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DESIGN AND ANALYSIS OF GRID STIFFENED CONCEPTS FOR AIRCRAFT COMPOSITE PRIMARY STRUCTURAL APPLICATIONS

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INTRODUCTION

Structural efficiency is of paramount importance in aircraft structures in order to produce affordable aircraft. This requirement has dictated use of stiffened composite structures where a flat or curved skin is reinforced with stiffeners by cocured, bonded, or bolted attachment. Of the above, stiffened structures produced by cocuring have reduced part count and, hence, are cost effective. Although many manufacturing processes are available to produce cocured structures, automated tow or tape placement and filament or tape winding methods have emerged as some of the most viable ones due to their amenability to automation.

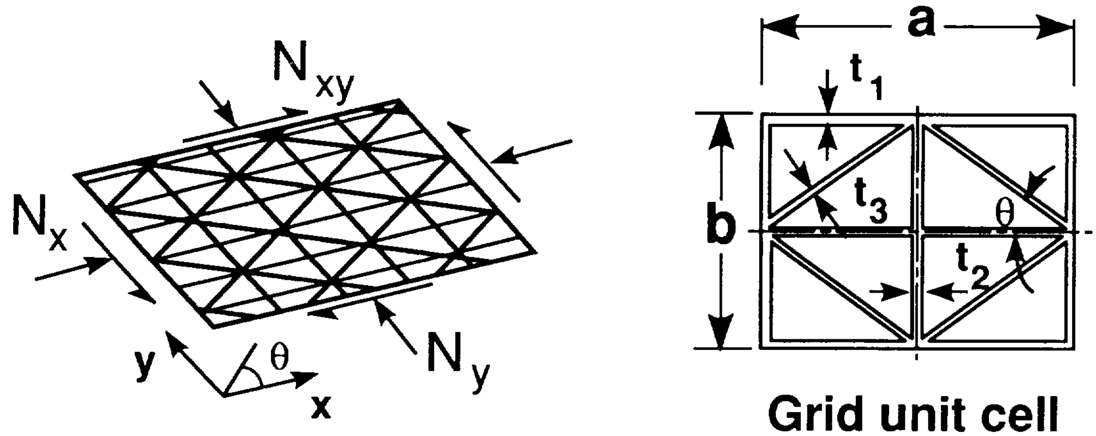
Although there have been many studies and applications involving continuous filament grid stiffened structures, most of these designs were based on prior experience and finite element analysis. Such an approach is cumbersome and does not always result in an optimum design. An analytical tool is thus necessary to understand the sensitivity of the buckling behavior of grid stiffened structures to different geometric and material parameters and to make rational choices of stiffening configurations based on detailed and well understood parametric studies. This paper presents an approach to buckling resistant design of general grid stiffened flat panels based on smeared stiffener theory for combined in-plane loading. Some results from parametric studies performed to assess the validity of smeared stiffener theory for practical stiffener configurations and to illustrate the benefits of different stiffening concepts are presented. Details of a design study are discussed where the present analysis method is used to design a grid stiffened panel for a fuselage application and verified using finite element analysis results.

a	Length of grid unit cell
a_1	Base dimension of triangular plate
A	Panel In-plane stiffness matrix
b	Width of grid unit cell
B	Panel bending-extension coupling stiffness matrix
C_{44}, C_{45}, C_{55}	Shear stiffnesses
d	Width of stiffener element
D	Panel bending stiffness matrix
E_{11}, E_{22}	Young's moduli of stiffener element in the longitudinal and transverse directions
G_{12}, G_{13}	Shear modulus of stiffener element
h	Height of triangular plate element
l	Length of the stiffener element
m,n	Number of half-waves in the plate length and width directions
M	Moment resultant
M_x, M_y, M_{xy}	Moment resultants about x and y axes and torsional moment
N	Force resultant
N_x, N_y, N_{xy}	Force resultants in the x and y directions and in-plane shear force
$[N_x]_{cl}$	Classical buckling load
$[N_x]_{cr}$	Critical load
Q_x, Q_y	Shear force resultants
$\overline{S}_z$	Transverse shear stiffness
t, t_1, t_2, t_3	Thickness of stiffeners
u,v,w	Displacements in the x, y, and z directions
x,y,z	Cartesian coordinates
$\varepsilon_x, \varepsilon_y$	Extensional strains in the x and y directions
ϕ_x, ϕ_y	Section rotations about x and y axes
$\gamma_{xy}, \gamma_{yz}, \gamma_{xz}$	Shear strains
$\kappa_x, \kappa_y, \kappa_{xy}$	Bending and twisting curvatures
μ_{12}	Major Poisson's ratio
θ	Grid angle, triangular plate base angle

