted with less financial burden. Subsystem designers were free to follow different development paths without interference issues from other subsystems.

DESCRIPTION OF PROBLEM

Bicycle riding is gaining popularity today in America, at least in part because more people are becoming health conscious, and tighter restrictions are being placed on automobile emissions. As a low emissions transportation alternative and an excellent source of physical exercise, people in metropolitan areas are commuting to work on bicycles. However, we can identify certain sectors of the population who would like to commute to work on a bicycle but are unable to do so. Some elderly members of the population do not have the physical stamina to travel the distance from home to work. Others do not wish to physically exert themselves before arriving at work for a variety of reasons.

A need then arises for a transportation alternative that provides a physical workout for the rider, but also provides some sort of assistance. Hybrid bicycles (or electric bikes) with electrical motor assistance currently available on the market can be pedaled as a traditional bicycle. The electrical assistance is controlled by the rider and may be used continuously or at the rider’s discretion. The power assist has allowed people to travel greater distances and over challenging topography.

Currently, many companies developing hybrid bicycles. Many of the standard size electric bikes (e.g. the Schwinn Sierra, Zap Electricruiser, Giant Lafree, EV Global Motors E-Bike, ETC New Century, and Trek Elektrek) weigh over 50 pounds, most are above 60. The electric drives tend to perform poorly in inclement weather where moisture and debris interfere with power transfer. The styling of these bikes also suffers. Typically, the electric drives are added in an ad hoc fashion. A lighter bike with a rugged electric motor drive and an aesthetically pleasing appearance is needed to take a commanding position in the current market.

APPROACH AND METHODOLOGY

The proposed hybrid electric-human powered bicycle is a complex electro-mechanical system. To be successful, the design process must integrate many subsystems, e.g., drive train, power source and electrical controls, into a lightweight, high strength structure. Two philosophies to design such a complex system were considered: A series approach and a parallel approach.

In the parallel approach, interdependent subsystems are engineered simultaneously with continuous design reviews. The design reviews ensure that all subsystems perform as needed and do not interfere with other subsystems. In order for the entire system to be successful, all subsystems must be successful. Therefore, high-risk subsystem designs place the entire system design at risk. The high-risk designs typically involve pushing the current limits of a technology. Using a fiber composite material in an application where it has not been used before would be considered high-risk. To reduce the system risk, low-risk alternative subsystem designs are performed concurrently with the high-risk designs. If the high-risk design fails, the alternative may be implemented into the system at the last moment. Due to the subsystem interdependence, this approach requires high expenditures of both manpower and budget. The interdependence requires that all enabling technologies and knowledge areas not only exist but also be readily available to the designers involved at the start of the project. Therefore, the majority of the design team must be experienced designers familiar with the technologies and knowledge areas. One advantage to the parallel approach is that the work (and thus the expenditures) takes a relatively short period of time.

In the series philosophy of design, each subsystem is sequentially but individually designed. This approach allows for a lower rate of expenditure of resources such as manpower and budget but it does take a substantially longer period of time than the parallel approach. The series approach provides the designers freedom to determine the order in which the subsystems are designed. Since each subsystem is designed independently, an additional iteration is required to integrate the individual designs into a working system design. During the final iteration, new technological advances and knowledge base developments may be incorporated into each subsystem. An advantage of the series approach is a reduction in the risk of performing high-risk designs. If one subsystem out of four fails, that subsystem can be repaired or redesigned during the final iteration. Failure of a single subsystem does not jeopardize the success of the entire system. Generally, when the final iteration stage is reached, the limit of technology that caused the subsystem failure has been expanded, eliminating the barriers that existed during the initial subsystem design. Furthermore, larger payoffs typically occur since technological breakthroughs are linked to high-risk designs.

In the design of the hybrid bicycle for this project, the series approach was adopted. To successfully design the bicycle, off-the-shelf technologies and applicable knowledge areas were identified. These are shown in Figure 1. Efforts in the off-the-shelf technologies primarily are aimed at familiarity so that competent design decisions can be made. The fuel cell technology that we hope to use in the hybrid bicycle is dependent on other outside researchers. This effort will use the best available fuel cell technology and if fuel cell development is insufficient, then an alternative power source such as batteries would be explored. The major effort expended in this reporting period has been in developing the enabling knowledge areas shown in Table 1. Specifically, we focused on developing efficient drive trains and computer-assisted materials selection. In future work, we plan to incorporate this work into the final enabling knowledge area, computer-assisted frame design.

Table 1 Hybrid Bicycle Off-the-Shelf Technologies and Knowledge Areas

Off-Shelf Technologies	Enabling Technologies
Drive line components (e.g., gears & bearings)	Efficient drive train designs
Electric Motors	Computer-assisted materials selection
Electric Controls	Computer assisted frame design
Bicycle Components	
Fuel Cell Technologies	

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

Parallel Hybrid Bicycle Planetary Gear Drive

Summary

The goal of the University of Idaho hybrid-bicycle project is to design, build, and test a hybrid bicycle that will out perform those models currently available. The first stage of the project was to design a prototype. The objective of the initial prototype was to develop a means of coupling the power from the rider and the electric motor within a purely mechanical system. A double planetary gear drive was designed to accommodate the multiple power sources and incorporated onto a common bicycle. This prototype was completed in April 2000 and showcased at the 2000 Idaho Engineering Design Exposition. Experimental testing is currently underway. The next phase of development will involve improving the gear drive design and developing the design of a bicycle frame to properly accommodate the drive. Initial results indicate the drive design may be incorporated into any parallel hybrid system.

Introduction

Currently, there are many companies developing hybrid bicycles. Many of the standard size bikes, such as the Schwinn Sierra, Zap Electricruiser, ETC New Century, Giant Lafree, EV Global Motors E-Bike and Trek Elektrek, weigh more than 50 pounds and most weigh over 60 pounds. Some bikes have less than optimal power transfer methods.

