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MULTI-PARAMETER OPTIMIZATION TOOL FOR LOW-COST COMMERCIAL FUSELAGE CROWN DESIGNS

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INTRODUCTION

This paper describes the work-in-progress on developing a methodology and software tool to aid in the optimal design of composite structures. The methodology is being developed to take advantage of the ability to tailor the composite material, in conjunction with the design of the structure.

- A fundamental objective during aircraft design is to identify "optimal" structural components
- Advanced composites allow the engineer to "design" the *material*, as well as the overall geometry of the structure
- A software tool is being developed using a state-of-the-art random search global optimization algorithm to find and explore the "best design"

OPTIMAL DESIGN OF A REINFORCED COMPOSITE PANEL

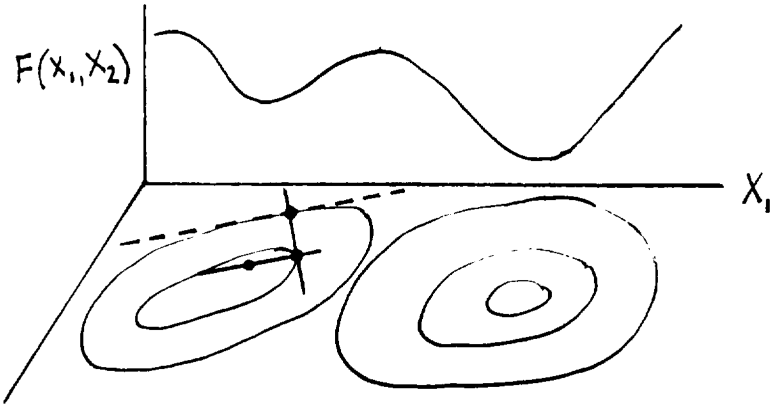
When designing a reinforced composite panel, two questions must be addressed: what are the design variables, and what makes a design the best? A list of possible variables that must be specified by the design engineer are included below. Stiffener geometry variables may include blade-, hat-, J-, and C- stiffeners, as well as height, width and stiffener spacing. The laminate description may include number of plies, ply angles, and stacking sequence. Possible criteria for an optimal design may include objectives such as minimum weight, maximum stiffness, maximum strength, maximum buckling stability, or minimum costs. Typically, a combination of these objectives must be included in optimization methodology that identify *trends in the designs* and aids the engineer in selecting an optimal design.

- What are the design variables? They include (at least)
  - type of material system(s) used
  - stiffener geometry
  - laminate description for both skin and stiffener
- All of these variables can be adjusted by the engineer. What is the "optimal" design?
  - low weight
  - high performance
  - low cost
- Typically, the user wants to optimize a *combination* of these objectives and identify TRENDS IN THE DESIGNS

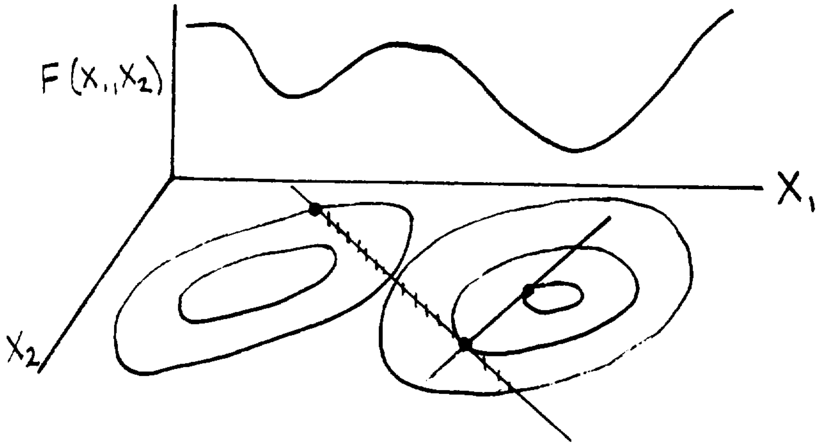
NEED AN OPTIMIZATION ALGORITHM TO FIND AN "OPTIMAL" DESIGN

Once the design variables and the criteria for an "optimal" design are identified, an optimization problem is specified. An optimization problem involves an "objective function" F(X), where F(X) is a user-defined function of the design variables X, and a set of constraint equations. The optimal solution is defined as the set of design variables which minimize the objective function F(X), while satisfying user-defined constraints. Now, an optimization algorithm must be chosen to automatically search the design space for the optimal solution. Two types of algorithms are available: "local" optimization algorithms and "global" optimization algorithms. The local optimization algorithms include quasi-Newton methods and gradient search, and converge quickly to a local minimum. If the objective function is not convex, but has several local minima, then the solution from a local optimizer depends on the starting point. The global optimization algorithms including random search methods converge slower, but have a high probability of finding the global minimum. These algorithms are less sensitive to the starting point. We are using a state-of-the-art global optimization algorithm called Adaptive-Mixing.

