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OPTIMAL DESIGN OF GRID-STIFFENED COMPOSITE PANELS USING GLOBAL AND LOCAL BUCKLING ANALYSES

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Abstract

A design strategy for optimal design of composite grid-stiffened panels subjected to global and local buckling constraints is developed using a discrete optimizer. An improved smeared stiffener theory is used for the global buckling analysis. Local buckling of skin segments is assessed using a Rayleigh-Ritz method that accounts for material anisotropy and transverse shear flexibility. The local buckling of stiffener segments is also assessed. Design variables are the axial and transverse stiffener spacing, stiffener height and thickness, skin laminate, and stiffening configuration. The design optimization process is adapted to identify the lightest-weight stiffening configuration and pattern for grid-stiffened composite panels given the overall panel dimensions, design in-plane loads, material properties, and boundary conditions of the grid-stiffened panel.

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Nomenclature

a	Axial stiffener spacing
b	Transverse stiffener spacing
h	Stiffener height
t	Skin laminate thickness
t_s	Stiffener thickness
$LAMI$	Design variable for stacking sequence of skin laminate
$ICON$	Design variable for stiffening configuration
λ_G	Global buckling load factor
λ_{sk}	Buckling load factor for skin segment
λ_1	Buckling load factor for axial stiffener segment
λ_2	Buckling load factor for transverse stiffener segment
λ_3	Buckling load factor for diagonal stiffener segment

Introduction

An aircraft in flight is subjected to air loads associated with all flight conditions including maneuver and gust conditions. These external loads are resisted by the structure, and an internal load distribution is established based on the structural layout and external loads. These internal loads, which depend on their location in the aircraft structure, may cause either overall panel buckling of stiffened panels, buckling of the skin between stiffeners, or stiffener crippling. Hence, an efficient and accurate method for developing a buckling-resistant design of general stiffened composite panels is needed to identify the most effective grid-stiffened geometries for structural panels subjected to combined inplane loading conditions at different locations in fuselage and wing structures. The identification of structurally efficient grid-stiffened geometries also requires integration of optimization techniques with accurate structural analyses. Optimization of composite structures has been of considerable interest in recent years. Composite plates have been optimized to maximize buckling loads and a summary of this work is presented in the literature survey of Reference 1. According to Reference 1, the basic design problem is to determine the stacking sequence of a composite laminate since, in many practical applications, the ply orientations are limited to either 0, 90 or ± 45 degrees and, the laminate thicknesses can only be integer multiples of commercially available ply thicknesses. Thus, the optimization of a laminate stacking sequence involves discrete design variables associated with manufacturing constraints and represents an integer programming problem.

The optimum design of stiffened panels that satisfies buckling constraints has also been of interest in recent years (e.g., Refs. 1-6). These studies did not consider stiffener spacing as design variables even though skin thickness, stiffener thickness and stiffener height were used as design variables. For the most part, gradient-based optimizers were used in References 3-6. However in Reference 2, the ranking method was used as the optimizer, while in Reference 1, a genetic algorithm[7,8] was used to optimize the laminate stacking sequence in the skin and stiffener elements. Geodesically stiffened panels were considered in References 3 and 6, while orthogrid panels were considered in Reference 2. Axially stiffened panels were considered in References 1 and 5. The optimization of grid-stiffened panels with stiffener spacing and stiffener layout as discrete design variables poses the same problems as that of optimizing the laminate stacking sequence discussed in Reference 1 and significantly expands the design space. Stiffening configuration and stiffener spacings are discrete variables since the optimum grid-stiffened geometry may contain any combination of axial, transverse and diagonal stiffeners, the stiffener spacing can only occur as certain multiples of the length and width of the panel, and the stiffener and skin thicknesses can only be integer multiples of commercially available ply thicknesses. The genetic algorithm has emerged as a viable tool for dealing with the problem of discrete variables and with the need to find multiple minima. A genetic algorithm evolves the design by randomly searching the design space and maintaining a family of designs for each generation (or iteration) of the design. This process provides multiple near-optimum designs for evaluation and selection rather than a single-design configuration provided by gradient-based algorithms.

The present paper presents the analysis and design strategy for grid-stiffened composite panels subjected to combined loads and a global buckling design constraint. The global buckling constraint for the grid-stiffened panel is important to prevent localized skin buckling. This constraint reduces the loss of aerodynamic performance caused by the buckling of wing or fuselage surfaces and prevent the failure of a panel by stiffener-skin separation[9] after buckling.

Panel Buckling Analysis

The analysis and design of grid-stiffened composite panels subjected to combined loads require several key steps. In the present study, acceptable designs are those which buckle globally and do not exhibit any local skin buckling or stiffener crippling. The first step in the design process is to assess the global buckling response of a grid-stiffened panel. Once this global buckling response is determined, the second step is to determine the local skin buckling response for the quadrilateral and/or triangular skin segments between the stiffeners. The third step is to determine whether stiffener buckling or stiffener crippling has occurred at this global buckling load level. This sequence of steps is performed repeatedly in a design cycle until an optimum or near-optimum design is obtained.