General Instability

Constitutive Relations

A general grid stiffened panel is shown in figure 1 where a flat skin is stiffened with solid rectangular blades in the x, y, and $\pm\theta$ directions. This generality in choosing the grid pattern is sufficient to address several stiffened panel configurations that are likely in aircraft fuselage and wing structures. The constitutive properties used in panel general instability analysis are based on smeared stiffener theory. The unit cell configuration used for this purpose is shown on the right side of figure 1. In the general constitutive relations of equation 1, the stiffness matrices A, B, and D and the shear stiffness coefficients C_{44}, C_{45}, and C_{55} assume values corresponding to the smeared plate problem that is being solved. The details at stiffener intersections are not included in this model.



Grid unit cell

Figure 1

$$
\begin{Bmatrix} N \\ M \end{Bmatrix} = \left[\begin{array}{c:c} A & B \\ \hdashline B & D \end{array}\right] \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix}
$$

$$
\begin{Bmatrix} Q_y \\ Q_x \end{Bmatrix} = \begin{bmatrix} C_{44} & C_{45} \\ C_{54} & C_{55} \end{bmatrix} \begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} \tag{1}
$$

Kinematic Relations and Stability Equations

The analytical model is for stiffened panels where the stiffeners are made of unidirectional material oriented along the stiffener length. While this material orientation is efficient structurally, the transverse shear stiffness that results is low and is largely determined by the matrix properties. The effects due to transverse shear deformation are shown to be important in reference 1 and are included in the global analysis through a first order shear deformation theory. This theory is an adequate representation of shear deformation for global buckling analysis. The linear kinematic relations used are given in equation 2 and governing equations for general stability are given in equation 3. For the case of a simply supported panel considered here, solution to this eigenvalue problem is obtained in a closed form for the case of compression loading while the Galerkin method is used to estimate the eigenvalues for combined in-plane loading.

$$
\begin{aligned}
\varepsilon_x &= u_{,x} \\
\varepsilon_y &= v_{,y} \\
\gamma_{xy} &= v_{,x} + u_{,y} \\
\gamma_{xz} &= \phi_x + w_{,x} \\
\gamma_{yz} &= \phi_y + w_{,y} \\
\kappa_x &= \phi_{x,x} \\
\kappa_y &= \phi_{y,y} \\
\kappa_{xy} &= \phi_{y,x} + \phi_{x,y}
\end{aligned}
\qquad (2)
$$

$$
\begin{gathered}
N_{x,x} + N_{xy,y} = 0 \\
N_{xy,x} + N_{y,y} = 0 \\
M_{x,x} + M_{xy,y} = Q_x \\
M_{xy,x} + M_{y,y} = Q_y \\
Q_{x,x} + Q_{y,y} + N_x W_{,xx} + 2 N_{xy} W_{,xy} + N_y W_{,yy} = 0
\end{gathered}
\qquad (3)
$$

Local Instability

Buckling analyses of stiffener and skin elements are included in the local analysis and are used as constraints on the panel design. The analytical modeling details for these buckling constraints are presented in this section.

Stiffener Buckling

The stiffener is modeled as an orthotropic plate with clamped boundary conditions at the ends and simply supported and free boundary conditions along the other two edges. A schematic of a stiffener element is shown in figure 2. The expression for the stiffener buckling load is given in equation 4. When transverse shear effects are included, this expression takes the form of equation 5. The approximate shear correction factor of 5/6 in equation 6 is taken from reference 2.