- A "local" optimization algorithm, e.g. gradient search



- A "global" optimization algorithm, e.g. adaptive mixing



OPTIMAL DESIGN OF COMPOSITE STRUCTURES

Optimal design of composite materials has recently become a well-known topic in the literature. One way our approach differs is in that we are using a "global" optimization algorithm, rather than a "local" optimization algorithm.

- Most existing composites optimization algorithms are based upon "local" optimizers. When using these codes, the user either
    - Reduces the number of design variables, such that the composite design process becomes a "local" problem, or
    - The global nature of the problem is ignored; results obtained depend on starting point.

- The objective of the UW study
    - To develop a composites design philosophy based on Adaptive Mixing, a state-of-the-art "global" optimization algorithm
    - To identify and implement objective function(s) (which may be global, nondifferentiable, discontinuous) and constraints which can be used to represent the many design variables involved in composite structures

APPROACH

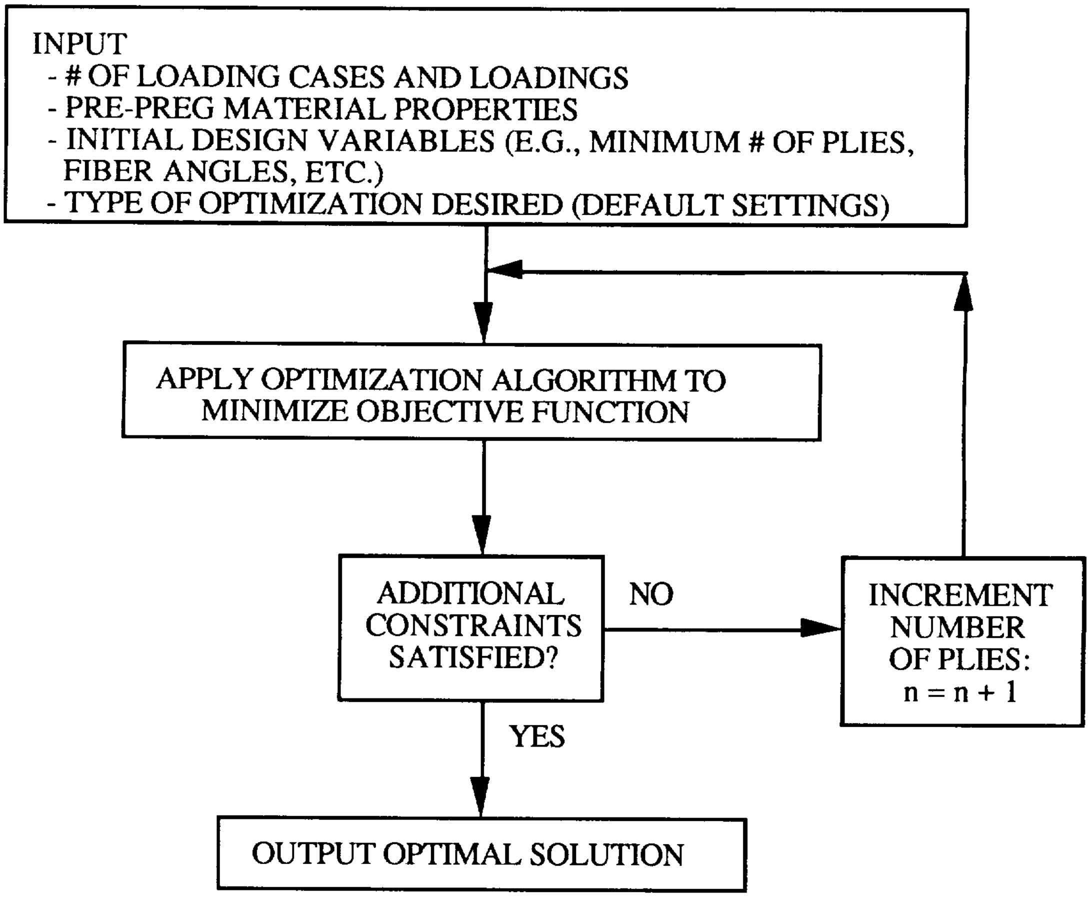
An optimization code called UWCODA (University of Washington Composite Optimal Design Algorithm) is being developed. The approach taken is to base UWCODA on classical lamination theory, and an Adaptive-Mixing "global" optimization algorithm.

