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Cost Optimization of Stiffened Panels Using VICONOPT

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A novel and versatile optimum-cost design approach that embraces the ideology of concurrent engineering is described. The approach is incorporated into optimum-design software to permit the determination of the least-cost design for prismatic assemblies of laminated composite plates, which occur in advanced aerospace construction. Comparisons between cost and mass optimum designs of different panel topologies for two proposed manufacturing processes are presented. The different panel topologies were obtained by varying the number of stiffeners and by using either blade or T stiffeners. In total, 40 different panels were optimized separately for manufacturing cost, mass, and total cost, i.e., including running costs. The running costs were included by associating a penalty function with the mass of the panels. The results show that the approach is extremely versatile and enables different topologies and manufacturing processes to be compared in detail.

Introduction

THE development of numerous new composite materials since the early 1960s heralded many predictions that the days of aluminum aerospace structures were numbered. Such predictions are easily understood because of the remarkable specific properties of the new materials, such as their high strength-to-weight ratio, which have resulted in component weight savings of up to 30%. However, the high cost of this relatively new technology has meant that the use of composite materials in commercial aerospace structures is still the exception rather than the rule.

The high cost of composite structural parts often is attributed to factors such as high material cost, high labor content, lack of automation, and high investment costs. It is therefore critical that composite structural parts be designed with cost-effectiveness in mind. Studies have shown that a large percentage of the final cost of a product is determined in the early phases of its life cycle.[1] Because of the importance of decisions made during preliminary design, it is critical that the impact of decisions made on other disciplines be accounted for as early as reasonably possible. Concurrent engineering is the name given to this process. It requires the designer to take more account of materials, structures, tooling, manufacturing, inspection, maintainability, and cost than are taken into consideration in a sequential approach. However, it is unreasonable to expect a designer to become familiar with all of the other disciplines that would affect cost. Therefore, better design tools are required for the designer to achieve the best affordable design.

A number of cost-estimating programs and models for nonaerospace[2–6] and aerospace structures[7–11] have been developed, including Northrop's Advanced Composite Cost Estimating Model (ACCEM).[12] The need to incorporate cost considerations within the design phase of computer design programs is a commonly recurring recommendation.[13,14] More recently, Northrop developed the Manufacturing Cost Model for Composites (MCMC),[15] a personal-computer-based design to cost model that facilitates rapid cost projections for multiple design concepts, and the Boeing Commercial Aircraft Group in collaboration with a number of subcontractors developed Composite Optimization Software for Transport Aircraft Design Evaluation (COSTADE).[16] COSTADE contains cost equations that relate the manufacturing costs directly to the structural design variables. The program uses the Improving Hit and Run method[17] to optimize the dimensions of the structure to reduce its cost while ensuring its structural integrity. The development of the generic cost optimization approach presented here and its application within VICONOPT similarly utilize cost equations that relate manufacturing cost to design variables. However, much more flexibility is permitted in the definition of cost equations and in the choice of design-element properties that form their arguments. For convenience, the generic approach is described later entirely in terms of its application within VICONOPT.

VICONOPT is an established computer program based on exact plate theory for the buckling and vibration analysis and optimum design of prismatic assemblies of anisotropic plates,[18–21] e.g., stiffened panels. The program covers any prismatic assembly of anisotropic plates, each of which can carry any combination of longitudinally invariant in-plane stresses. For a design problem, VICONOPT uses buckling analysis results and material strength constraints to find a stable, low-mass or low-cost design. The user may select any set of plate breadths, ply thicknesses, and ply angles as design variables, which the program adjusts independently. The remaining plate breadths, ply thicknesses, and ply angles, together with any plate or substructure rotations and offsets, are either held fixed or are linked to the values of the design variables to become dependent variables.

The optimization technique couples the well-proven mathematical programming local optimizer CONMIN[22] and an efficient scaling method that converges on a just feasible design. Mass previously was used as the objective function, whereas, now, cost or a combination of cost and mass can be used. The new method allows the user to design a panel so as to minimize manufacturing cost while also optionally incorporating running, i.e., life cycle, costs.

