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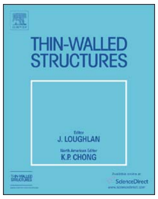

Full length article

Mechanical response of a hexagonal grid stiffened design of a pressurized cylindrical shell-application to aircraft fuselage

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ABSTRACT

Aircraft structures must meet several design requirements such as, minimum weight, high stiffness and fail safe design; these competing criteria must all be met by the final design. A new stringer design concept for conventional aircraft fuselage proposed in [1] showed some encouraging results; this paper is a continuation of the work there in where supporting frame elements are added to the fuselage structure. The proposed design is simulated using a finite element model that has been validated through experimental data available from the literature. Results show improved performance of the structure in terms of eigenfrequencies and virtually unchanged performance in terms of stresses and displacements.

1. Introduction

In conventional aircraft, the fuselage is a structure composed of thin shells and a supporting airframe that consists of circumferential frames and axial stringers [2]. Most frequently, these components are manufactured from aluminum alloys and are joined together by rivet lines and lap joints. The primary role of the airframe is to bear a major part of the external loads such as lift, thrust, drag, gravity in addition to cabin pressurization; it acts as a skeleton for the fuselage structure and stiffens the skin against buckling and fatigue failure. The airframe (and the aircraft in general) must be of low weight, high stiffness and have a fail safe and/or safe-life design. According To the Code of Federal Regulations CFR 25.305 and CRF 25.571 [3] the airframe structure must be able to support limit loads without detrimental deformation and that catastrophic failure due to fatigue (among many other factors) may be avoided during the life of the aircraft as well as tolerance to damage.

The use of grid patterns as reinforcing elements to thin shells is not an uncommon concept. Several grid patterns have been used in the designs of the shells of missiles and spacecraft, such as isogrids, anisogrids, regular hexagonal grid [4–6], etc. These grids are most common in structures made from composite materials since they are much easier to build with such materials [4,5,7].

Recent research efforts on modeling grid stiffened panels subject to buckling by Boni and Fanteria [4,7] used an analytical method for fuselage design validated through finite element models. Several theoretical studies were accomplished by Totaro [5,6,8] on the buckling of anisogrids and their optimization. Composite materials are frequently used in the design of shells because of their high stiffness to weight ratio. Nonetheless, they are still prone to buckling. Wang et al. [13,14] conducted buckling analysis of composite shells under axial loading as well as Weber et al. [15] and Ehsani et al. [16].

Featherston et al. [9] examined the dynamic buckling of a series of longitudinally stiffened panels of varying radii of curvature including, in the limit, a flat plate subject to axial compression. Grondin et al. [10] conducted a parametric study on the buckling behavior of stiffened plates using the FEM-based commercial program ABAQUS [11]. Buragohain et al. [12], carried out the buckling analyses of the composite hexagonal lattice cylindrical shells using the energy-based smeared stiffener model.

Fedor et al. [17] used optimal reinforcement concepts like lattice and wafer to increase airframe integrity based on conventional mechanical fastener replacement by high-efficiency hybrid metal-to-composite joints providing great potential for the structure's weight reduction.

In a recent study by the authors [1]; a new hexagonal tessellation grid is proposed and compared to the original orthogonally stiffened structure in terms of eigenfrequencies and static response to external loading. Results show that the hexagonal grid stiffened structure yields higher eigenfrequencies with stresses and displacements comparable to those of the original structure. The work proposed in this paper is a continuation of this study. It has two objectives; first, to investigate the effect of adding frames to the Hexagonal Grid Stiffened Panel (HGSP) in

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Nomenclature

Acronyms

OGSPwF	Orthogonal Grid Stiffened Panel with Frames.
HGSPwF	Hexagonal Grid Stiffened Panel with Frames.
HGSPwMS	Hexagonal Grid Stiffened Panel with Material Swap.
MPC	Multi Point Constraint.

Suffixes

wF	Panel section with frames.(eg. HGSPwF).
wMS	Panel section with Material swap.(eg. HGSPwMS).
SG	Strain gages