- The current objective functions and constraints being developed are based on
    - Minimum weight of skin and stiffener
    - Maximum strain failure criteria
    - Multiple load cases
    - Various "design" tools (provided by Boeing engineers), representing
        - Hoop tension damage tolerance criteria
        - Axial load damage tolerance criteria
        - Buckling resistance criteria
        - Impact resistance criteria

- Future objective functions and constraints will be developed based on minimum cost:
    - Material cost
    - Labor cost, as a function of stringer type, stringer spacing, ...

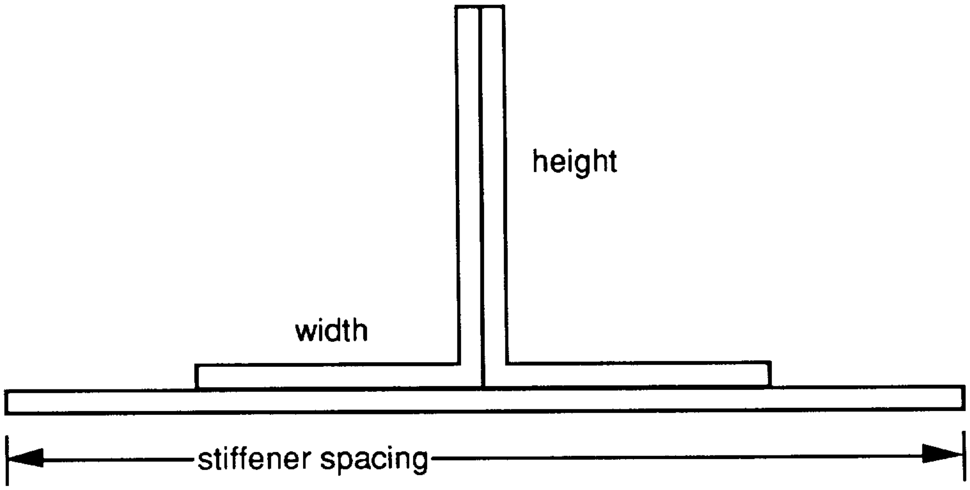
OVERALL FLOW DIAGRAM OF UWCODA

Below is a flow diagram of UWCODA. Notice that the additional constraints are checked after the optimization routine is applied. This allows the optimizer to select an "infeasible" design, that is, one that does not meet all of the constraints, while providing feedback to the engineer of the best possible design with n plies. If the design is infeasible with n plies, the outer loop increments the number of plies and reoptimizes. This outer loop encourages finding a minimum number of plies, and consequently minimum weight, that satisfy all of the constraints.



POSSIBLE DESIGN VARIABLES FOR A STIFFENED COMPOSITE PANEL

A list of possible design variables are listed below. These variables include parameters that a design engineer can control. The ply angles and stiffener geometry variables are currently included in UWCODA. The type of material is a potential design variable for future development.



- Ply fiber angles and number of plies for both the skin and the stiffener
  - n plies in the skin
  - n' plies in the stiffener
- Stiffener geometry
  - type of stiffener (blade-, hat- stiffeners)
  - width and height of stiffener
  - stiffener spacing
- Type of materials used
  - type of material for skin
  - type of material for stiffener
  - type of material for each individual ply

TYPICAL OBJECTIVE FUNCTION

The objective function used in UWCODA is a combination of weight and several performance criterion. This type of combined function is sometimes referred to as a multi-objective function. The equations used to calculate ply strains come from classical lamination theory, and the other equations are provided by Boeing in the form of "design tools". The approach of taking a normalized difference in the exponent, as shown below, is similar for all of the terms. This also makes a straightforward approach for extending the objective function to include additional criterion.

