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Structural Concepts Study of Non-circular Fuselage Configurations

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ABSTRACT

A preliminary study of structural concepts for non-circular fuselage configurations is presented. For an unconventional flying-wing type aircraft, in which the fuselage is inside the wing, multiple fuselage bays with non-circular sections need to be considered. In a conventional circular fuselage section, internal pressure is carried efficiently by a thin skin via hoop tension. If the section is non-circular, internal pressure loads also induce large bending stresses. The structure must also withstand additional bending and compression loads from aerodynamic and gravitational forces. Flat and vaulted shell structural configurations for such an unconventional, non-circular pressurized fuselage of a large flying-wing were studied. A deep honeycomb sandwich-shell and a ribbed double-wall shell construction were considered. Combinations of these structural concepts were analyzed using both analytical and simple finite element models of isolated sections for a comparative conceptual study. Weight, stress, and deflection results were compared to identify a suitable configuration for detailed analyses. The flat sandwich-shell concept was found preferable to the vaulted shell concept due to its superior buckling stiffness. Vaulted double-skin ribbed shell configurations were found to be superior due to their weight savings, load diffusion, and fail-safe features. The vaulted double-skin ribbed shell structure concept was also analyzed for an integrated wing-fuselage finite element model. Additional problem areas such as wing-fuselage junction and pressure-bearing spar were identified.

1. Introduction

Fuselage configuration and structural design of a very large transport aircraft is a major task. For such a design, extensive experience and database exists[1] for conventional aircraft. For an unconventional aircraft such as a flying-wing, in which the fuselage is part of the wing, partially circular or non-circular sections need to be considered. Efficient structural design of such an unconventional non-circular pressurized fuselage imposes a special challenge since extensive experience and databases do not exist. Moreover, during the conceptual design stage, loading conditions, material properties, detailed configuration and structural dimensions of the fuselage are usually not known. Hence, in this preliminary structural analysis stage, it is often convenient to assume a representative configuration with appropriate dimension and undertake a comparative study using simple finite element modeling and analysis[2] for a typical set of loads and material properties. Although this procedure may initially lead to a conservative design, it often provides guidance towards a better configuration through comparative weight and stress analysis, and could be used to identify new concepts which may impose less weight penalty to this unconventional construction in an otherwise efficient flying wing with aerodynamic advantages.

First, basic design issues of partially circular and non circular load-bearing pressure vessels were discussed. Based on their relative advantages and disadvantages, two non-circular pressure vessel concepts were selected for analysis: a) a flat sandwich shell concept and b) a vaulted sandwich shell concept, both with a honeycomb core. Simple structural finite element models (FEM) were used for displacement and stress analysis, followed by a limited sizing study. Next, an alternate concept was investigated for weight reduction. In this concept, the honeycomb was replaced by a double-skin shell with vertical spanwise and chordwise rib stiffeners. Both the flat and vaulted double skin shell construction were analyzed and compared. Finally, one integrated cantilever wing-fuselage configuration using the vaulted ribbed shell concept was analyzed.

2. Basic Issues

For a very large conventional subsonic transport, a scaled-up fuselage with a double-deck circular cross section is often considered as shown in Fig. 1, where the shaded area is the pressurized section. When the cross section of a fuselage is circular, the internal pressure is resisted efficiently by the thin skin via hoop tension. The hoop stress, based on force equilibrium, is given by $\sigma = pr.D/2t$, where pr is the internal pressure, D is the diameter and t is the skin thickness. Any buckling instability is prevented by stiffening the thin skin with frames and stringers. The fuselage end pressure and concentrated loads from landing gear, engine and wing mount are carried by heavy bulkheads.

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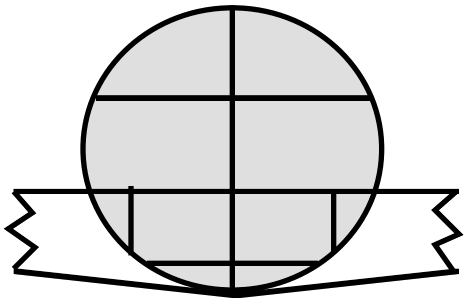


Fig. 1. Conventional circular fuselage.

