ABSTRACT

The grid-stiffened family of panels has recently been added in the HyperSizer® structural analysis and sizing optimization software. Isotropic, equivalent orthotropic (Quick Composite Optimization) and general laminated composites are fully supported for the IsoGrid, OrthoGrid, XGrid, YGrid, BiGrid, and GeneralGrid rib-stiffened panel concepts. Sandwich BiGrid, IsoGrid, and OrthoGrid concepts are also included. The HyperSizer implementation is quite general. For sizing optimization, the webs of the longitudinal (0), transverse (90), and angle (theta) can all have different thicknesses, spacings, and heights. The angle web can have any angle between zero and ninety degrees. The facesheets and webs can be different materials, laminates, or layups. The Mindlin plate form is used to represent the equivalent continuum of grid layout and as a result can be directly incorporated with the FEM technique. Full unsymmetric, B_{ij}, stiffness and thermal coefficient membrane-bending coupling terms are derived on the panel level and on the laminate level and are used in the 1) panel formulations 2) ply-by-ply strain/stress analyses and 3) in the panel buckling and frequency computations. This generality, accuracy of analysis, and quick optimization capability provides some new insight into the potential performance of grid-stiffened panels.

KEY WORDS: Advanced Composites, Software, Grid Stiffened Panels

1. INTRODUCTION

A new tool for analyzing and optimizing grid stiffened panels made with either isotropic or composite materials is introduced. This tool will be useful for structural engineers and material scientists. For the structural engineer it will automate stress analysis, perform sizing optimization
for reduced weight, and automatically generate HTML reports of the resulting design such as optimum cross sectional dimensions and layups for a given set of mechanical and thermal loadings. For the material scientist it will quantify the effects of varying fiber volume and material systems for trade studies of different grid stiffened panel concepts.

1.1 Applications Some various shaped stiffening members commonly used for panel structural concepts are "T", "Z", "J", "I", blade, and hat shaped stiffened. The stiffening member provides the benefit of added load-carrying capability with a relatively small additional weight penalty. Most stiffened panel designs provide high bending stiffness in only one direction. Such unidirectionally designed panels are easier to manufacture and most applications do not require high bending stiffness in both directions.

![Figure 1 A general grid-stiffened panel with longitudinal, transverse, and angle ribs.](image)

However there are many applications for grid-stiffened structures that have stiffeners running in two, three, and four different directions. In the aerospace industry they have and continue to be used for external surfaces of aircraft and space launch vehicles. Thermal forces and moments induced from temperature gradients are smaller for stiffened panels than they are for sandwich type panels. These reduced thermal loads make them efficient as hot structure for space applications and launch vehicles. Their use in the past has mostly been with isotropic, machined metals [1]. Only recently has the industry developed methods to economically fabricate, grid stiffened panel concepts with fiber-reinforced advanced composite material [2]. One solution uses multiple tooling materials which leads to the name "Hybrid Tooling". The combination of materials allows for precise control of lateral rib compaction, while maintaining process controllability. The Hybrid Tooling concept, developed by the Air Force Research Laboratory, Space Vehicles Directorate is proven to be compatible with filament winding and expected to be compatible with fiber placement. In their studies, the traditional equilateral pattern, which leads to the name isogrid, has been abandoned in favor of stiffener patterns optimized to specified loading situations.
1.2 Issues By nature of their shapes, grid-stiffened panels are both orthotropic and unsymmetric, even when fabricated with conventional metallic materials. These additional panel behaviors complicate the formulation of stiffness, thermal expansion, and thermal bending. Quantifying these behaviors is important because they significantly alter computed force, moment, curvature, strain, stress, and load carrying capability. The thermoelastic panel formulation shown in the next section quantifies the membrane-bending response.

2. IMPLEMENTATION

2.1 Thermoelastic Formulations
The grid-stiffened panel formulation begins with a review of laminate formulations. For a layered material, the membrane, membrane-bending coupling, and bending stiffnesses are noted as

\[
\begin{aligned}
(A_{ij}, B_{ij}, D_{ij}) &= \frac{h}{2} \int_{-h/2}^{h/2} (\overline{Q}_{ij})_k (l,-z,z^2) dz \\
&= (3)
\end{aligned}
\]