- Minimize (weight)(sum of performance criterion)
  where (sum of performance criterion) = (sum of ply strains) + (hoop tension damage tolerance) + (axial load damage tolerance) + ...
  and (sum of ply strains) =

$$\sum_{j=1}^{m}\left[\sum_{k=1}^{n}\left[\left(\delta*\exp\frac{|\varepsilon_1^k|_j-\varepsilon_1^{cr}}{\varepsilon_1^{cr}}\right)+\left(\delta*\exp\frac{|\varepsilon_2^k|_j-\varepsilon_2^{cr}}{\varepsilon_2^{cr}}\right)+\left(\delta*\exp\frac{|\gamma_{12}^k|_j-\gamma_{12}^{cr}}{\gamma_{12}^{cr}}\right)\right]\right]$$

and (hoop tension damage tolerance) =

$$\sum_{j=1}^{m} n*\left(\delta*\exp\frac{|P_h^j|-P_h^a}{P_h^a}\right)$$

where n = number of plies
m= number of loading cases

$$\delta = \text{magnification factor} = \begin{cases} 1 \text{ if numerator is positive} \\ 10 \text{ if numerator is negative} \end{cases}$$

TYPICAL ADDITIONAL CONSTRAINTS

Note that when using a multi-objective function and minimizing a summation, there is a possibility that the total summation is at a minimum even though an individual term may violate a constraint. For example, if two terms should be less than 1, a sum of 0.2 and 1.01 is less than the sum of 0.8 and 0.8. The possibility is lessened by using exponentiation and a magnification factor; however, we also check all individual terms in additional constraints. If any constraint is violated the design is considered infeasible.

- the maximum strain failure criterion must satisfy the additional constraints:

$$|\varepsilon_1^k|_j < \varepsilon_1^{cr}$$

$$|\varepsilon_2^k|_j < \varepsilon_2^{cr}$$

$$|\gamma_{12}^k|_j < \gamma_{12}^{cr}$$ for k=1,n (# of plies) and j=1,m (# of load cases)

- the hoop tension damage tolerance must satisfy the additional constraint:

$$|P_h^j| < P_h^a$$ for j=1,m (# of load cases)

- other constraints, such as axial load damage tolerance and cost constraints will be included

SAMPLE RESULTS WITH UWCODA: MATERIAL INPUTS

Sample results using UWCODA are shown for a laminated plate subjected to different combinations of variables. IM6, AS4, and S-Glass fibers were chosen for comparison since they represent a range of structural properties and cost. To show the importance of failure criteria on the optimization results, two different sets of strain failure allowables were applied to the optimization. The first failure criteria is applied such that matrix cracking is prevented (ε_2^{cr} is based on the in-situ strength for a -75°/Dry condition). The second failure criteria is a tension damage tolerance allowable such that crack growth is suppressed in a pressurized cylinder with an 8" notch. This is typical of a failsafe load criteria. The ε_1^{cr} (fiber failure) is limited to a lower value than used previously to resist this failure mode. The shear strain allowable (γ_{12}^{cr}) is also reduced to constrain the optimized laminate layup against nonlinear shear distortion. The material properties used as inputs to the program are listed below:

MATERIAL PROPERTIES

	IM6/3501-6	AS4/3501-6	S-Glass
E_1 (msi)	22.30	19.20	7.40
E_2 (msi)	1.32	1.36	2.20
G_{12} (msi)	0.78	0.72	0.77
ν_{12}	0.32	0.32	0.264
MATRIX CRACKING ALLOWABLE STRAINS			
ε_1^{cr}	0.0145	0.0140	0.0420
ε_2^{cr}	0.0060	0.0060	0.00825
γ_{12}^{cr}	0.0200	0.0200	0.0200
TENSION DAMAGE TOLERANCE ALLOWABLE STRAINS			
ε_1^{cr}	0.0026	0.0028	0.0079
ε_2^{cr}	0.0060	0.0060	0.00825
γ_{12}^{cr}	0.0100	0.0100	0.0100

SAMPLE RESULTS WITH UWCODA: MECHANICAL BEHAVIOR

Sample results describing the mechanical behavior of the laminated plates constrained by the two different failure criteria are presented. A significant number of additional plies are required for damage tolerance, indicating that it is more critical than matrix cracking criteria for the load conditions studied. Note that several of the optimum layups were unbalanced. Additional constraints could be imposed during optimization to force balanced layups.