The Zap Electricruiser and ETC New Century bikes use inefficient friction drives to transmit power from the motor to the wheel. A majority of the less expensive bicycles do not efficiently combine the power from the rider and motor. Pedaling speed from the rider must match the reduced speed from the motor to efficiently combine the power. If this does not occur, either the rider will be overdriving the motor or vice versa. Other bicycles, such as the Giant Lafree, have controllers to measure the torque applied by the rider and proportionally adjust the output from the motor. Therefore, the power from the motor is matched to the power from the rider via a controller.

To justify the extra weight involved in an electric bicycle, the combination of rider power and electric power should be of optimum efficiency. Several belt and gear drives solve the problem [1]. The drives may be classified as either torque or speed summing. Most of the bicycles listed above are torque summing, which require the rider and motor to have matching speeds. A speed summing drive requires the torques of the rider and motor to be equal. It is assumed that matching torque will be more comfortable for the rider, and therefore a planetary gear drive was chosen for this project.

A planetary gear train has four basic components: a ring gear, planet gears, a sun gear, and a planet carrier. Referring to Figure 1, power may be inputted or outputted through the ring gear, sun gear, or the planet carrier also referred to as the carrier. Typically, one of the components is prevented from rotating while speed is reduced or increased through the remaining two components. Planetary gear arrangements have several advantages over other styles. Planetaries are compact, have reduced noise and vibration, input and output shafts are concentric, and the resultant radial forces are small.

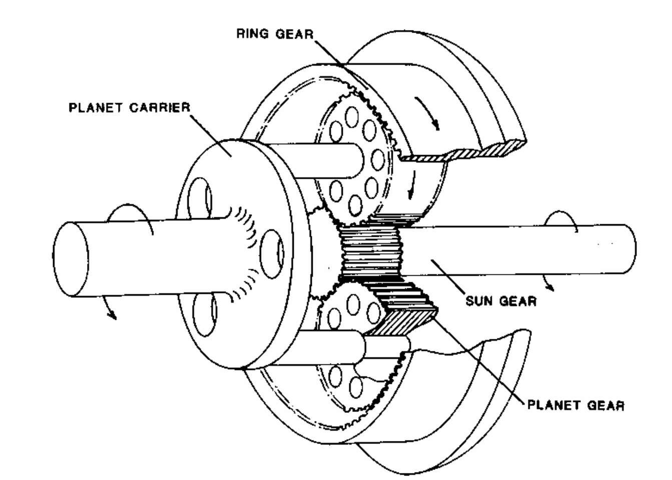


Figure 1. Typical components of a planetary gear train [2]

Methods

To increase the likelihood that all aspects of the design were met before components were ordered, a holistic style of product development [3] was adopted. A team was assembled to address the design of the gear drive: the principal designer and project engineer, the assistant designer, the machinist, and the project coordinator. Throughout the design development process, all team members were involved and offered suggestions. Issues such as manufacturability, changing customer needs, and component availability were considered early in the design process when design changes are easier to accommodate. This method led to a gear drive that was fully function the first time it was assembled.

Results

The result of this work is a double planetary gear drive. The gear drive was installed on the modified Huffy bicycle frame pictured in Figure 2. The original bottom bracket of the bicycle was removed and mounting hardware was installed onto the frame. The majority of the gear housing was composed of aluminum to minimize weight. The gearing and internal components were fabricated from medium carbon steel due to its high strength to weight ratio.

Figure 2. The gear drive installed on a Huffy bicycle frame

Figure 3 illustrates a simplified representation of the gear drive. The drive contains two complete planetaries. The primary planetary has input from only the pedal crankshaft of the bike. In the secondary planetary, input from the motor is combined with the input from the primary planetary. Pedaling the bike produces a torque on the crankshaft, which is coupled to the primary carrier. The speed of the crankshaft is then amplified by 1:2.5 and outputted through the sun gear to the secondary planetary. The sun gear speed is then reduced 2.5:1 and outputted through the secondary carrier to the chain sprocket. The motor drives the worm in the secondary. The worm and worm gear provide a reduction of 4:1 that then drives the ring gear of the secondary. This speed is then reduced 1.2:1 through the secondary carrier to the sprocket. This results in a total speed reduction of 4.8:1 for the motor. The worm prevents the motor from being driven by the crankshaft. As a safety precaution, the pedals of the bicycle must be constrained by the rider's feet in order if only the motor drives the rear wheel of the bike. Both the ring and sun gears of the secondary may be driven simultaneously to incorporate both power sources.

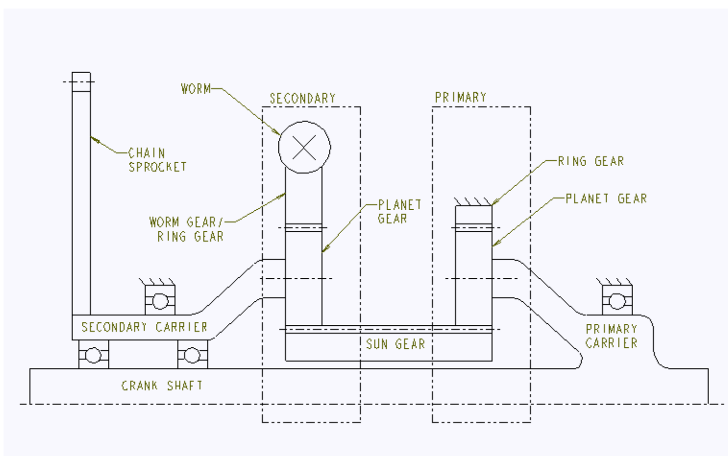


Figure 3. Schematic diagram of double planetary gear drive.