Cost Model Definition

The required cost model is defined entirely within the input data file of VICONOPT, allowing the user the freedom to decide and define the format of the cost model that is to be used. This generic approach to minimum cost design permits any desired cost driver to be defined as the argument to any desired cost function. Instead of merely applying coefficient values to a selection of predefined equations, highly complex cost calculations can be performed by the combination of simple expressions in an unlimited multilevel manner. The simple expressions are defined using polynomial, transcendental, and logarithmic functions whose arguments are design parameters such as element dimensions and material properties. Once defined, such expressions can be reused with different arguments.

Figure 1 illustrates simple expressions and their combination into more complex expressions by performing simple arithmetic operations (Fig. 1b), by using different expressions over different ranges of the argument to represent a discontinuous function (Fig. 1c), by using the value of one expression as the argument of another (Fig. 1d), and by combining expressions with different arguments (Figs. 1e and 1f). The values of such complex expressions may contribute directly to the total cost of the structure or may be used as the

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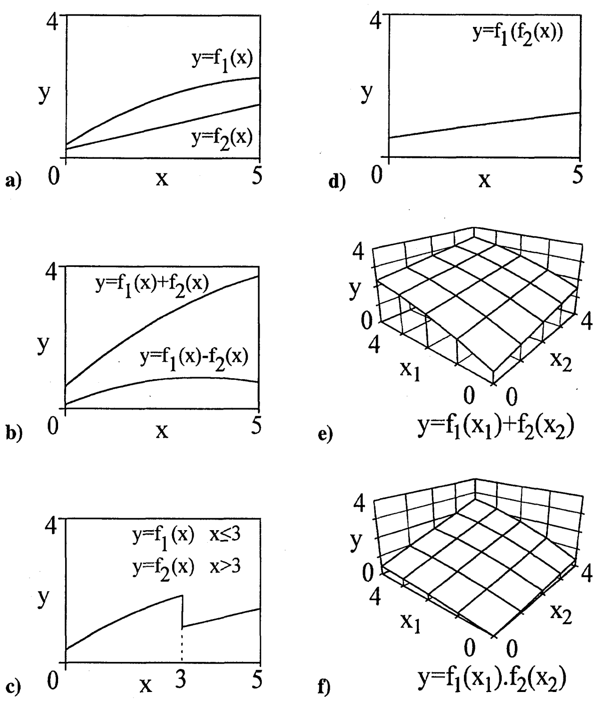

Fig. 1 Definition of cost model: a) simple expressions and b–f) their combination into more complex expressions.

arguments of even more complex expressions. The expressions thus form building blocks for cost calculations of any required complexity and that involve any number of design parameters. Note that a design parameter may appear in many different cost expressions, e.g., representing its influence on the total cost during different stages of the manufacturing process. Such a generic approach allows the user to define virtually any desired cost model and its parameters entirely within the data input. The few limitations that are present in VICONOPT have been introduced to save coding effort but are not inherent to the novel approach presented.

Although VICONOPT currently cannot change the basic topology of a panel, e.g., the number of stiffeners, during optimum design the costs associated with such factors can be modeled by using specially defined constants. This powerful feature permits the same set of cost functions to be used on separate runs of VICONOPT, covering a range of problems with different panel topologies, so that cost comparisons between different topologies can be made consistently and efficiently. These special constants can be used in defining the cost functions themselves or as their arguments. The input data typically include a list of such constants, e.g., material prices, labor rates, number of stiffeners in the panel. The program therefore allows a company to generate its own standard and confidential library of cost models and costing data, which can be incorporated as part of the VICONOPT data input as required. Hence, VICONOPT is suitable for wide dissemination because the code itself and its documentation contain no sensitive information on costs or on any one particular cost model.

Minimum Cost Design of a Composite Panel

To demonstrate the generic cost approach incorporated in VICONOPT, various alternative prismatic panels were optimized for minimum cost while satisfying the same design load conditions. The objective was to find the least-cost design for a panel of length 0.762 m, width 1.2192 m, and maximum stiffener height h of 0.07 m. A total axial load $P = 2$ MN combined with an in-plane shear load in the skin of $N_S = 800$ kN/m was applied to each panel (Fig. 2). For convenience, stress constraints were not included. By using separate VICONOPT runs, two alternative stiffener cross sections were used, namely simple blade or T stiffeners, and the number of such stiffeners also was varied. Hence a large number of different panel topologies were considered.