Skin Buckling

Skin geometries of rectangular and triangular shapes are included in the analysis. The skin element is treated as a laminated plate with specially orthotropic properties and simply supported edges. The buckling loads of rectangular plates are obtained using expressions from reference 3. For triangular plate buckling analysis a deflection function shown in equation 7 is used. This function satisfies all simply supported boundary conditions on the triangular plate shown on the right of figure 2 except the zero moment condition along the inclined edges. Hence, the modified Galerkin method is used here to obtain the buckling load. Transverse shear deformation effects in the skins are neglected due to its thinness.

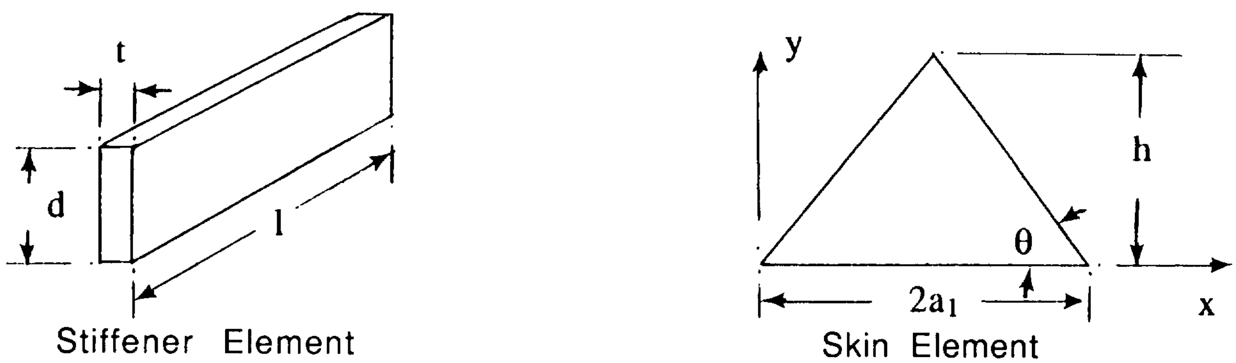


Figure 2

$$[N_x]_{cl} = t^3 \left[\frac{4\,\pi^2 E_{11}}{12\, l^2 \left[1-\mu_{12}^2 \dfrac{E_{22}}{E_{11}}\right]} + \frac{G_{12}}{d^2} \right] \tag{4}$$

$$[N_x]_{cr} = \frac{\bar{S}_z}{2}\left[\sqrt{1+\frac{4\,[N_x]_{cl}}{\bar{S}_z}} - 1\right] \tag{5}$$

$$\bar{S}_z = \frac{5}{6} G_{13}\, b \tag{6}$$

$$w = \sum_m \sum_n w_{mn} \left[\sin\frac{m\pi x}{a_1} \sin\frac{n\pi y}{h} - \sin\frac{n\pi x}{a_1} \sin\frac{m\pi y}{h}\right] \tag{7}$$

PARAMETRIC STUDIES

A computer program has been written to facilitate a systematic parametric design search. For a given set of loading conditions, stiffening concept, and skin laminate choice, minimum weight designs are sought by varying the stiffener spacings a and b, diagonal stiffener orientation angle θ and stiffener dimensions.

Several parametric studies are conducted to ensure applicability of the present analysis approach that uses smeared stiffener theory for its constitutive relations and also to assess the efficiency of different stiffening concepts. Some of the results obtained on a flat panel of 30 in. length and 24 in. width with a symmetric skin layup of +45,-45, and 0 degree plies made of AS4/3501-6 graphite-epoxy material are presented in this section.