Symbols

n_F	Number of frames in the panel.
n_S	Number of stringers in the panel.
n_a	Number of hexagonal cells in the axial direction.
n_θ	Number of hexagonal cells in the circumferential direction.
N_m	Number of eigenmodes extracted.
$\varepsilon_{\theta\theta}$	Tangential strain.
ε_{aa}	Axial strain.
r_r, r_θ, r_Z	Rotations around the axes of the cylindrical reference (rad).
α	Inscribed hexagonal cell angle (degrees)
t_P	Skin thickness (mm).
t_F	Frame thickness (mm).
t_S	Stringer thickness (mm).
R_P	Skin radius of the panel section (mm).
L_a	Axial length of the panel section (mm).
L_θ	Circumferential length of the panel (mm).
ℓ_a	Axial length of stringer (mm).
ℓ_θ	Circumferential length of the Frame (mm).
ℓ_S	Inter-stringer distance (mm).
ℓ_F	Inter-frame distance (mm).
a	Lengths of the sides of the hexagonal cell (mm).
L_L	Total stringer length of the orthogonal grid (mm).
L_H	Total stringer length of the hexagonal grid (mm).
u_r, u_θ, u_Z	Displacements in the cylindrical reference frame (mm).
r, θ, Z	Radial, tangential and axial coordinates in the cylindrical reference frame (mm, rad, mm).
A_S	Cross-sectional area of the stringer (mm2).
A_F	Cross-sectional area of the frame (mm2).
$\mathbf{F}^S_a$	Force applied to the skin in the axial direction (kN).
$\mathbf{F}^S_\theta$	Force applied to the skin in the tangential direction (kN).
$\mathbf{F}^F_\theta$	Force applied to a frame in the tangential direction (kN).
k_{spring}	Stiffness of the support spring (kN/mm).
$\sigma_{\theta\theta}$	Tangential stress (MPa)
σ_{aa}	Axial stress (MPa)
p	Internal pressure applied to the skin (MPa).

a cylindrical shell subject to loads due to cabin pressurization. The second objective is to analyze the response of the grid structure when the material of the frames is swapped into (added to) the hexagonal grid pattern. The performances of the new structures mentioned above are compared to that of the conventional Orthogonal Grid Stiffened Panel with Frames (OGSPwF). A particular attention is directed towards natural frequencies, displacements and stresses.

The paper is structured as follows; two finite elements models of the fuselage structure are built, the first with the new hexagonal grid and frames, and the second with the material of the frames swapped into the hexagonal grid pattern. The eigenvalues of both structures and their static response (stress and displacement) to a pressurization load are determined. The study is repeated for the conventional panel noted OGSPwF. In the results section, selected panels with optimal hexagonal grid with frames noted HGSPwF [1] and panels with material swap noted HGSPwMS, are presented as well as their corresponding finite element results (eigenfrequencies, stress and displacement); results from OGSPwF are also presented. In the discussion section and conclusion, results from the HGSPwF and HGSPwMS are compared to those obtained from the baseline case of OGSPwF.

2. Statement of the problem

We aim to compare the performance in terms of eigenfrequencies, stress and displacement of two new proposed structures to the baseline conventional structure. These structures represent a panel section from the fuselage of an aircraft; they are described as follows:

- Orthogonal Grid Stiffened Panel with Frames (OGSPwF): this is the baseline structure; it represents the conventional design used in aircraft as shown in Fig. 1(a).
- Hexagonal Grid Stiffened Panel with Frames (HGSPwF): in this structure the axial stringers of OGSPwF are replaced by a hexagonal grid of equivalent length as shown in Fig. 1(b). This will be discussed further.
- Hexagonal Grid Stiffened Panel with Material Swap (HGSPwMS): in this structure the frames are removed and their material mass is added to the hexagonal grid to strengthen it further. Hence, the material of the frame is swapped for additional material into the hexagonal stringer grid shown in Fig. 2.

In a previous study by the authors, an optimization problem was conducted to search for the best hexagonal stringer grid configuration whose length is equivalent to that of the original conventional stringer configuration. Under this length equivalency condition, the masses of the original stringer grid and the optimized grid should be approximately the same; the parameter λ in Eq. (1) measures percentage length difference which also corresponds to the percent stringer grid mass difference between the two structures. Therefore $\lambda = 0$ indicate the both structures have the same stringer length and the same mass assuming all other parameters are kept the same. The search yielded several candidate solutions four of which were selected for further

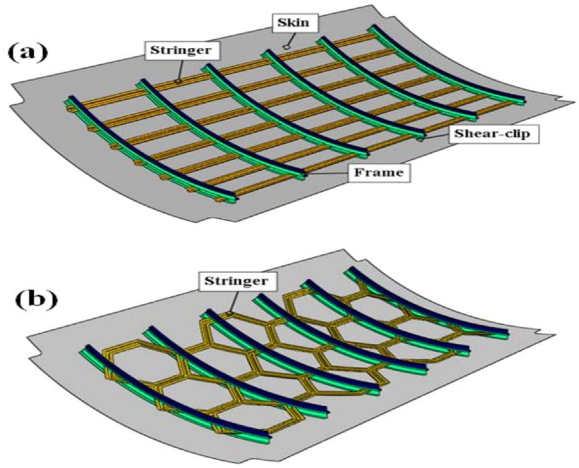

Fig. 1. (a) Orthogonal Grid Stiffened Panel with Frames (OGSPwF); (b) Hexagonal Grid Stiffened Panel with Frames (HGSPwF).