Two simple cost models were used, to describe two alternative construction methods. The cost models are not meant to be accurate because accurate information is highly commercially sensitive. They are only used for demonstration purposes, to reflect how the cost advantages and disadvantages of manufacturing processes can be compared. The first cost model assumed the complete construction of a panel by the manual layup of prepreg tape followed by curing and nondestructive testing (NDT). The second cost model assumed that the skin and stiffeners were constructed separately, with a tape-laying machine used to lay the plies of the skin, whereas the stiffeners were constructed by manual placement of prepreg tape.

Cost Model for Complete Manual Ply Placement

The stiffener shapes were dependent on the prepreg tape placement process used. It was assumed for the first cost model that, because the layer placement was performed manually, the stiffener plies were interlaced with the plies of the skin. Figure 3a shows the cross section of a stiffened panel with eight blade or T stiffeners. The plates of the skin and stiffeners were constructed from layers of two different composite materials with different orientations. The physical properties of the two different composite thermoplastic carbon–epoxy materials are shown in Table 1. Because the prepreg tape used in the cost model had a thickness of 0.2 mm and a width of 0.1016 m, the cost model assumed that each layer was constructed from a stack consisting of a discrete number of plies that all share the same thickness 0.2 mm and the same ply angle. However, in the design routine of VICONOPT, the layer thicknesses were assumed to be continuous design variables. As a precaution against delamination, the thickness of any layer was not allowed to exceed 1.4 mm.

In Fig. 3b the general layer layup of the panel skin and stiffener plates is presented as they were modeled within VICONOPT. When considering the assembly cost and the actual layer layup, the four bottom layers of the skin would curve downward to form the layers of the stiffeners with, optionally, ply dropoff at the stiffener–skin junctions. Hence, all layer thicknesses t_i ($i = 1, 2, \ldots, 6$) were design variables together with the breadth of the web of the stiffeners b_w

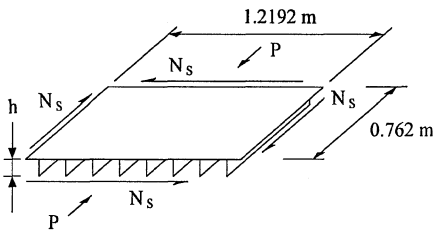

Fig. 2 Isometric view of panel, showing applied loading and required panel dimensions.

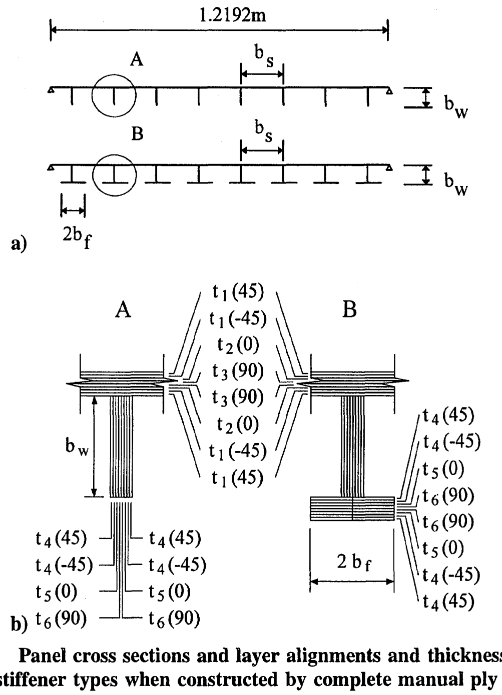

Fig. 3 Panel cross sections and layer alignments and thicknesses for both stiffener types when constructed by complete manual ply placement.