In equation (1) the

\[
\overline{Q}_{ij} = Q_{ij} [T]^4
\]

and are the transformed reduced layered elasticities of the laminae. [T]^4 is a fourth order transfer tensor and Q_{ij} are, as an example

\[
Q_{11} = \frac{E_x}{(1-\nu_{21}\nu_{12})}
\]
In equation (2) the
\[ \Phi_i = Q_{ij} \alpha_i [T]^2 \]
are the transformed reduced layered thermal force coefficients. \( \alpha_i \) are the material expansion coefficients. This approach extended to panel concepts has been shown in references [3] to be
\[ \left( A_{ij}, B_{ij}, D_{ij} \right) = \int_{-h/2}^{h/2} \left( \frac{h}{2} \Phi_{ij} \right) (1, -z, z^2) dz \]
and
\[ \left( A_{ij}^\alpha, B_{ij}^\alpha, D_{ij}^\alpha \right) = \int_{-h/2}^{h/2} \left( \frac{h}{2} \Phi_{ij}^\alpha \right) (1, -z, z^2) dz \]
for the panel membrane, membrane-bending coupling, and bending stiffness terms and thermal coefficients. The asterisks indicate laminate and not lamina properties. The laminate properties are defined as
\[ Q_{ij}^* = \frac{A_{ij}}{t} \]
\[ \Phi_i^* = \frac{A_i^\alpha}{t} \]
Material properties interpolated from a database, providing non-linear temperature and load dependent data based on the aircraft trajectory event. The FEA computed tension or compressive load and in-plane and through-the-thickness temperature gradients are used to generate these laminate or metallic sheet properties. If the panel sheets are laminates, the properties of the sheet are treated as being homogeneous, which is a valid assumption because the panel depth is much greater than the laminate thicknesses \( t_1, t_2, \) or \( t_3. \) This assumption is also made in classical lamination theory because each ply is treated as being homogeneous even though it is a mixture of fiber and matrix.

The equivalent plate formulation of any stiffened panel shape, through extension of classical lamination theory, is accomplished by locating a reference plane, identifying its layers with a \( k_i \) value, and defining the \( h_i \) heights from the reference plane. The panel layers, in this sense, are the facesheet and rib laminates. This approach produces the following general equations for panel stiffness terms and thermal coefficients.
\[ \left( A_{ij}^p, -2B_{ij}^p, 3D_{ij}^p \right) = \sum_{k=1}^{n} \frac{h_{k-1}^m - h_k^m}{S_k} \left( Q_{ij}^* \right)_k \left[ \frac{w_k}{C_1} \right] (m = 1, m = 2, m = 3) \]
\[ (A^p_i, -2B^p_i, 3D^p_i) = \sum_{k=1}^{n} \frac{h_{k-1}^m - h_k^m}{S_k} \left( \Phi_i^* \right)_k \left[ \frac{w_k}{C_1} \right] (m = 1, m = 2, m = 3) \] (11)

where for the angle web and the case of

\[
\begin{align*}
ij = 11 & \quad C_1 = 2\cos\theta^4 \\
ij = 22 & \quad C_1 = 2\sin\theta^4 \\
ij = 12, 21, 33 & \quad C_1 = 2\cos\theta^2\sin\theta^2
\end{align*}
\] (12)

S_k is the distance of the repeating pattern of rib spacing (0, 90, or angle) and w is the width, t is the thickness, and \( \theta \) is the angle of the "angle stiffener" segment. Each stiffness term and thermal coefficient is the summation of all laminate/metallic-sheet segments. In this way, each segment and its direction can be accounted for in any panel concept.

Out-of-plane Gij stiffnesses are included. For relatively thick and closely spaced webs, torsional stiffnesses of the stiffeners are included.

2.2 Failure Analyses All classical lamination theory loading components are included: Nx, Ny, Nxy, Mx, My, Mxy, and the out-of-plane Qx and Qy shears. All analyses begin with a graphical image of the balanced FBD allowing the user to choose any general combination of boundary conditions for thermal and mechanical loading environments. Force equilibrium and strain compatibility accuracy checks documented for all panels/beams. For user-defined loading, the virtual forces and moments are derived for any edge boundary condition or applied force or strain field.