Figure 4 illustrates the assembled gear drive before installation onto the bike. The electric motor is a continuous 100-watt permanent magnet DC motor. In the figure, it is disconnected from the drive. Figure 5 shows the gear drive with the right housing panel removed, with the bike facing right.

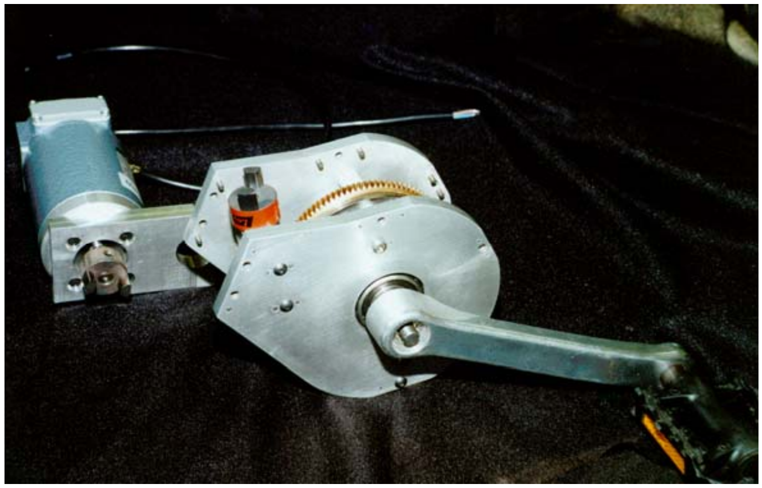


Figure 4. Assembled gear drive with motor disconnected

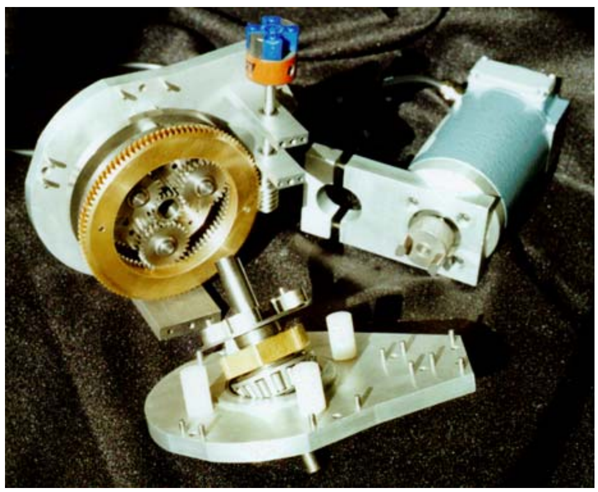


Figure 5. Exploded view of gear drive

Designing Ply Orientations of Composite Laminates with Genetic Algorithms

Summary

One goal of this study was a develop the software program that would assist in the design of lightweight structures fabricated with laminated composite materials. UI Composite, the software developed, works by coupling a genetic algorithm to a standard laminate point stress analysis program. UI Composites then finds possible lamina orientations and material selections to meet these required inputs.

Introduction

Many structures are fabricated using high performance composite material laminates. When designing these structures, it is sometimes difficult to find a set of lamina orientations that efficiently satisfy the design requirements. This becomes a tedious task when designing large composites of 50 to 300 plies. Currently, composite material software programs require the user to first specify the material and lamina orientation of each ply of the laminate. Laminate properties are then calculated and used in a structural analysis. If the results of the structural analysis do not meet the design requirements, the designer must modify the material and lamina orientations to improve the laminate properties.

To understand the program, it is important to understand laminate theory. A composite is a mixture of two or more materials at a macroscopic level. While each material retains its individual identity, the resulting assembly of material has characteristics much different from the individual materials alone and usually results in an anisotropic material. This can be advantageous because it allows engineers to tailor material properties to match the loads and conditions required for specific applications. Common examples of composites include steel reinforced concrete, plywood, and polymers reinforced with fibers.

A special class of composites is unidirectional fiber reinforced composites. These composites are constructed from unidirectional fibers and bonded together in a polymer matrix. One ply of this is commonly referred to as a lamina. These laminae are combined at different angles to create a laminate. In order to predict how the laminate behaves mechanically, the properties for each lamina must first be known. Using the Classical Lamination Theory, the lamina properties are combined to give laminate properties. Our goal was to determine the number of lamina and the lamina angle of each to obtain the desired composite.

A genetic algorithm is a method of searching based on Darwin's theory of evolution. The method, introduced by John Holland in 1975, is used today to solve complex problems where many possible solutions exist. Genetic algorithms can be used to optimize complex problems, including those where the domain is not continuous and calculus and gradient search methods do not work well.

Before discussing genetic algorithms, we would like to define a few terms as we use them:

Seed: Randomly selected parents for the first generation

Crossover: How the parents' traits are recombined to produce offspring. The hope here is that good parents make better children. The selection of parents is based on how well they satisfy the design requirements.

Mutation: Injects a new characteristic into the population to recover from any potential losses that might have occurred during crossover or not initially selected in the seed population.

Search Space: Represents every possible solution to a problem. The seed population is randomly chosen from the search space.

Fitness: Defines how well a particular string satisfies the requirements for which the genetic algorithm is searching.

A genetic algorithm starts by randomly selecting a seed population from within the search space. The strings in the population are then evaluated and, based upon their fitness, selected for crossover. The selection for crossover is based upon some kind of ranking selection scheme.