The global buckling analysis is based on a Rayleigh-Ritz method using a first-order, shear-deformation theory and an improved smeared-stiffener modeling approach discussed in Reference 10. The buckling analysis of local skin-segments is also based on a Rayleigh-Ritz analysis using a first-order, shear-deformation theory and accounts for material anisotropy. Boundary restraints on the skin segments are provided by the stiffeners and hence, the analysis must be capable of accommodating a variety of boundary conditions and a variety of skin segment shapes.[11,12] In most cases, the skin segments for grid-stiffened panels will have either a general parallelogram-shaped or a general triangular-shaped planform.

In addition to analyzing the local skin segment for buckling, the local stiffener segments must be analyzed to determine whether stiffener crippling will occur.[4] Accordingly, the stiffener segment at the nodes or intersection points of the stiffeners are assumed to be clamped while the stiffener-skin attachment is assumed to be a simple support.

These global and local analysis methods have been integrated into a computer code to provide a computationally efficient tool for predicting the buckling load of grid-stiffened composite panels.

Panel Design Procedure

The design of grid-stiffened composite panels requires that many of the design variables, such as stiffener spacing and stiffener thicknesses, may only have certain discrete values rather than varying continuously over design space. Also, a "family" of acceptable designs is often needed for selecting designs that accommodate manufacturing constraints rather than a single-point design. Gradient-based methods for structural optimization are not appropriate in this case, since they lead to a single-point design.

Over the last several years, researchers have investigated the use of genetic algorithms as a method for "evolving" a given design problem to a family of near-optimum designs (e.g., see References 1, 7 and 8). Based on Darwin's theory of the survival-of-the-fittest, the genetic algorithm involves the random creation of a design population that "evolves" towards some definition of fitness. The genetic algorithm is attractive due to the simplicity of its approach using discrete variable combinatorics. The genetic algorithm can be used directly to solve unconstrained optimization problems, while constrained optimization problems must first be transformed into an unconstrained optimization problem (e.g., use of an exterior penalty function). Stochastic processes are used to generate an initial population of individual designs, and the algorithm then applies the principles of natural selection and survival of the fittest to find improved designs. Furthermore, since the discrete design procedure works with a population of designs, it can explore a large area of design space and identify multiple minima or maxima. This attribute is a major advantage since the converged solution contains many optima of comparable performance. The cost of having a large number of function evaluations is offset by the fact that many near-optimum designs are now available. In a gradient-based optimization procedure, only a single-point design, usually the extremum closest to the starting point, is obtained. However, different starting points can be tried to increase the chance of locating the global optimum as well as other local optima. The genetic algorithm produces a population or family of good designs which may include the global optimal design, rather than a single design. The above mentioned advantage of the genetic algorithm makes it an appropriate optimizer that can be exploited in developing a design optimization tool for general grid-stiffened panels.

Design Problem Definition

The present design problem is to minimize the weight per unit area of a grid-stiffened composite panel given the design loading condition, the length and width of the panel, the material properties for the skin and stiffeners, and the boundary conditions of the panel. As shown in Figure 1, a general grid-stiffened panel may be considered as an assembly of a repetitive unit or a unit cell. A unit cell is a repetitive unit of skin and stiffener elements. The design variables include stiffener spacings (a, b), skin stacking sequence, stiffening configuration, stiffener thickness (t_s), and stiffener height ($h_1 = h_2 = h_3 = h$). The stiffener spacings (a, b), stiffener height (h), and stiffener thickness (t_s) are shown in the figure of the unit cell of Figure 1. Also shown in Figure 1 is the skin thickness (t) which depends on the skin stacking sequence. The stiffening configuration depends on the combination of axial, transverse and diagonal stiffeners in the unit cell (Figure 1). For manufacturing and assembly reasons, all stiffeners are assumed to be of the same height and thickness. The design sought here is a panel of minimum weight in a certain design space which buckles globally at the design loads. This design problem can be defined by setting up the optimization procedures in the following way. First, the global buckling load is assumed to be a scalar multiple of the design loads and has the form

$$\begin{aligned} (N_x)_{cr} &= \lambda_G N_x, \;\; (N_y)_{cr} = \lambda_G N_y, \\ (N_{xy})_{cr} &= \lambda_G N_{xy} \end{aligned} \tag{1}$$

where N_x, N_y, N_{xy} are the applied in-plane prebuckling loads. These values represent the design loads for the grid-stiffened panel. Second, the design constraints imposed on the panel include requirements that

1. The critical buckling load should be greater than or equal to the design loads, that is, $\lambda_G \geq 1$.

2. The skin segments should not buckle at the critical buckling load, that is, $\lambda_{sk} \geq 1$.

3. The stiffener segments should not cripple at the critical buckling load, that is, $\lambda_1,\ \lambda_2,\ \lambda_3 \geq 1$ where $\lambda_1,\ \lambda_2,\ \lambda_3$ are the crippling load factors of the x-direction stiffener, y-direction stiffener and diagonal stiffener, respectively.