LOADING CONDITIONS

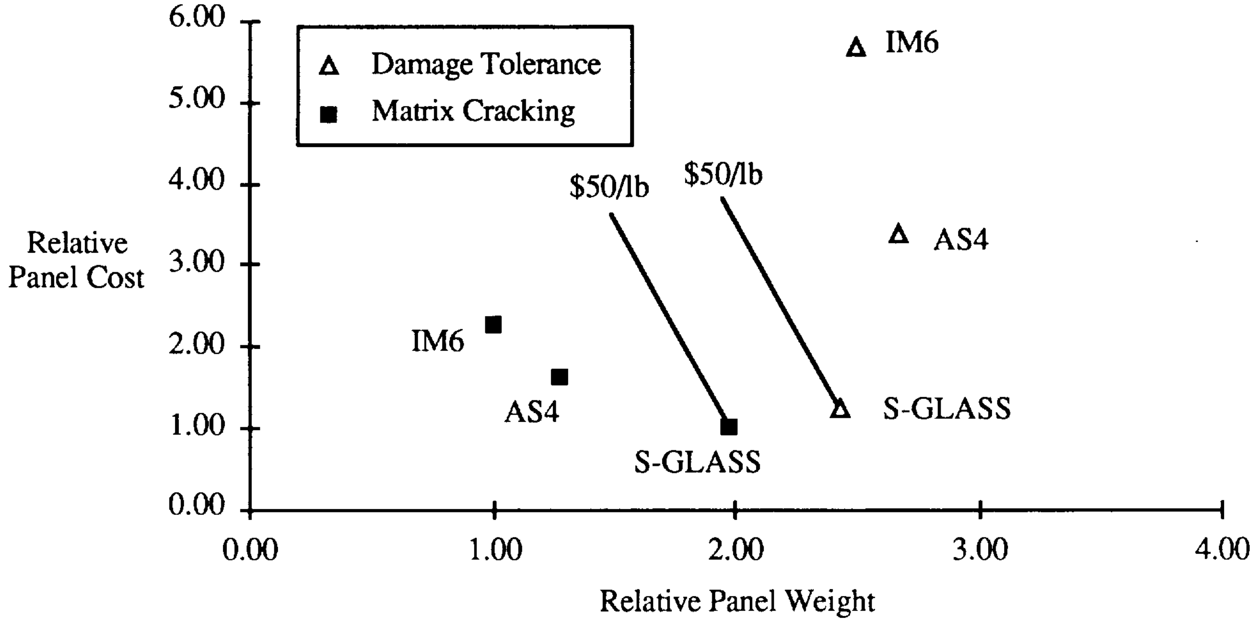
Load Case	N_x	N_y	N_{xy}
1	4000 lbs/in	0	0
2	0	4000 lbs/in	0
3	0	0	2000 lbs/in
4	0	0	-2000 lbs/in

	MATRIX CRACKING		DAMAGE TOLERANCE	
MATERIAL	**LAYUP**	**# PLIES**	**LAYUP**	**# PLIES**
IM6/3501-6	$[12/-12/78/-78]_S$	8	$[15_3/80_3/-20_2/-68/-84]_S$	20
AS4/3501-6	$[90_2/-17_2/17]_S$	10	$[0_5/70_3/-67_2/\overline{-67}]_S$	21
S-GLASS	$[-51.5/-30_3/65/38/\overline{65}]_S$	13	$[22_2/-22_2/-66_2/66_2]_S$	16

SAMPLE RESULTS WITH UWCODA: COST VS WEIGHT

The results from the sample cases comparing relative cost and weight are presented. A significant difference in the cost/weight relationship can be seen depending on the failure criteria imposed. For the damage tolerance criteria, the weight of the optimized laminate is nearly the same for the three different material systems considered, but the cost varies widely. For the matrix cracking criteria, the weight and cost relationship is much different. To evaluate which material is most desirable for a given criteria, a dollar value must be established for every pound of weight added to a design. This dollars/pound ($/lb) value can be evaluated by plotting lines centered at the lowest cost design. "Good" designs (i.e. cost effective) will fall below the line of interest and "bad" designs (i.e. not cost effective) will fall above the line. Using this approach and a value of $50/lb, it can be seen that S-Glass is the best material for tension damage tolerance and that the more expensive IM6 is the most cost effective material to resist matrix cracking. This type of range in the results indicate the importance of choosing the right criteria. In an aircraft application involving both criteria, the damage tolerance was found to be dominant. Therefore, the cost savings associated with using fiberglass are apparent and can be significant. Other criteria such as overall limit of fuselage flexibility will likely force the material used in this application to be stiffer than fiberglass. This leads one to consider a graphite/fiberglass hybrid material to attain a compromise in stiffness and damage tolerance characteristics.