Perhaps the easiest selection scheme to understand is the roulette wheel analogy. The roulette wheel works by summing the fitness of all strings in a population and obtaining total population fitness. Each string in the population is then given a percentage of the roulette wheel based on the individual fitness divided by the total population fitness. Using this method, the strings that are more fit are given larger portions of the roulette wheel and those less fit are given smaller portions. Each parent is then selected by a spin of the roulette wheel. Once two parents are selected, they create children either by undergoing a crossover or by being copied. Whether a crossover or exact copy occurs is determined by the probability of crossover. If the two parents are chosen for crossover, they are recombined to produce children. The simplest example of a crossover is the single point crossover. In the single point crossover, the strings in each parent are recombined so that the first portion of one parent is crossed with the second portion of the other parent to make one offspring, and the reverse is applied to make another offspring.

After the children are created, the next step is to determine whether or not any of the chromosomes are to be mutated. This is determined on a bit-by-bit basis and the probability of mutation. If a chromosome is selected for mutation, then the chromosome is mutated to another possibility. In binary coding, this means a 1 becomes a 0 or a 0 becomes a 1. The spinning of the roulette wheel and the crossover of parents are repeated until there are as many children as there are parents, after which time the parents are retired and the children become the parents for the next generation. This process is repeated for a set number of generations. During the entire process, the best-so-far solution is remembered and reported at the end of the search.

Methods

The genetic algorithm in the UI Composites software program generates the ply orientations of a given laminate. Most genetic algorithms use binary encoding to represent the strings of possible solutions. That is, each solution in the search space is represented by as a string of 1s and 0s. Computer scientists have accepted some form of binary encoding as the best way to encode a genetic algorithm. Binary encoding works best on problems whose search space has 2^n solutions. UI Composites allows the user to choose the number of plies for the laminate and the possible angles the laminate is to be constructed from. The robustness of this allows the search space used by UI Composites to vary and the search space is not going to always fit within the 2^n size very well. Because of this, binary encoding does not work well for UI Composites and value encoding is used instead.

The closest program to UI Composites in angle selection is one developed by Malott for finding the ply orientations for an aircraft wing [4]. Malott divides the angle range $-90 <$ possible angles < 90 into 64 equal partitions ($64 = 2^6$) and uses these angles as the possible lay-up angles. Value encoding works by each chromosome in the string actually containing a value instead of the binary 1 or 0. By using value encoding, each lamina within the laminate is represented by one chromosome, and the value within that chromosome is one of the possible angles, allowing the number of possible angles to be user defined.

Once the ply orientations are selected, they are processed through the micromechanics algorithm to determine the properties and fitness of the laminate. Micromechanics consists of several models used to predict effective modulus of continuous fiber-reinforced lamina. These methods are usually based on either a mechanics of materials approach or an elasticity approach.

Some of the micromechanic calculations are method dependent. For these calculations UI Composites gives the user a choice of five different methods for calculating the micromechanics of a lamina. The choices available to the user are: Halpin-Tsai, Spencer, Inverse Rule of Mixtures, Rosen, and Contiguity. The micromechanic parameters dependant on the calculation method include: transverse modulus of elasticity (E_2), shear modulus of elasticity (G_{12}), transverse failure stresses ($S_2^{(+)}$, $S_2^{(-)}$), and shear failure stress (S_{12}). The rest of the micromechanic parameters are not method dependant, and include: longitudinal modulus of elasticity (E_1), major poisson ratio (ν_{12}), coefficients of thermal expansion (α_1, α_2), coefficients of hygroscopic expansion (β_1, β_2), and longitudinal failure stresses ($S_1^{(+)}$, $S_1^{(-)}$).

With the lamina properties defined by micromechanics, the next step is to determine how multiple laminae interact when stacked together. Classical Lamination Theory describes the mechanical properties of a laminate. In micromechanics, each lamina's mechanical properties are described in the longitudinal and transverse directions. When stacking a laminate, laminae are stacked at different angles. The laminate needs a coordinate system independent of the longitudinal–transverse coordinate system defined in micromechanics for each lamina. Because of this, the laminate is given its own coordinate system, the XY coordinate system, and the longitudinal–transverse coordinate system for each lamina is transformed into this new coordinate system so all lamina share a common coordinate system. This requires transforming the stiffness matrix for each lamina from the longitudinal-transverse coordinate system into the XY coordinate system. This transformation is accomplished by the transformation tensor. Once each lamina has been transformed into the XY coordinate system, the overall mechanical properties are calculated for the composite. Classical Lamination Theory then combines the transformed stiffness matrices for each lamina and creates the ABD matrix, where the A matrix is a stiffness matrix, the B matrix is a laminate coupling stiffness matrix, and the D matrix is a bending stiffness matrix. The ABD matrix can then be used to calculate the global mechanical properties of the laminate including E_x, E_y, ν_{xy}, ν_{yx}, and G_{xy}.

Results

UI Composites was written in MS Visual Basic. UI Composites has been verified to be numerically correct having been numerically benchmarked against commercially available software that include: Composite Pro, CompCalc, and CADEC. The results showed the ABD, or the stiffness matrix, and the ply-by-ply stresses and strains in the X-Y and 1-2 directions agree to 3 significant digits. The numerical correctness was verified for both the micromechanics and laminate material properties. The first verification was done for the micromechanic calculations. Several micromechanics comparisons were performed, with one of the comparisons shown in Table 2.