The general form of each constraint equation is written as

$$g_j = (\frac{1}{\lambda_j} - 1) \leq 0.0 \quad j = 1, ..., N_c \qquad (2)$$

Finally, the "Fitness" expression based on an exterior penalty function approach is

$$\text{Fitness} = \quad (\frac{Q}{F(\mathbf{X}, r_i)}) =$$

$$\text{Max} \frac{Q}{W(\mathbf{X}) + r_i \sum_j^{N_c} \ [|g_j(\mathbf{X})| + g_j(\mathbf{X})]^2} \qquad (3)$$

where

$\mathbf{X}$ = design variable vector

$F(\mathbf{X}, r_i)$ = modified objective function

$W(\mathbf{X})$ = weight of panel per unit area

$r_i \sum_j^{N_c} \ [|g_j(\mathbf{X})| + g_j(\mathbf{X})]^2$ = penalty function

Q = normalizing constant

N_c = number of design constraints

r_i = penalty parameter

i = generation or iteration cycle in the optimization procedure.

Once the global buckling load factor has been determined, the loads acting on the stiffener and skin segments have to be determined by distributing the loads among the skin and stiffeners based on their extensional stiffnesses. The procedure for distributing the applied loads for a general grid-stiffened panel is discussed in References 6 and 13.

The weight per unit area of the grid-stiffened panel is

$$W \quad = \quad \frac{\rho}{ab}(w_1 + w_2 + w_3 + w_s)$$

where

$$\begin{aligned} w_1 &= 2\,h\,a\,t_s \\ w_2 &= 2\,h\,b\,t_s \\ w_3 &= 2\,h\,t_s\,\sqrt{a^2+b^2} \\ w_s &= a\,b\,t \end{aligned} \qquad (4)$$

w_1 is the volume of the axial stiffeners in the unit cell, w_2 is the volume of the transverse stiffeners in the unit cell, w_3 is the volume of the diagonal stiffeners in the unit cell, w_s is the volume of the skin in the unit cell, t is the thickness of skin, and ρ is the mass density of the material.

Design Process Based on a Genetic Algorithm

Implementation of the genetic algorithm is shown schematically in Figure 2. The design process begins with a random selection of a specified number of designs which comprise the initial population (i.e., first generation) for the genetic algorithm. The problem parameters such as material properties, length and width, boundary conditions of the panel, and design loads are input into the analysis processor routine. The buckling analyses are performed which provides the critical eigenvalues for the global buckling response of the grid-stiffened panel, and the local buckling response of the skin and stiffener segments. The weight per unit area of the grid-stiffened panel is also computed. This procedure is repeated for each design configuration in the population. The "fitness" processor then evaluates the "fitness" of each design using Equation (3) and assigns a rank based on the fitness expression or the objective function. The current population of design configurations is then processed by the genetic operators (crossover, mutation, and permutation) to create a new population of design configurations for the subsequent generations which combines the most desirable characteristics of the previous generations. Designs from previous generations may be replaced by new ones (i.e., children) except for the "most fit" designs (i.e., parents) which are always included in the next generation. The process is repeated until design convergence is obtained, which is defined herein by specifying a maximum number of generations that may occur without any improvement in the best design. The design procedure is demonstrated on flat and curved grid-stiffened panels in the following sections.

Numerical Results for Flat Grid-stiffened Panels

A 20.0-in.-long and 56.0-in.-wide flat grid-stiffened composite panel representative of a generic transport helicopter fuselage structural component is designed to demonstrate the capabilities of the present design optimization tool. The panel is optimized for a load case with 400.0 lbs/in. of axial compression, which is considered to be the critical load case for this panel. The termination criterion is 30 generations, and the population size is eight. The probabilities used for crossover, mutation, and permutation are 1.0, 0.10, and 0.95, respectively. Also, the penalty parameter r_i is kept constant for all iterations since the genetic algorithms maximize Equation (3) more efficiently. The skin laminate stacking sequence selected is $[\pm 45/90/0]_s$. The stiffeners are made of 0^o material only. The nominal ply mechanical properties used are: E_{11} = 20.2 Msi; E_{22} = 1.9 Msi; $G_{12} = G_{13} = G_{23}$ = 0.73 Msi and ν_{12} = 0.3. The mass density of the material ρ, is 0.0570 lbs/in.^{3} The grid-stiffened panel has simply supported boundary conditions on all edges, and the skin segments are also considered to be simply supported. The grid-stiffened panel is assumed to have only axial and diagonal stiffeners. The axial and transverse stiffener spacings considered are such that all stiffener patterns closely approximate an isogrid configuration. Hence, the axial stiffener spacing a and transverse stiffener spacing b are not independent but are considered as a single design variable, (i.e., (a_s, b_s) is one design variable). The stiffener height h and thickness t_s are also design variables. The design space explored is indicated in Table 1, where the height of the triangle $(b_s/2)$ is kept between 2.9 and 6.0 in., and the stiffener aspect ratio (h/t_s) is kept between 4.5 and 9.0 due to manufacturing constraints. Each design variable is permitted to assume only eight discrete values by the genetic algorithm FORTRAN code being used.