	MATRIX CRACKING			DAMAGE TOLERANCE		
MATERIAL	**# PLIES**	**WT**	**COST**	**# PLIES**	**WT**	**COST**
IM6/3501-6	8	1.00	2.27	20	2.50	5.68
AS4/3501-6	10	1.27	1.61	21	2.68	3.38
S-GLASS	13	1.98	1.00	16	2.44	1.23



POTENTIAL FUTURE OBJECTIVE FUNCTIONS

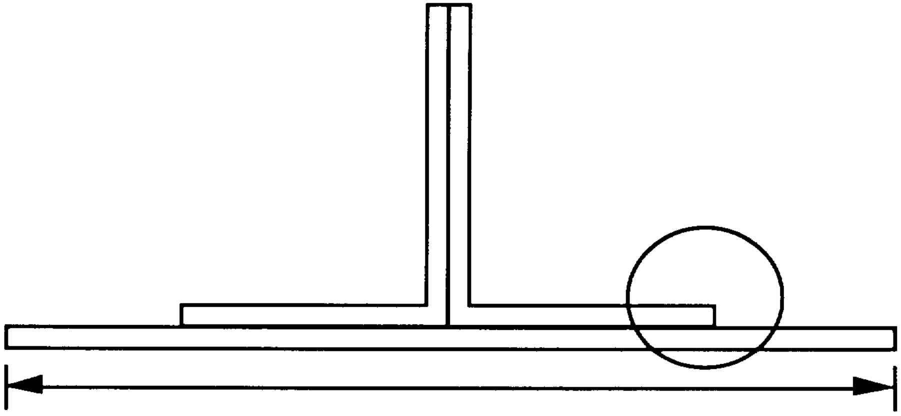
It is possible to develop future objective functions to optimize the cost-weight relationship, as well as satisfying the performance criterion. Several potential objective functions are listed below, as well as future constraints. Cost considerations will include material costs as well as operating costs, production costs, and assembly costs. Manufacturing considerations may include ease of layup, and sensitivity to manufacturing tolerances.

- Need to develop an objective function to reflect cost/weight/performance trades, such as
  - Minimize (weight)(sum of performance criterion)
  - Minimize (cost)(sum of performance criterion)
  - Minimize (cost)(weight)(sum of performance criterion)
  - Minimize (cost)(weight)

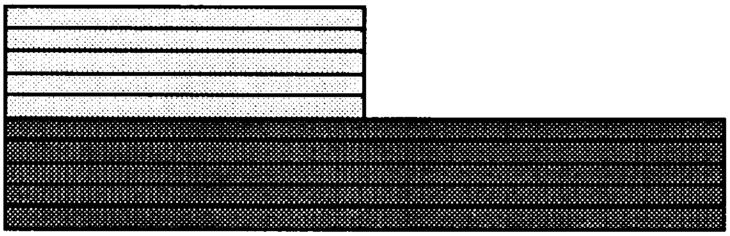
- Need to develop additional constraints or goals, such as
  - satisfy performance criterion
  - cost considerations
  - manufacturing considerations

POTENTIAL FUTURE DESIGN OPTIONS

The type of material may be included as a future design variable in several options.



- Design option 1: user specifies materials for the skin and stiffener
- Design option 2: optimizer selects materials for the skin and stiffener



▓ Material A, B or C
░ Material A, B or C

- Design option 3: optimizer selects materials for individual plies

SUMMARY AND CONCLUSIONS

The composites optimization design software UWCODA has been found to be very successful in preliminary testing and early experience. There is a lot of potential to make the program very useful to design engineers working with composite structures.

- UWCODA is a composites optimization design algorithm
    - uses number of plies and fiber angles as design variables
    - uses Adaptive-Mixing "global" optimization algorithm
    - uses maximum strain failure criteria for objective function and additional constraints
    - includes Boeing "design tools" for stiffened panels
    - includes stiffener geometry in the design variables

- Future work
    - develop "cost tools" to include in UWCODA
    - expand design variables to include material types
    - refine optimizer
    - apply UWCODA to the design of a composite fuselage crown panel