The comparison in Table 2 was done using E-Glass and Epoxy with a fiber volume of 60%. The five different ways of calculating the micromechanics available in UI Composites was compared to the single method for calculating micromechanics available in Composite Pro. Some micromechanic values are calculated based on mechanics of materials are the same no matter which method is chosen. UI Composites and Composite Pro completely agree on the longitudinal modulus and hygrothermal stresses. There is a slight discrepancy in the calculated longitudinal tensile stress. The longitudinal tensile stress should be calculated with a simple rule of mixtures, and therefore all programs give the same results. After some investigation, it was discovered that Composite Pro neglects the matrix contribution to the

Table 2 Micromechanical Comparison between UI Composites and Composite Pro

	UI Composites					**Composite Pro**
	Halpin-Tsai	Spencer	Inverse Rule	Rosen	Contiguity	(Chamis Method)
E1 (Msi)	6.55	6.55	6.55	6.55	6.55	6.55
E2 (Msi)	2.52	1.42	4.61	1.64	2.11	2.29
G12 (Msi)	.77	.53	1.74	.77	1.03	.77
NU12	0.256	0.256	0.256	0.256	0.256	0.256
CTE1 (in/in/F) $\times 10^{-6}$	3.75	3.75	3.75	3.75	3.75	3.75
CTE2 (in/in/F) $\times 10^{-6}$	0.134	0.134	0.134	0.134	0.134	0.134
CME1 (in/in/%m) $\times 10^{-3}$	0.121	0.121	0.121	0.121	0.121	0.121
CME2 (in/in/%m) $\times 10^{-3}$	1.68	1.68	1.68	1.68	1.68	1.68
+S1 (ksi)	168	168	168	168	168	162
-S1 (ksi), In Phase Buckling	28.3	28.3	28.3	28.3	28.3	96.0
-S1 (ksi), Poisson's Strain	248	248	248	248	248	
-S1 (ksi), Direct Shear	33.0	33.0	33.0	33.0	33.0	
+S2 (ksi)	19.1	10.8	35.0	12.4	16.0	9.44
-S2 (ksi)	38.2	21.6	70.0	24.8	32.0	23.4
+S12 (ksi)	12.5	8.68	28.3	12.5	16.8	11.7

longitudinal tensile failure. As a result, Composite Pro uses the equation $S_l^{(+)} = S_f^{(+)}\upsilon_f$, which always under-predicts the longitudinal tensile failure.

UI Composites uses three methods to calculate the longitudinal compressive failure stress. The three methods are a result of three failure mechanisms, microbuckling, matrix rupture caused by Poisson's strains, and direct shear of the fibers. The three mechanisms give results either larger or smaller than Composite Pro, which only uses the Chamis Method. The micromechanic parameters that are method sensitive include the transverse modulus (E_2), shear modulus (E_{12}), transverse tensile stress ($S_2^{(+)}$), transverse compressive stress ($S_2^{(-)}$), and shear stress (S_{12}). UI Composites users have a choice of five different methods for these parameters. These methods are: Halpin-Tsai, Spencer, Inverse Rule of Mixtures, Rosen, and Contiguity methods. For the Halpin-Tsai method, UI Composites requires two fitness variables be defined, ξ_2 and ξ_{12}. Gibson suggests choosing ξ_2 as two and ξ_{12} as one respectively [5]. These are the default values supplied by UI Composites and the values used in this test case. UI Composites and Composite Pro are thus in close agreement for the transverse modulus and shear modulus. However, this method resulted in UI Composites over-predicting the transverse stresses by approximately two.

The second method available to UI Composite users is the Spencer method. When using the Spencer method the transverse and shear modulus are found to be about two-thirds the value predicted by Composite Pro, while the transverse and shear stresses are fairly close. The third method available to UI Composite users is the Inverse Rule of Mixtures. The Inverse Rule of Mixtures does not work well and was found to over-predict the transverse modulus, shear modulus, transverse stress, and shear stress. The fourth method available to UI Composite users is the Rosen Method. The Rosen Method was found to under-predict the transverse modulus and was fairly close with the shear modulus, transverse stress, and shear stress. The final method available to UI Composite users is the Contiguity method. For the Contiguity method, UI Composites requires the level of contiguity be defined, where the level of contiguity estimates how many fibers are touching each other. With a contiguity of .2, the method was found to slightly under-predict the transverse modulus, over-predicted the shear modulus, and over-predicted the failure stresses by about 40 percent.

REFERENCES

1. Moore, S. W., Ehsani, M., “A Charge Sustaining Parallel HEV Application of the Transmotor,” *Hybrid Vehicle Engines and Fuel Technology*, SAE 1999-01-0919.
2. Lynwander, P., “Gear Drive Systems Design and Application,” Marcel Dekker, Inc. 1983, pg. 294.
3. Takeuchi, H., Nonaka, I., “The New New Product Development Game,” *Harvard Business Review*, 1986, 64(1), pp. 137-146.
4. Malott, B., Averill, R.C., Goodman, E.D., Ding, Y., and Punch, W.F., 1996,“Use of Genetic Algorithms for Optimal Design of Laminated Composite Sandwich Panels With Bending-Twisting Coupling,” American Institute of Aeronautics and Astronautics, 1-10.
5. Gibson, Ronald F., 1994. *Principles of Composite Material Mechanics*. McGraw-Hill, New York. p. 91.