The five best designs from the optimization are shown in Table 2. These designs buckle globally at the indicated load factor of λ_G, since the local buckling load factors (λ_{sk}, λ_1, λ_3) are all greater than one. The first and third designs have a global buckling load factor λ_G of 0.995 and 0.991, respectively, and could still represent acceptable designs. The second and third designs have different stiffener spacing, and yet the global buckling load factor and weight per unit area of these two panels are very close to one another. The fourth and fifth designs also, have similar results. Hence, the ability of the genetic algorithm to obtain multiple optima of comparable performance is demonstrated. The best design for the grid-stiffened panel with a $[\pm 45/90/0]_s$ skin laminate is the first design given in Table 2. Design convergence was achieved after 40 iterations.

The grid-stiffened panel is now assessed using a representative flight-load conditions given in Table 3. The results are also shown in Table 3. Of the six load cases shown in Table 3, load cases 2 to 5 are the flight-load cases. The first and sixth load cases are used to complete the shear and axial-load interaction curve. The panel buckles globally for most of the load cases considered. Crippling of the diagonal stiffener occurs for the load case of N_{xy} = 100 lbs/in. and N_x = 10 lbs/in. In addition, the grid-stiffened panel exhibits local skin buckling for the load case of N_x = 174.0 lbs/in. and N_{xy} = 154.0 lbs/in. The global buckling load factor λ_G for this load case is 2.2382, and the skin local buckling load factor λ_{sk} is 0.9855. The buckling load factor is 2.2057 for the load case of N_x = 174.0 lbs/in. and N_{xy} = 154.0 lbs/in.

Numerical Results for Curved Grid-stiffened Panels

The fuselage design of a generic wide-body transport aircraft is typically divided into four different quadrants. These quadrants include a crown panel, two side panels and a keel panel. A side-quadrant panel is considered herein and designed for global buckling. The side-quadrant panel is shown in Figure 3 and longerons and frames divide the side-quadrant panel into four curved panels. Each panel is chosen to be 22.0-in. long and 22.0-in. wide with a radius of 120.0 in. in the width direction. The dimension of 22.0 in corresponds to the frame spacing. Panel 1 is the forward-top panel of the side-quadrant panel and is subjected to N_x = 1250 lbs/in., N_{xy} = 250 lbs/in., and N_y = -2200 lbs/in. (hoop tension). Panel 2 is the aft-top panel of the side-quadrant panel and is subjected to N_x = 300 lbs/in., N_{xy} = 1350 lbs/in., and N_y = -2200 lbs/in. (hoop tension). Panel 3 is the bottom-top panel of the side-quadrant panel and is subjected to N_x = 2250 lbs/in., N_{xy} = 250 lbs/in., and N_y = -2200 lbs/in. (hoop tension). The panel hoop tension is due to internal pressurization of the fuselage. The nominal ply mechanical properties used are: E_{11} = 20.2 Msi; E_{22} = 1.9 Msi; $G_{12} = G_{13} = G_{23}$ = 0.73 Msi and ν_{12} = 0.3. The mass density of the material ρ is 0.0570 lbs/in.^{3} The grid-stiffened panel is assumed to have simply supported boundary conditions on all edges, and the individual skin segments are considered to be simply supported also. The stiffeners are made of unidirectional material. The termination criterion for the design evolution is 25 generations with no improvement in the "best " design, and the population size is twelve. The probabilities used for crossover, mutation, and permutation are 1.0, 0.10, and 0.95, respectively. Also, the penalty parameter r_i is kept constant for all iterations.