Table 1 **Physical properties of carbon–epoxy composite materials**

Physical property	Material 1	Material 2
Young's modulus in direction of axis 1, E_1	75 GN/m^2	150 GN/m^2
Young's modulus perpendicular to axis 1, E_2	5.5 GN/m^2	18.6 GN/m^2
In-plane shear modulus, E_{12}	2 GN/m^2	6.4 GN/m^2
Poisson's ratio, ν_{12}	0.34	0.21
Density, ρ	1500 kg/m^3	1600 kg/m^3
Layers containing composite material (see Figs. 3 and 4)	t_1, t_3, t_4, t_6	t_2, t_5

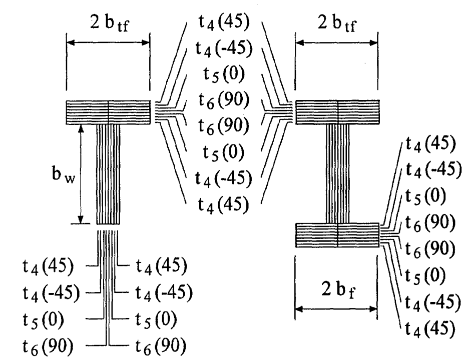

Fig. 4 Cross sections for both stiffener types when constructed by second cost model.

and the breadth of the bottom flanges b_f in the case of the T stiffeners. For each layer, the orientation of axis 1, measured clockwise in degrees from the longitudinal panel direction, is shown in parentheses. The stiffener spacing b_s was equal to the overall breadth of the panel divided by the number of stiffeners present. Different numbers of stiffeners were tried in separate runs of the program, ranging from 6 to 15. Only one global constant, referring to the number of stiffeners present on a panel, was changed for the cost model used in these separate runs.

Cost Model for Separate Skin and Stiffener Ply Placement

In the second cost model, the skin and stiffeners were formed separately and then connected by co-consolidation. A connection flange therefore was required at the top of each stiffener to ensure that a sufficiently large connection area was provided (Fig. 4). The total width $2b_{tf}$ of the connection flange was included as a design variable but with a lower limit of 40 mm to ensure an adequately large bonding surface. The layer thicknesses of the skin are defined as on Fig. 3.

Cost Model

The total manufacturing cost of a panel was taken to be the sum of the composite-material purchasing cost, the assembly cost for placement of plies to form a panel, the curing cost, and the cost of NDT. The cost data used to define the first and the second cost models are shown in the Appendix. The complexity of the cost equations depended on the manufacturing stage being modeled, and these equations also are included in the Appendix.

Results and Discussion

The layer thicknesses and stiffener dimensions were given the same initial values at the beginning of each separate design run. A separate design run was performed for each panel topology considered. The use of two cost models, each requiring two stiffener types and between 6 and 15 stiffeners, meant that 40 separate design runs were performed.

Figure 5 shows the optimized panel manufacturing cost vs the number of stiffeners present for panels constructed by manual ply layup. The contributions made to the final cost by material

Table 2 **Percentage by which material placement cost increased in model 1 over model 2**

	Number of stiffeners	
Stiffener type	6	15
Blade	16%	28%
T	15%	17%

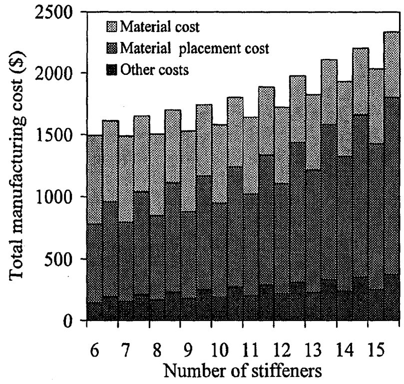

Fig. 5 Total manufacturing cost vs number of stiffeners using the first cost model. The left-hand column of each pair of results is for blade stiffeners; the right-hand column is for T stiffeners.