APPENDIX

UI Composite User Interface

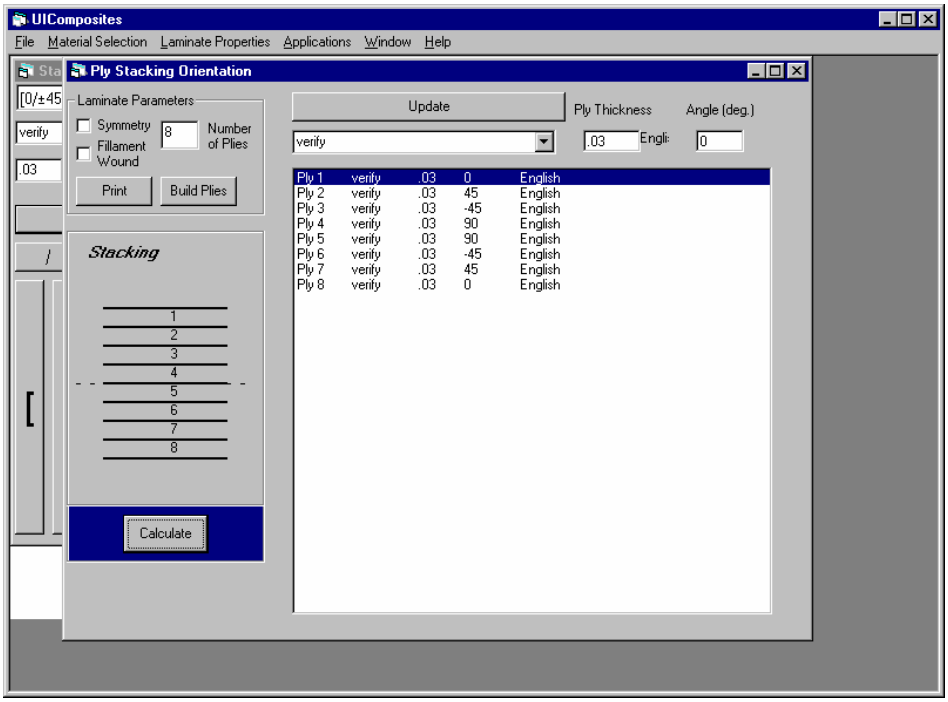


Figure 0.1. Laminate Orientation Shortcut

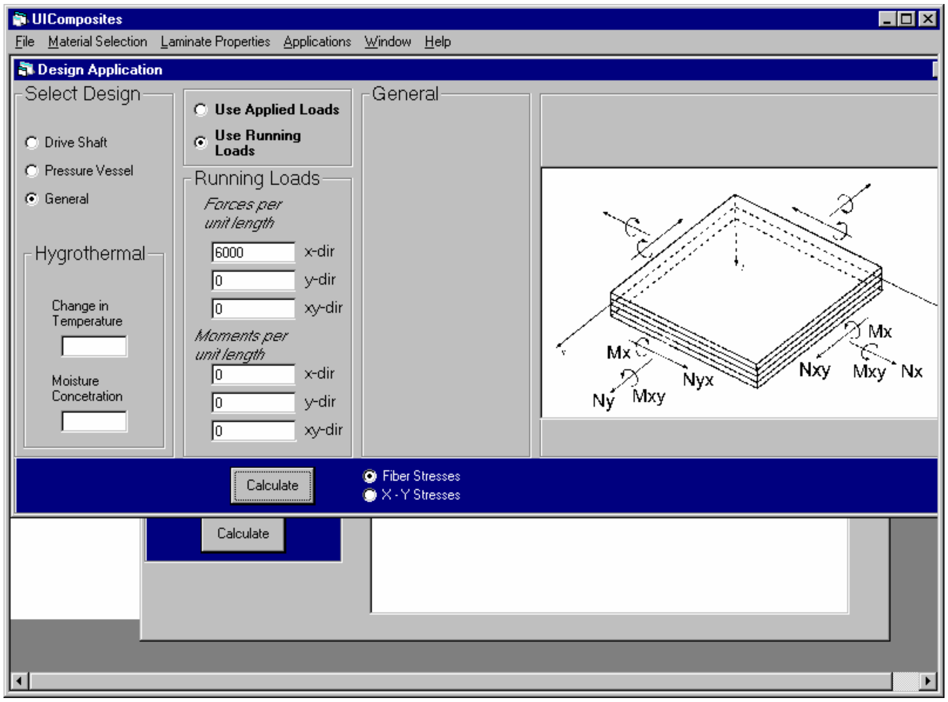
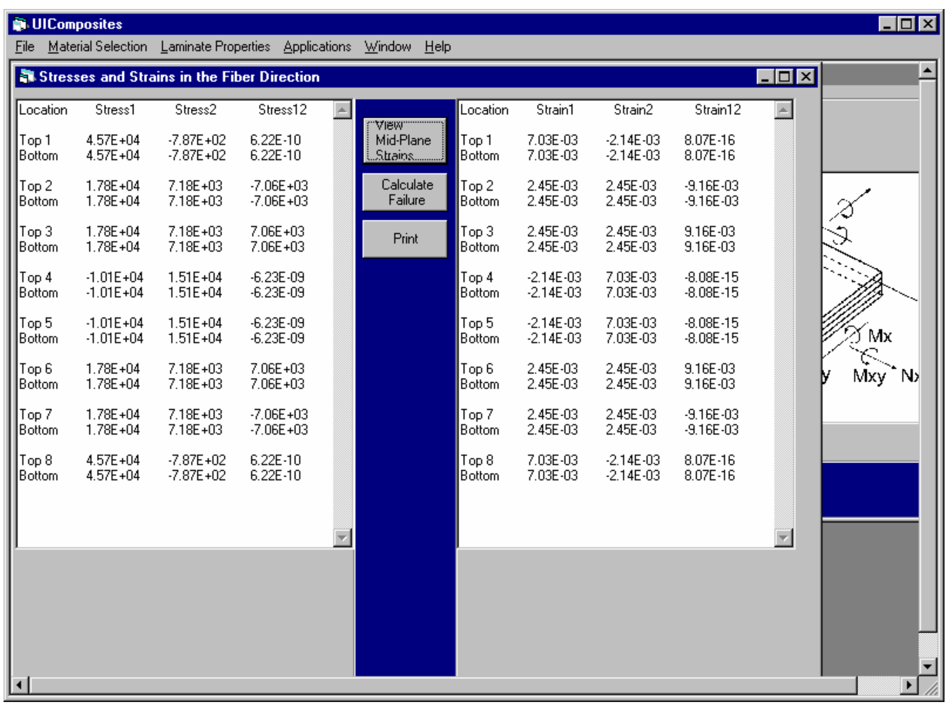