Assessment of Smeared Stiffener Theory

Buckling load results obtained from the present analysis on prismatic stiffened panels are compared with those from the Panel Analysis and Sizing COde (PASCO), which uses a discrete stiffener analysis for a prismatic stiffened panel subjected to axial compression (reference 4). This study is primarily to establish the range of stiffener spacing for which the present analysis method is applicable. The minimum weight results of prismatic stiffened panels obtained from each of these analysis methods for two compression loading cases are presented in figure 3 for increasing numbers of unit cells. The unit cell definitions used in this paper for different stiffening configurations are shown on the left side of figure 3. In both load cases, the present analysis gives an upper bound for panel weight. At an applied axial loading of 3,000 lb/in., the PASCO analysis results and the present results agree well when the number of unit cells is larger than four. The maximum difference between the two sets of results is seven percent and corresponds to the case with two unit cells. A similar trend is obtained for an applied loading of 10,000 lb/in., and the maximum difference in results for two unit cells is 13 percent. This study suggests that the present approach is adequate for studying the buckling response of panels with practical stiffener spacings which are normally less than 8 in.

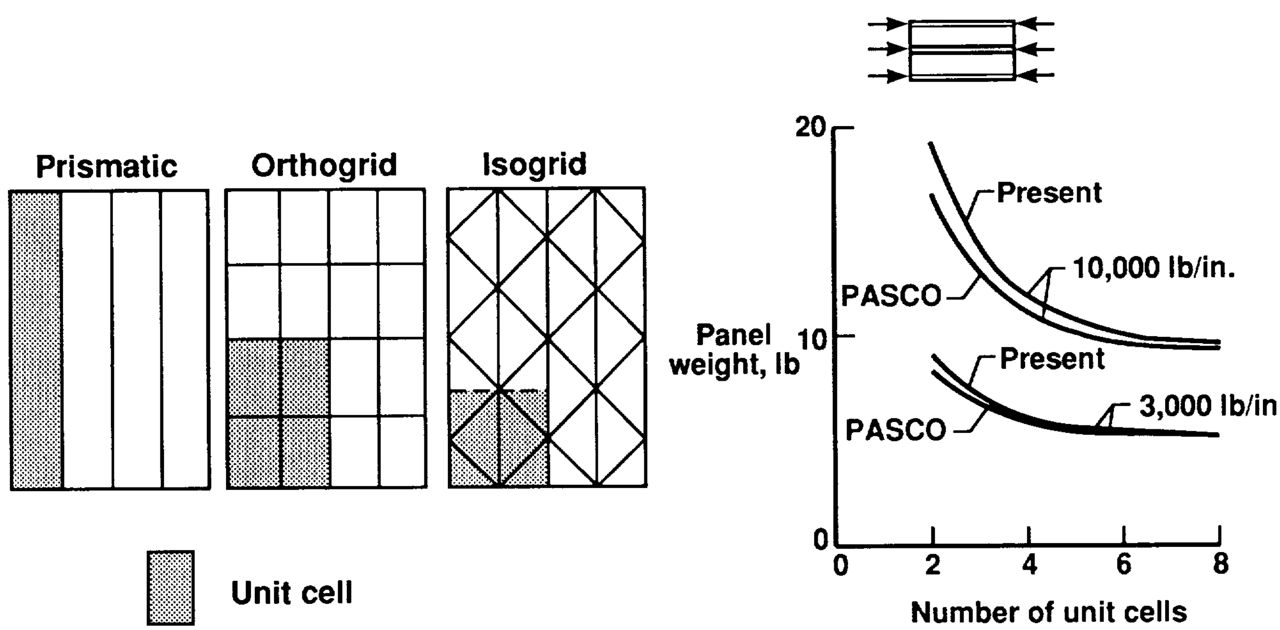


Figure 3

C-5

Evaluation of Stiffening Concepts

Results from preliminary studies on prismatic stiffener, orthogrid, and isogrid structural configurations are presented in figure 4. The figure to the left illustrates the weight efficiencies of the above structural configurations for an axial compression loading of 3,000 lb/in. as a function of the number of unit cells along the panel width. The number of unit cells shown on the abscissa of figure 4 for the orthogrid configuration represents the number of unit cells in both the panel width and length directions. Such choice was made for this study in spite of the flexibility to choose any number of unit cells along the panel length. In the case of an isogrid structural concept, the number of unit cells along the panel length are dependent on the number of unit cells along the panel width. For the panel length of 30 in., the numbers of unit cells along the length of the isogrid panel are rounded off to be 4, 8, 13, and 17 and correspond to 2, 4, 6, and 8 unit cells across the panel width. This resulted in a variation of the diagonal stiffener angle θ from 58 to 60 degrees. The results for this compression loading case suggest that the orthogrid and isogrid stiffener concepts are more efficient than the prismatic stiffener concept by at least 11 percent.

A loading case with a combination of 3000 lb/in. axial compression loading and 1500 lb/in. shear loading is also investigated and the results of this study are presented on the right side of figure 4. Weight efficiency trends similar to the compression loading case are plotted. The orthogrid and isogrid concepts demonstrate 13 and 16 percent weight advantage, respectively, compared to the prismatic stiffener concept.