When the grid-stiffened panel concepts are sized for detail design, the follow analyses are preformed:

**Analyze material strength**
- Isotropic yield/ultimate stress allowables and stress interactions
- Composite ply-by-ply failure theories: max stress, max strain, Tsai-Hill, Tsai-Wu, Tsai-Hahn, and Hoffman for all laminates of a panel/beam cross section
- Strain/stress fields for all panel locations including bond line/joint areas and their associated stress discontinuities
- Composite unloaded holes and bolt bearing loads, color plot displacement field
Analyze thermoelastic stiffness effects
- Strain and curvature deformations, and panel and beam midspan deflections for simple and fixed boundary conditions due to pressure
- Panel and local modal frequencies

Analyze panel and beam buckling
- Any longitudinal, transverse, and shear force combination including load interactions
- Unsymmetric, biaxial, membrane-bending panel buckling and bending-twisting coupling effects, and out-of-plane transverse shear flexibility effects
- Ritz energy buckling solutions, cylindrical, multiple boundary conditions, color mode shapes
- Buckling-crippling, Johnson-Euler interaction
- Analyze local buckling

Analyze local buckling
- All facesheet and rib spans, widths, and thicknesses are automatically identified per design concept
- Boundary conditions are automatically determined, such as free versus simple supports

Analyze crippling
- Isotropic materials for formed and extruded sections
- Composite materials using the Dij bending stiffness terms of the panel and beam laminates as recommended in the recent Mil-Hdbk-17-3E.

2.3 Sizing Optimization

The approach used to effectively analyze any panel concept within the grid-stiffened family is to identify analysis_objects that make the common set of building units for a panel concept.

Figure 3 Analysis objects of an Isogrid panel.
In the case of the isogrid shown in the figure 3, the basic building units are the facesheet, the 0 (longitudinal) Web and the Angle web. Each analysis object has particular characteristics. Many panel concepts, such as the orthogrid and isogrid share the same analysis objects. Because of the generality of the thermoelastic panel formulations and the assignment of analysis methods to each of the analysis objects, the HyperSizer tool is able to optimize all panel concept design options simultaneously.

While in the software interface, the user is able to select the most general of cross sectional dimensions to the panel objects. As shown as a way of illustration in the figure to the right, the user is able to click on different pieces of the panel, and then specify unique sizing optimization bounds to each of the thicknesses, heights, spacings, materials, and layups. The generality also handles all material types, such as aerospace metallics (isotropics), Polymer fiber reinforced composites (orthotropics/layups/laminates), and Hybrid laminates with plies of tape, fabric, metallic sheet, foam, and honeycomb material.

To handle manufacturing objectives, the software can also automatically link independent variables. This is portrayed in the bottom right figure where all of the rib heights are required to be the same.

*Figure 4 Each panel facesheet and rib can have independent thicknesses, heights, spacings, materials, and layups, or can be linked.*
Figure 5 The user can select any one panel concept from the grid-stiffened family, or any combination to let the optimizer determine the optimum for a given thermomechanical loading.

2.4 Coupling to FEA The Mindlin plate form is used to represent the equivalent continuum of grid layout and as a result can be directly incorporated with a FEM. Mathematical coupling to MSC/NASTRAN, I-DEAS, and FEMAP is incorporated. HyperSizer has automated the process of passing data with these solvers and modelers.
3. DISCUSSION

Verifications show that all analysis objects are getting the correct values of 3-D transformed laminate strain fields based on linear Kirchoff plane section strains and curvatures. Each analysis object's strain field is computed by transforming the panel's reference plane (1/2 facesheet thickness) strains and curvatures into each analysis object's local rib coordinate system. These strains are then transformed again into ply-by-ply strains. By using each ply's constitutive properties, a ply-by-ply stress field is integrated to achieve the fully coupled laminate force and moment components in each object's local rib coordinate system. These force and moment contributions are then transformed again into the panel coordinates to verify that their weighted summations equal the applied panel external loadings. Therefore Free Body Diagram force equilibrium and strain compatibility is ensured throughout the process of going from each analysis object to the resulting built-up panel.

4. CONCLUSIONS

There are many software techniques used in the development of HyperSizer that are not discussed in this paper. See [5]. This paper shows the engineering approach used by HyperSizer to analyze and size grid-stiffened panel concepts. This approach provides the analytical foundation for a more productive, user friendly, and robust software tool than current spreadsheets being used today. Spreadsheets have the convenience of writing equations based on cell identifiers. Though practical for small problems that have few equations, spreadsheets become unwieldy for even moderately complex panel analyses and have been determined difficult to maintain and unreliable for production use.

The graphical display of analysis and design results is shown to provide the engineer with a powerful insight into the structural problem, and in so doing, allows ‘real-world’ expertise in the optimization process.

Figure 6 3-D panel graphics, with rendered shadow effects of the optimized design, are generated and automatically displayed in the VRML browser.
5. REFERENCES


6. TRADEMARKS

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