The design variables are the axial stiffener spacing (a), the transverse stiffener spacing (b), the stiffener height (h), the stiffener thickness (t_s), the stacking sequence of the skin laminate ($LAMI$), and the stiffening configuration ($ICON$) which is a design variable indicating the combination of axial, transverse, and diagonal stiffeners in a unit cell. The design space explored for a, b, h, and t_s is shown in Table 4 for Panels 1 and 3, and in Table 5 for Panel 2. The design space for $LAMI$ and $ICON$ is described in Table 6 for Panels 1, 2 and 3, e.g., when $LAMI = 1$, then the skin stacking sequence is $[\pm 45/0]_{2s}$ and when $ICON = 1$, then the stiffening configuration consists of axial stiffeners. In either design space, the minimum stiffener spacing is restricted to two inches, and the aspect ratio of the stiffener (h/t_s) is kept between 3.5 and 10.5 due to manufacturing constraints. Each design variable can assume eight discrete values. A modified Sanders-Koiter shell theory is used to account for transverse shear deformation in the Rayleigh-Ritz buckling analysis.[13]

The results obtained for Panel 2 using the present optimization tool are shown in Table 7. The panel designs presented in Table 7 buckle globally at the corresponding global load factor of λ_G. The genetic algorithm produces a large pool of acceptable designs in this case. Most of the acceptable designs only have axial stiffeners. These axially stiffened panels have stiffener spacings similar to those of the first three designs presented in Table 7, but with different values of stiffener height and thickness. The fourth design in Table 7 has transverse and diagonal stiffeners ($ICON = 6$); however, this design is 14 percent heavier than the first design. Panels stiffened in multiple directions have redundant load paths and typically exhibit better damage tolerance characteristics than panel stiffened in one directions. Therefore, the design process was repeated using a modified design space for the stiffening configuration where values of $ICON$ = 1 and 2 are replaced by $ICON$ = 5 and 6, respectively. That is, all designs include stiffeners in multiple directions. The results for this optimization are shown in Table 8. The panels presented in Table 8 buckle globally at the corresponding global load factor of λ_G. The genetic algorithm produces a large pool of acceptable designs with axial and transverse stiffeners ($ICON = 3$). These panels have stiffener spacings represented by the first four designs of Table 8, with variation in stiffener height and thickness and with a skin laminate stacking sequence of $[\pm 45/0]_{2s}$ ($LAMI = 1$) or $[\pm 45/90]_{2s}$ ($LAMI$ = 2). The weight of each panel is comparable to the weight of the axially stiffened panels presented in Table 7. The fifth design has both axial and diagonal stiffeners ($ICON = 5$), while the sixth design is the same as the fourth design presented in Table 7. The best design for Panel 2 is the design with transverse and diagonal stiffeners, which is the fourth design in Table 7 and the sixth design in Table 8. This design is preferred over the lighter weight axially stiffened panel and the axially and transversely stiffened panel since the panel with diagonal stiffening may be more damage tolerant.[9] The sixth design in Table 8 is also preferred over the fifth design in Table 8, since it has more stiffeners than the axially and diagonally stiffened panel and its weight is close to that of the latter. The convergence behavior of the genetic algorithm for Panel 2 is shown in Figure 4. The convergence is faster when there is no restriction on the stiffening configuration variable ($ICON$). The optimization process is performed for Panels 1 and 3, and the best design obtained for these two panels are shown in Table 9.

The results for the best design obtained for Panel 3 for the design load cases used for Panel 1 and Panel 2 are shown in Table 10. For the loads corresponding to Panel 1, the panel buckles globally at a buckling load factor of 2.114, and hence, this design represents a conservative design for these loads. For the loads corresponding to Panel 2, the buckling load factor of the diagonal stiffener is 0.255, and, hence, the buckling deformation contains local buckling of the diagonal stiffener at a load factor of $\lambda_3 \times \lambda_G = 1.172$. Therefore, this design also represents a conservative design for the loads for Panel 3. Hence, the best design for Panel 3 can also be used for Panel 1 and Panel 2 with a weight penalty of 6.7 and 22.9 percent, respectively, when compared to their respective best design. For a grid-stiffened fuselage structure construction, it is desirable that all the panels have the same stiffener pattern due to both manufacturing and structural considerations. The region where stiffeners from two different panels connect (heavy lines in Figure 3) have to be joined and is a critical area especially if the stiffening patterns of the two panels are not the same. To alleviate that problem, these regions have to be reinforced, which could result in a higher weight penalty.

Concluding Remarks

A minimum-weight design optimization tool with buckling constraints has been developed for grid-stiffened panels using global and local buckling analyses and a genetic algorithm. Design variables used are axial and transverse stiffener spacing, stiffener height and thickness, skin-laminate stacking sequence, and stiffening configuration. Results for flat and curved grid-stiffened panels indicate that the best design configurations obtained by the genetic algorithm depend mostly on the load cases. For most combined applied load cases, the best designs have diagonal stiffeners. However in certain cases, the best design obtained by the genetic algorithm, based on buckling considerations only, may not be suitable for structural applications due to manufacturing, joining, and damage-tolerance considerations. In this case, the pool of acceptable designs obtained by the genetic algorithm provides alternative design options for a given structural application.

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Table 1 Design space for flat grid-stiffened panels.