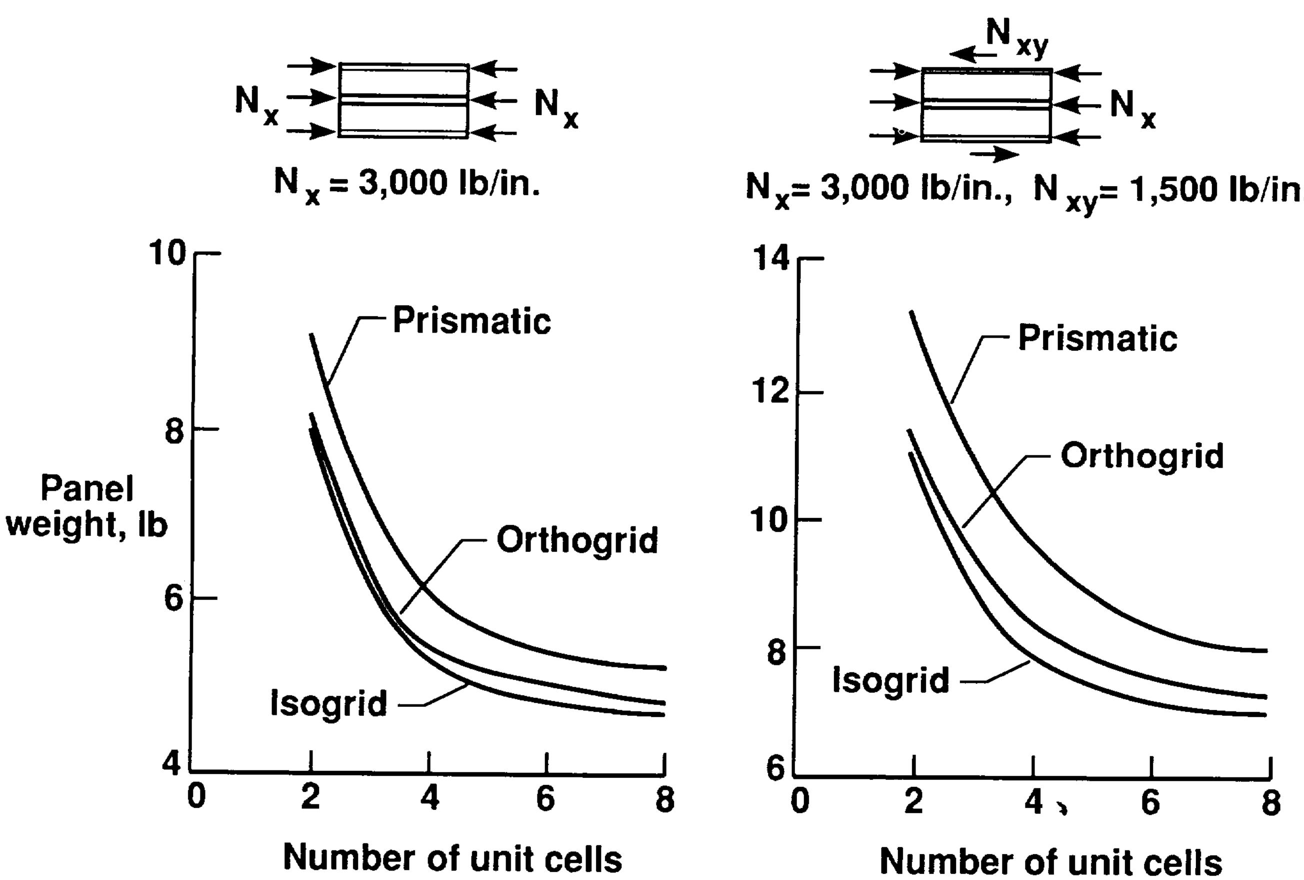


Figure 4

The purpose of this study is to design a panel to carry a combined loading condition that is typical of a fuselage structure using the present sizing procedure and to verify the accuracy of this design with finite element analysis. The dimensions of the panel, applied loading, skin ply details, and material type considered are listed in table 1. The final stiffener dimensions of the panel presented in this table were obtained with a preselected orientation of the diagonal stiffeners equal to 24 degrees.

A finite element model of the above panel has been generated using the DIAL Finite Element Analysis System (reference 5) and is shown in figure 4. Modified shear deformable shell elements are used for modeling both skin and stiffeners. The total number of degrees of freedom for this problem is about 19000. A bifurcation buckling analysis has been performed on this structure with simply supported boundary conditions to obtain buckling loads and corresponding mode shapes.

Panel dimensions:	60 in. length, 36 in. width
Design Loading:	N_x = -3000 lb/in., N_y = 1500 lb/in., N_{xy} = 600 lb/in.
Diagonal stiffener angle:	24 degrees
Skin layup:	$(45/0_2\,/\text{-}45/0_2\,/\text{-}45/90/45)_s$
Material:	IM7/8551-7A graphite-epoxy
Final stiffener dimensions:	1.65 in. height, 0.32 in. width