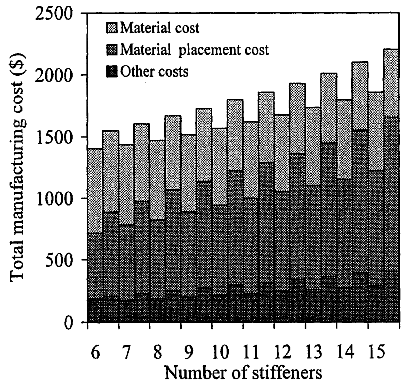

Fig. 6 Total manufacturing cost using the second cost model. The left-hand column of each pair of results is for blade stiffeners; the right-hand column is for T stiffeners.

purchasing cost, ply placement cost, and other costs (curing and NDT) also are shown. As the complexity of the panel increases, either by increasing the number of stiffeners or increasing the complexity of stiffener shape, the cost associated with its manufacture also increases. Such increases in cost also occur in all cost categories except the material purchasing cost. This exception occurs because the increased structural efficiency of having more stiffeners results in lower panel masses, and hence lower material purchasing costs.

Figure 6 contains the corresponding results for the second cost model, i.e., for separate construction of the skin and stiffeners, and leads to conclusions similar to those drawn from Fig. 5. From Figs. 5 and 6, it can be seen that there is a greater rate of increase in total manufacturing costs with respect to the number of stiffeners for manual construction, i.e., in the first cost model, mostly due to the material placement cost. Table 2 quantifies this result. Hence, as the number of stiffeners increases, the second construction method becomes considerably more cost-effective than its alternative. A major reason for this is that the placement rate for stiffener plies was assumed to decrease as the number of stiffeners increased for the first cost model because of the decreasing work space around each stiffener, whereas this penalty was not incorporated in the second cost model because each stiffener was constructed separately. Generally, the first cost model produced lower-mass panels than the second cost model, which required structurally inefficient connection flanges.

Figure 7 shows the variation of cost and mass for the blade-stiffened panels obtained by cost optimization using the first cost model. The general shape of the two curves is as expected, i.e.,

Table 3 Mass and manufacturing costs for the four optimum designs of Fig. 8

Stiffeners		Cost	Mass,	Manufacturing
Type	Number	model	kg	cost, $
Blade	10	1	11.100	1592
Blade	9	2	11.414	1515
T	10	1	10.318	1796
T	8	2	11.271	1653

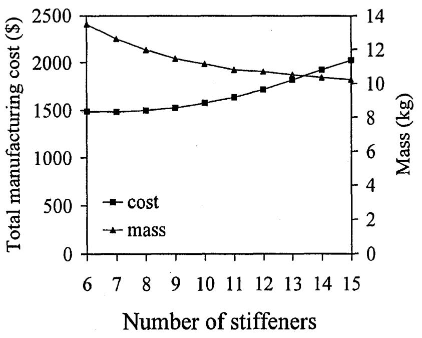

Fig. 7 Mass and cost variation relative to number of blade stiffeners for first cost model.

the cost increases for more complex and hence more structurally efficient structures. If the number of stiffeners were to vary from one to a high number, then both curves would exhibit minima, indicating optimum-cost or -mass designs. Similar variations occurred for the other panel topology cases and manufacturing processes.

When a panel was optimized for least mass, it was found that the mass of the optimum design was usually within 2% of that of the cost-optimized panel with the same number and type of stiffeners, and vice versa. This was expected because the cost models were based on calculating the time required to assemble each panel, and then multiplying it by an overhead and a labor rate. Because the costs associated with tool setup, curing, and NDT were dependent mainly on the number and type of stiffeners on a panel, the cost associated with varying the design variables during one design run only altered the calculation of the ply placement time, which was inherently dependent on the amount of material to be placed. However, this should not be considered to be true for all cost design situations.

The results presented so far are for manufacturing cost associated with a composite panel, i.e., they have not incorporated any running costs in the objective function. The tradeoff between the mass and the production cost of a structural part is a crucial design decision that is based on the anticipated aircraft acquisition and running-cost tradeoff preferences of potential customers. To illustrate the effects of accounting for running costs, the generic cost approach again was used to design the panels while automatically incorporating a tradeoff between the mass and the cost of each panel. The tradeoff was represented by a penalty cost of $150/kg for the amount by which the mass of the panel exceeded 9 kg. The design had to be rerun because the penalty cost causes convergence to a different final design. Figure 8 shows the results obtained for all four general topology types, i.e., for the two manufacturing methods and the two stiffener types.