Stiffener spacing, in. (a_s, b_s)	Stiffener height, in. (h)	Stiffener thickness, in. (t_s)
(6.667 , 11.200)	0.49375	0.060
(5.714 , 10.182)	0.50000	0.066
(5.000 , 8.615)	0.50625	0.072
(4.444 , 8.000)	0.51250	0.078
(4.444 , 7.467)	0.51875	0.084
(4.000 , 7.000)	0.52500	0.090
(3.636 , 6.222)	0.53125	0.096
(3.333 , 5.894)	0.53750	0.102

Table 2 Best designs obtained by the genetic algorithm for a grid-stiffened panel.

Design variables	Buckling load factors	weight, lbs/ft^2
a_s = 5.000 in., b_s = 8.615 in., h = 0.5375 in., t_s = 0.06 in.	$\lambda_G = 0.995$, $\lambda_{sk} = 1.024$, $\lambda_1 = 1.341$, $\lambda_2 = 21.208$	0.578
a_s = 4.444 in., b_s = 8.000 in., h = 0.5375 in., t_s = 0.06 in.	$\lambda_G = 1.047$, $\lambda_{sk} = 1.179$, $\lambda_1 = 1.470$, $\lambda_2 = 25.608$	0.596
a_s = 4.444 in., b_s = 7.467 in., h = 0.5125 in., t_s = 0.06 in.	$\lambda_G = 0.991$, $\lambda_{sk} = 1.392$, $\lambda_1 = 1.637$, $\lambda_2 = 24.507$	0.594
a_s = 4.444 in., b_s = 7.467 in., h = 0.5125 in., t_s = 0.072 in.	$\lambda_G = 1.139$, $\lambda_{sk} = 1.285$, $\lambda_1 = 2.146$, $\lambda_2 = 32.120$	0.634
a_s = 4.444 in., b_s = 8.000 in., h = 0.5375 in., t_s = 0.072 in.	$\lambda_G = 1.207$, $\lambda_{sk} = 1.084$, $\lambda_1 = 1.920$, $\lambda_2 = 33.458$	0.636

Table 3 Buckling loads for grid-stiffened panels.

Load case number	N_x, lbs/in.	N_{xy}, lbs/in.	Buckling load factor, λ
1	400.0	0.000	0.995^a
2	396.0	130.0	1.002^a
3	326.0	178.0	1.211^a
4	271.0	139.0	1.458^a
5	174.0	154.0	2.206^b
6	10.00	100.0	4.145^c

^{a}global buckling.
^{b}skin buckling.
^{c}diagonal stiffener buckling.

Table 4 Design space for a, b, h and t_s of Curved Panels 1 and 3.

a, in.	b, in.	h, in.	t_s, in.
11.000	11.000	0.49375	0.060
8.800	8.800	0.50000	0.066
7.333	7.333	0.50625	0.072
6.286	6.286	0.51250	0.078
5.500	5.500	0.51875	0.084
4.889	4.889	0.52500	0.090
4.400	4.400	0.53125	0.096
4.000	4.000	0.53750	0.102

Table 5 Design space for a, b, h and t_s of Curved Panel 2.

a, in.	b, in.	h, in.	t_s, in.
11.000	11.000	0.30	0.042
8.800	8.800	0.32	0.048
7.333	7.333	0.34	0.054
6.286	6.286	0.36	0.060
5.500	5.500	0.38	0.066
4.889	4.889	0.40	0.072
4.400	4.400	0.42	0.078
4.000	4.000	0.44	0.084

Table 6 Description of design space for $ICON$ and $LAMI$ for Panels 1, 2, and 3.

Integer value	$LAMI$	$ICON$
1	$[\pm45/0]_{2s}$	axial stiffeners
2	$[\pm45/90]_{2s}$	transverse stiffeners
3	$[\pm45/0/90]_{2s}$	axial and transverse stiffeners
4	$[\pm45/0_2]_{2s}$	diagonal stiffeners
5	$[\pm45/90_2]_{2s}$	axial and diagonal stiffeners
6	$[\pm45/0_2/90]_{2s}$	transverse and diagonal stiffeners
7	$[\pm45/0/90_2]_{2s}$	axial, transverse and diagonal stiffeners
8	$[\pm45/0_2/90_2]_{2s}$	no stiffeners

Table 7 Best designs obtained by the genetic algorithm for grid-stiffened Curved Panel 2.