Figure 0.2. Stacking Sequence for Regular Operation



Location	Stress1	Stress2	Stress12
Top 1	4.57E+04	-7.87E+02	6.22E-10
Bottom	4.57E+04	-7.87E+02	6.22E-10
Top 2	1.78E+04	7.18E+03	-7.06E+03
Bottom	1.78E+04	7.18E+03	-7.06E+03
Top 3	1.78E+04	7.18E+03	7.06E+03
Bottom	1.78E+04	7.18E+03	7.06E+03
Top 4	-1.01E+04	1.51E+04	-6.23E-09
Bottom	-1.01E+04	1.51E+04	-6.23E-09
Top 5	-1.01E+04	1.51E+04	-6.23E-09
Bottom	-1.01E+04	1.51E+04	-6.23E-09
Top 6	1.78E+04	7.18E+03	7.06E+03
Bottom	1.78E+04	7.18E+03	7.06E+03
Top 7	1.78E+04	7.18E+03	-7.06E+03
Bottom	1.78E+04	7.18E+03	-7.06E+03
Top 8	4.57E+04	-7.87E+02	6.22E-10
Bottom	4.57E+04	-7.87E+02	6.22E-10

Location	Strain1	Strain2	Strain12
Top 1	7.03E-03	-2.14E-03	8.07E-16
Bottom	7.03E-03	-2.14E-03	8.07E-16
Top 2	2.45E-03	2.45E-03	-9.16E-03
Bottom	2.45E-03	2.45E-03	-9.16E-03
Top 3	2.45E-03	2.45E-03	9.16E-03
Bottom	2.45E-03	2.45E-03	9.16E-03
Top 4	-2.14E-03	7.03E-03	-8.08E-15
Bottom	-2.14E-03	7.03E-03	-8.08E-15
Top 5	-2.14E-03	7.03E-03	-8.08E-15
Bottom	-2.14E-03	7.03E-03	-8.08E-15
Top 6	2.45E-03	2.45E-03	9.16E-03
Bottom	2.45E-03	2.45E-03	9.16E-03
Top 7	2.45E-03	2.45E-03	-9.16E-03
Bottom	2.45E-03	2.45E-03	-9.16E-03
Top 8	7.03E-03	-2.14E-03	8.07E-16
Bottom	7.03E-03	-2.14E-03	8.07E-16