It can be seen from these results that using a penalty cost enables the designer to compare completely different designs and manufacturing processes. Table 3 shows the final mass and the total manufacturing cost of the optimum design for each of the four sets of results shown in Fig. 8.

Cost-optimized panels with complete manual layup were usually lighter than their second cost model counterparts but were more expensive to manufacture. In deciding the best overall design, the tradeoff between mass (i.e., effectively, running cost) and manufacturing cost is critical. It therefore must be emphasized that the value of the penalty function was subjective, which in a real design situation would be at the discretion of the designer. If the value was increased progressively, then the complete manual ply-layup cost model would eventually become the most cost-effective construction method because the resulting panel masses are usually lower. However, the results and cost model presented here are only

Table 4 Initial and final design variable values of least manufacturing and running cost design

Design	Dimension, m	
variable	Initial	Final
t_1	0.00098	0.000951
t_2	0.00059	0.000314
t_3	0.00052	0.000204
t_4	0.00024	0.000406
t_5	0.00092	0.0014
t_6	0.00012	0.000204
b_w	0.05	0.0495
b_{tf}	0.025	0.02

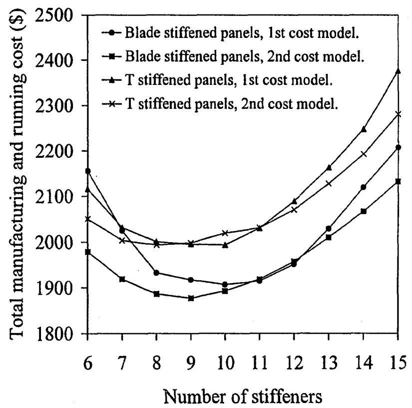

Fig. 8 Variation of total cost of panels given as the sum of their manufacturing and running costs.

meant to show the capabilities and the possible results and conclusions obtainable from the new cost optimization capabilities within VICONOPT.

For the design problem specified and the manufacturing cost models used, the final optimum design including running costs was found to be a blade-stiffened panel with nine blades constructed by separately assembling the skin and the stiffeners, followed by co-consolidation (see Fig. 8). The values of the design variables for the initial and the final design are given in Table 4.

Conclusions

A novel optimum-cost design approach to aerospace prismatic assemblies is presented. The objective function of most previous computerized design programs, namely mass, has been replaced by an objective function of cost, mass, or a combination of both. To illustrate the design capabilities of the code, a number of different prismatic panels are considered as possible solutions to a common design problem of a typical aerospace wing panel, with two different manufacturing processes being considered. Simple cost models are used to define the likely cost structure of the two manufacturing processes and are incorporated in the design of the panels.

The results show that the new design approach can be used to design panels within the concept of concurrent engineering because all cost considerations can be included in the objective function of the computer optimizer.

Appendix: Cost Model Equations

Manufacturing costs were calculated in both cost models in the same general way. The cost of each plate or structural part was evaluated according to its construction method and such costs were summed to give the total cost of the panel. The general cost equation used is as follows:

$$\begin{aligned}\text{Total cost} &= \text{material purchasing cost}\\ &+ C_1 \times \text{initial tool setup time}\\ &+ C_1 \times \text{total ply placement time}\\ &+ C_1 \times \text{curing time, etc.}\\ &+ C_2 \times \text{time of NDT}\end{aligned} \tag{A1}$$

Table A1 Cost data used for complete manual layup of plies

Cost data	Value
Labor rate (general assembly), \$/h	15
Overhead rate (general assembly), \$/h	10
Labor rate (NDT), \$/h	20
Overhead rate (NDT), \$/h	15
Placement rate for 0- and 90-deg plies, kg/h	1.5γ
Placement rate for 45-deg plies, kg/h	1.4γ
Setup time per prepreg strip laid, h	0.002
Manual cutting rate per layer, m/h	152.4
(Visual) inspection time per layer, h	0.05
Number of voids per blade stiffener	1
Number of voids per T stiffener	2
NDT inspection runs per blade stiffener	2
NDT inspection runs per T stiffener	5
Purchasing cost of material 1, \$/kg	50
Purchasing cost of material 2, \$/kg	65
Initial tool setup time per part, h	0.5
Time to construct a 90-deg bend per ply, h	0.04
Void filling time per meter run, h/m	0.16
Curing time, h	3.00
Curing preparation time per stiffener, h	0.25
NDT time per meter run, h/m	0.1