Design variables	Weight, lbs/ft^2	Buckling load factors
$b = 11.0$ in., $h = 0.360$ in., $t_s = 0.060$ in., $LAMI = [\pm45/0]_{2s}$, $ICON = 1$	0.6232	$\lambda_G = 1.061$, $\lambda_{sk} = 16.494$ $\lambda_1 = 2.745$
$b = 7.333$ in., $h = 0.340$ in., $t_s = 0.042$ in., $LAMI = [\pm45/0]_{2s}$, $ICON = 1$	0.6229	$\lambda_G = 0.998$ $\lambda_{sk} = 221.17$ $\lambda_1 = 1.62$
$b = 6.2857$ in., $h = 0.340$ in., $t_s = 0.042$ in., $LAMI = [\pm45/0]_{2s}$, $ICON = 1$	0.6283	$\lambda_G = 1.129$ $\lambda_{sk} = 206.79$ $\lambda_1 = 1.45$
$a = 5.5$ in., $b = 6.2857$ in., $h = 0.320$ in., $t_s = 0.054$ in., $LAMI = [\pm45/0]_{2s}$, $ICON = 6$	0.711	$\lambda_G = 0.996$, $\lambda_{sk} = 5.01$, $\lambda_2 = -.30$, $\lambda_3 = 1.650$

Table 8 Best designs obtained by the genetic algorithm for grid-stiffened Curved Panel 2, with $ICON$ = 1, 2 excluded from the design space.

Design variables	Weight lbs/ft^2	Buckling load factors
a = 11.0 in., b = 8.8 in., h = 0.340 in., t_s = 0.042 in., $LAMI$ = $[\pm45/0]_{2s}$, $ICON$ = 3	0.6389	λ_G = 1.038, λ_{sk} = 3.05, λ_1 = 2.01, λ_2 = -0.149
a = 11.0 in., b = 11.0 in., h = 0.340 in., t_s = 0.048 in., $LAMI$ = $[\pm45/90]_{2s}$, $ICON$ = 3	0.6396	λ_G = 1.022, λ_{sk} = 2.07 λ_1 = 1.28, λ_2 = -0.360
a = 11.0 in., b = 7.333 in., h = 0.320 in., t_s = 0.042 in., $LAMI$ = $[\pm45/90]_{2s}$, $ICON$ = 3	0.6411	λ_G = 1.076, λ_{sk} = 4.141 λ_1 = 1.07 λ_2 = -0.366
a = 8.8 in., b = 8.8 in., h = 0.340 in., t_s = 0.042 in., $LAMI$ = $[\pm45/90]_{2s}$, $ICON$ = 3	0.6442	λ_G = 1.083, λ_{sk} = 2.979 λ_1 = 1.08, λ_2 = -0.300
a = 11.0 in., b = 11.0 in., h = 0.340 in., t_s = 0.084 in., $LAMI$ = $[\pm45/0]_{2s}$, $ICON$ = 5	0.6938	λ_G = 2.160, λ_{sk} = 2.442 λ_1 = 3.23, λ_3 = 1.234
a = 5.5 in., b = 6.2857 in., h = 0.320 in., t_s = 0.054 in., $LAMI$ = $[\pm45/0]_{2s}$, $ICON$ = 6	0.711	λ_G = 0.999, λ_{sk} = 5.01 λ_2 = -.30 λ_3 = 1.650

Table 9 Best designs obtained by the genetic algorithm for grid-stiffened Curved Panels 1 and 3.

Design variables	Weight, lbs/ft^2	Buckling load factors
Panel 1		
a = 4.8890 in., b = 6.2857 in., h = 0.500 in., t_s = 0.060 in., $LAMI$ = $[\pm45/90]_{2s}$ $ICON$ = 6	0.819	λ_G = 1.080, λ_{sk} = 1.290, λ_2 = -0.394, λ_3 = 18.189
Panel 3		
a = 5.500 in., b = 4.400 in., h = 0.50625 in., t_s = 0.072 in., $LAMI$ = $[\pm45/90]_{2s}$, $ICON$ = 6	0.874	λ_G = 1.014, λ_{sk} = 1.369, λ_2 = -0.781, λ_3 = 1.191

Table 10 Buckling loads for the best design of Panel 3 subjected to the load cases of Panels 1 and 2.

Panel number	Load, lbs/in.	Buckling load factors
Panel 1[a]	N_x = 1250, N_y = -2200, N_{xy} = 250.	λ_G = 2.114, λ_{sk} = 1.488, λ_2 = -0.374, λ_3 = 1.0113,
Panel 2[b]	N_x = 300, N_y = -2200, N_{xy} = 1350.	λ_G = 4.595, λ_{sk} = 2.409, λ_2 = -0.172, λ_3 = 0.255

[a]Global buckling at λ_G = 2.114
[b]Local buckling of diagonal stiffener at $\lambda_{critical}$ = 1.172

Figure 1: Unit cell of a grid-stiffened panel showing design variables.

Figure 2: Flow chart for the optimization using the genetic algorithm.

Figure 3: Side quadrant panel of fuselage structure.

Figure 4: Design convergence for composite grid-stiffened curved panel (Panel 2).