Figure 0.3. Loads For Regular Operation

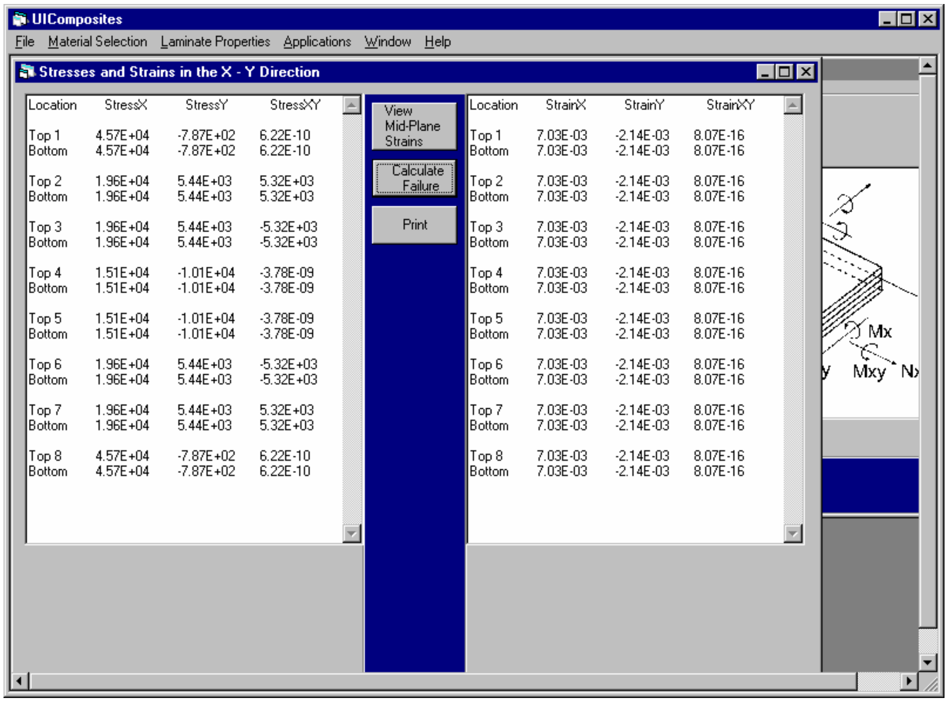


Figure 0.4. Longitudinal and Transverse Stress Calculations

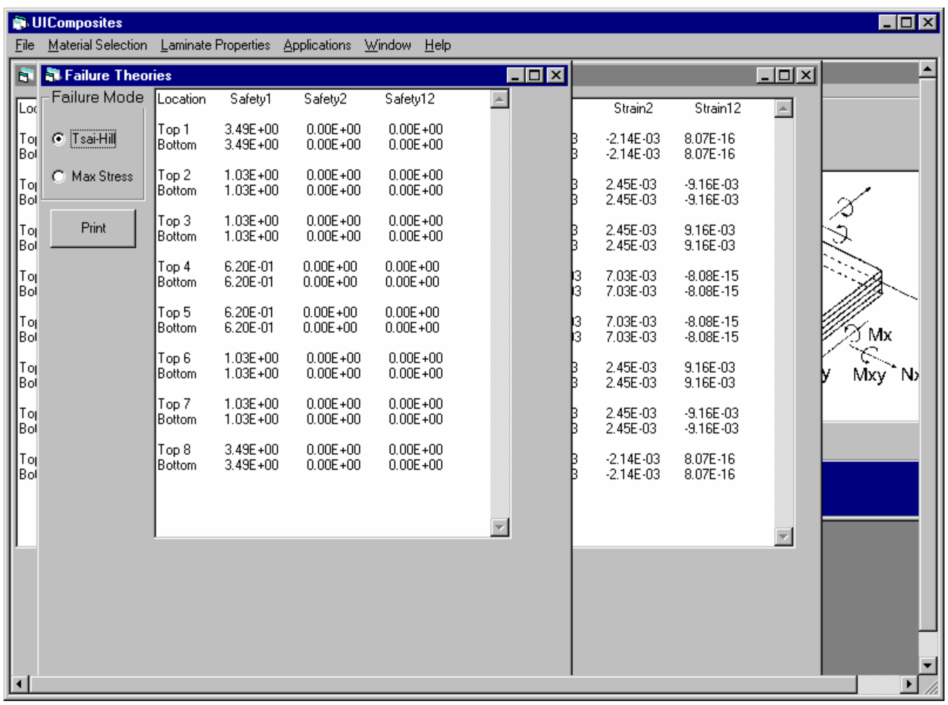


Figure 0.5/ X and Y Stress Calculations

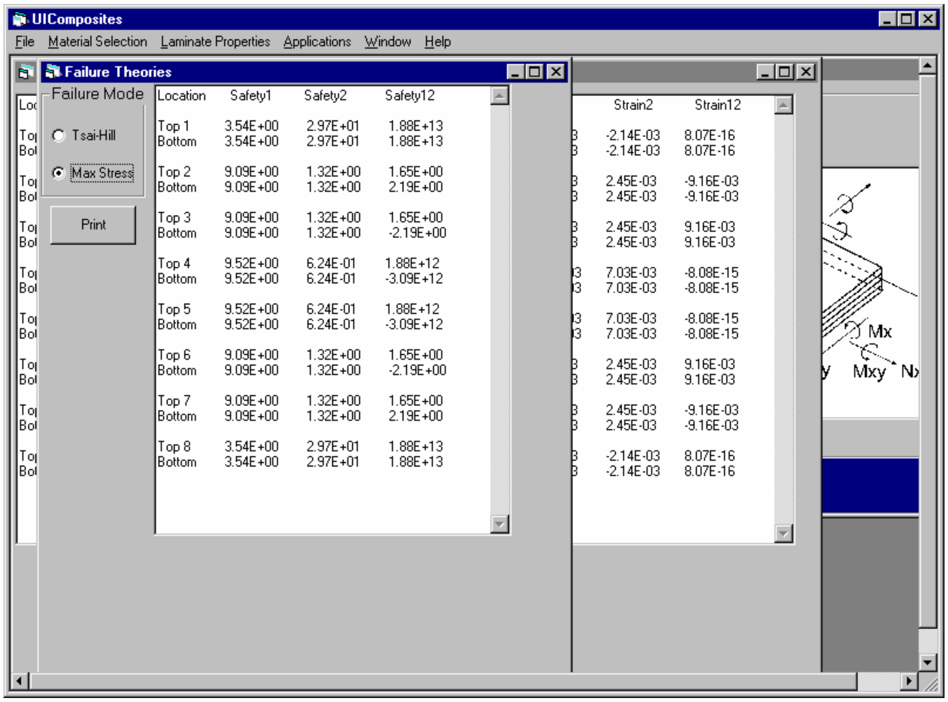


Figure 0.6. Tsai-Hill Failure Theory

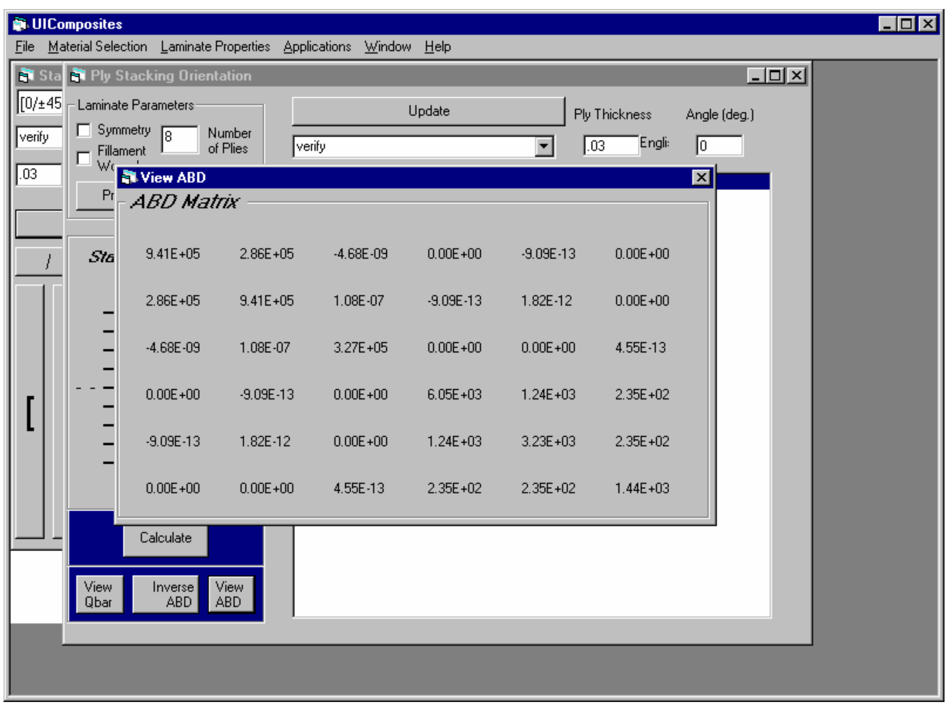


Figure 0.7. Maximum Stress Failure Theory