Table 1

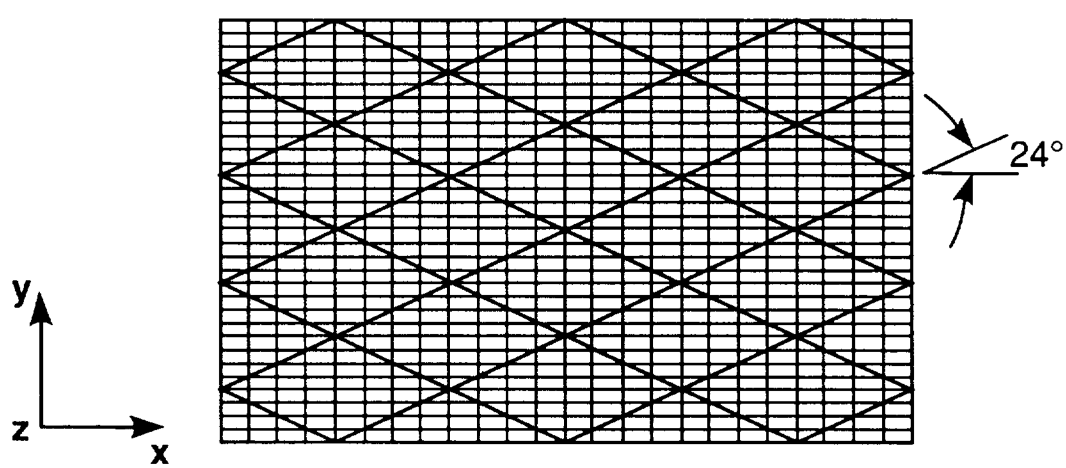
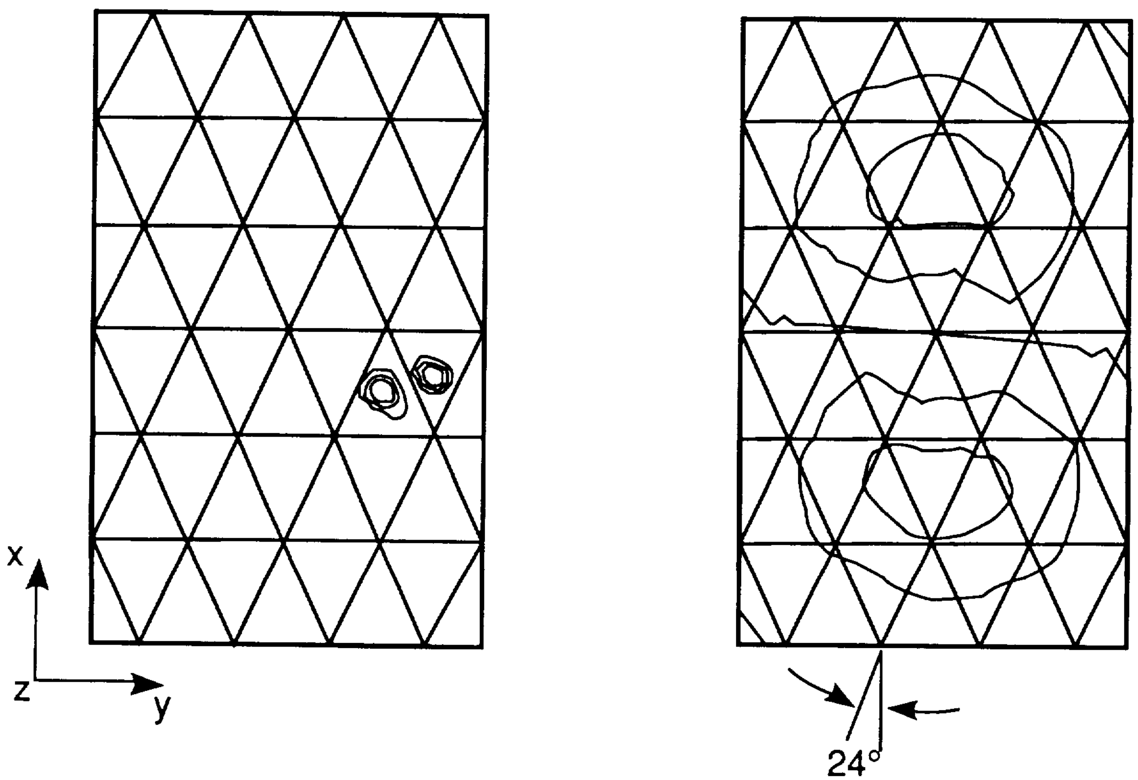


Figure 5

Finite Element Analysis Results

The buckling analysis results obtained using this finite element model are presented in figure 6 which shows the out-of-plane deflection contours. The first buckling event occurs at 92 percent of the design loading and involves local buckling of the triangular skin elements as shown on the left side of figure 6. There are three additional skin buckling modes prior to the global buckling of the panel illustrated on the right side of this figure. The finite element analysis result corresponding to this global buckling mode is 113 percent of the design load for essentially the same mode shape of two half waves in the length direction obtained from the present analysis. This design study demonstrates that the present analysis approach provides a good tool for preliminary sizing of general grid stiffened flat panels subjected to combined in-plane loading.



Local mode at 92 percent of design load

Global mode at 113 percent of design load

Figure 6

CONCLUDING REMARKS

The parametric studies conducted to date suggest that the present approach for analyzing general grid stiffened panels for combined loading with buckling constraints is adequate for design purposes. Comparison of present results with PASCO analysis results established the applicability of this approach for practical stiffener spacings. Results from weight efficiency studies on prismatic, isogrid, and orthogrid structural configurations for different loading conditions suggest sensitivity of the design to geometric and loading parameters. The design study demonstrates the usefulness of the present analysis method in the preliminary design phase of general grid stiffened structures subjected to combined loading.

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