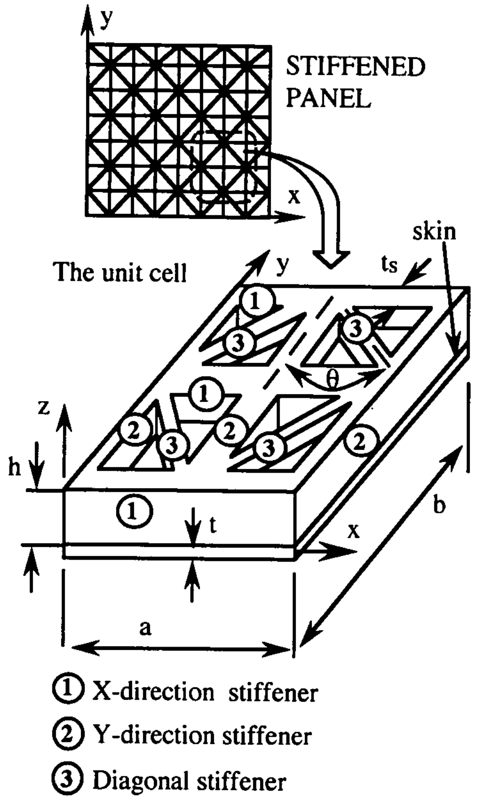

Figure 1 Unit cell of grid-stiffened panel showing design variables.

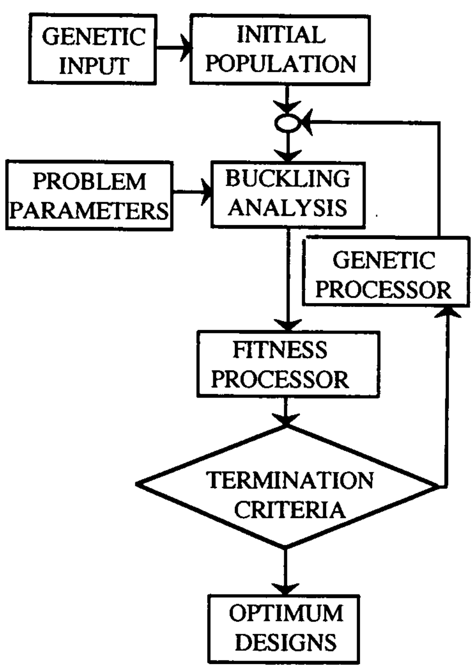

Figure 2 Flow chart for the optimization procedure using the genetic algorithm.

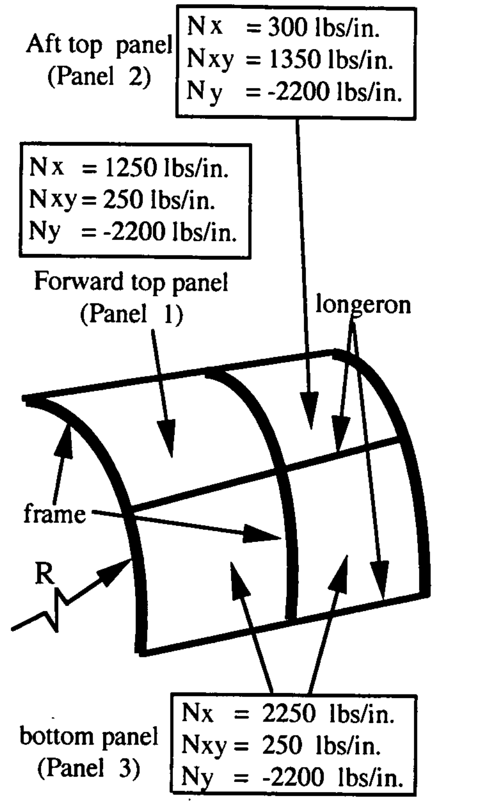

Figure 3 Side quadrant panel of a fuselage structure.

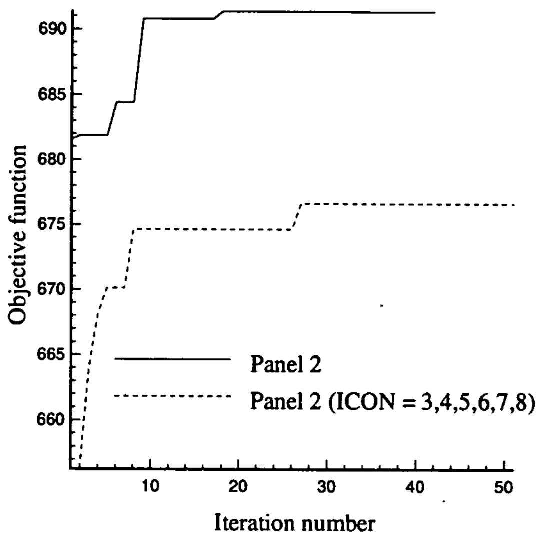

Figure 4 Design convergence history for a composite grid-stiffened curved panel (Panel 2).