Table A2 Changes to Table A1 for second cost model: separate construction of stiffeners and skin followed by coconsolidation

Cost data	Value
Placement rate for all skin plies, kg/h	3.5
Placement rate for stiffener plies, kg/h	1.5
Initial tool setup time for skin, h	1
Initial tool setup time for stiffeners, h	0.25
Curing preparation time per stiffener, h	0.35

Different cost coefficients contained in the generic data input file (Tables A1 and A2) were used to obtain the quantities appearing in Eq. (A1). Equations (A2–A6) define the separate quantities as follows, in which summations are over i or over i and j; C_1 = sum of labor rate and overhead rate; C_2 = sum of labor rate and overhead rate for NDT; p_r = datum prepreg tape placement rate; γ = variation of datum placement rates with respect to the accessibility of the work area [see Eq. (A7)]; n_p = number of tape strips covering layer area; n_{pl} = number of plies in layer thickness; t_s = setup time per prepreg strip laid; n_c = manual cutting rate; i_t = visual inspection time per layer; n_s = number of stiffeners; n_{vs} = number of voids formed by bending the two central layers of the stiffeners to form the flanges or when interlacing into the skin; and n_r = number of NDT runs required per stiffener:

Material purchasing cost

$$= \sum (\text{mass of material } i \times \text{cost of material } i) \qquad \text{(A2)}$$

Initial tool setup time

$$= \sum \text{time of initial setup and tooling for part } i \qquad \text{(A3)}$$

Total ply placement time

$$= \sum\sum \frac{(\text{mass of layer } j \text{ of plate } i)}{(p_r \times \gamma)}$$
$$+ \sum\sum n_p \times n_{\mathrm{pl}} \times t_s$$
$$+ \sum\sum n_c \times (\text{edge length for layer } j \text{ of plate } i)$$
$$+ \sum\sum \text{ply bending time} \times (n_{\mathrm{pl}} \text{ for layer } j \text{ of plate } i)$$
$$+ \sum i_t \times (\text{number of layers in plate } i)$$
$$+ n_s \times n_{\mathrm{vs}} \times (\text{void filling rate}) \qquad \text{(A4)}$$

Curing time, etc. = curing time

$$+ n_s \times (\text{curing preparation time per stiffener}) \qquad \text{(A5)}$$

Time of NDT

$$= \text{NDT time per meter run} \times \text{run length} \times n_r \times n_s \qquad \text{(A6)}$$

The variation in the placement rate γ represents the reduction in the rate of ply placement due to the increased difficulty of the task as space between the stiffeners is reduced. For the first cost model, $\gamma = 1$ if $n_s \leq 6$. Otherwise $\gamma = 1$ for the top four skin layers, and γ for the remaining skin layers and stiffener layers has the following values:

$$\gamma = 0.35 \times \cos[2 \times \pi \times (n_s - 7)/16] + 0.65 \qquad \text{for } 6 < n_s \leq 14$$

$$\gamma = -0.0153 \times n_s + 0.51 \qquad \text{for } n_s \geq 15$$

The generic cost approach was used to define the above expressions in detail and link them to their appropriate design variables. For example, assume a flat layer of length l, breadth b, thickness t, and density ρ. Then, by reference to Eq. (A4), the total ply placement time for this layer is expressed as

$$\text{Ply placement time} = \frac{(t \times l \times b \times \rho)}{(p_r \times \gamma)}$$
$$+ (n_p \times n_{\mathrm{pl}} \times t_s) + (n_c \times 2b \times 2l) + i_t \qquad \text{(A7)}$$

where $n_p = l \times \sin\Theta/w + b \times \cos\Theta/w$, w = prepreg tape width, and Θ = ply orientation.

Acknowledgments

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