For a very large flying-wing type transport, it may be necessary to place several non-circular fuselage bays in tandem locations inside the wing. In such a situation, the fuselage could be built as a multi-bubble partially-circular section as shown in Fig. 2, where the shaded area represents the pressurized section. Then the outer skin can carry pressure efficiently by hoop stress and the cabin walls can be used to balance the vertical component of the hoop stress of adjacent bubble sections as shown by arrows in Fig. 2. In general, if the fuselage section is non-circular, any internal pressure load would also induce substantial bending in the structure. In addition, the tandem fuselage must also withstand additional spanwise bending and compression load like a regular wing. Bending load along with any asymmetry usually induce large stress at the bubble joints.

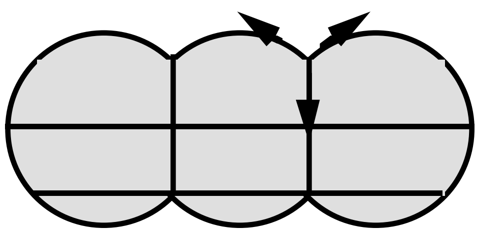


Fig. 2. Multi-bubble section and stress balance.

Vaulted Sandwich Shell: For a very large flying wing, the multi-bubble fuselage must be placed inside a wing with smooth aerodynamic outer surface. A simplified cross -section sketch is shown in Fig. 3 where the shaded area represents the pressurized section. This tandem fuselage configuration requires a double-skin construction which could be stiffened or filled with light honeycomb filler in between to transmit the external aerodynamic load from the outer skin, and to prevent local buckling. This makes a load-bearing non-circular pressurized fuselage construction very inefficient and imposes excessive weight penalty due to the high volume of honeycomb filler material. It is also not very attractive from a fabrication complexity viewpoint.

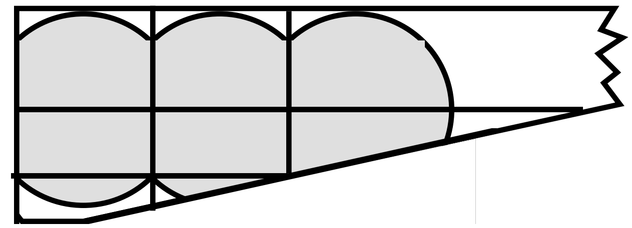


Fig. 3. Multiple tandem vaulted shell fuselage sections inside flying wing.

Flat Sandwich Shell: A possible alternative is to use uniformly deep honeycomb or stiffened frame construction which follows the outer aerodynamic contour as shown in Fig. 4. Although such nearly flat shells are not suitable for carrying large internal pressure, and have numerous highly stressed T junctions, with careful design this concept might be very attractive due to the simplicity of construction, and reduced volume of honeycomb filler material. This configuration also does not need additional flooring which is essential for a partially circular or vaulted shell construction shown in Fig. 3. Hence, it would be interesting to investigate this alternative structural configuration.

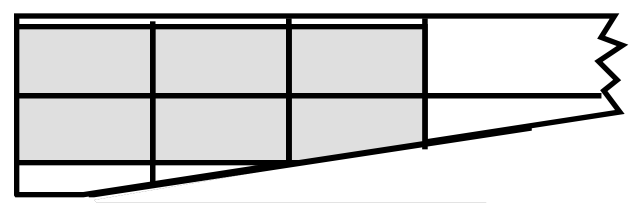


Fig. 4. Uniform depth flat shell fuselage.

Advantages and Disadvantages: Both of these configurations have other advantages and disadvantages. The upper section of the vaulted fuselage is under compressive loading due to the cumulative bending moment from the wing load, and can be assumed to act like a beam-column as shown in Fig. 5a. The mid section, which carries a large bending moment, possesses the least bending stiffness. It might be possible to choose a shallow cylindrical arc for the vaulted contour to provide larger section moment of inertia at mid span, and do an extensive optimization study to determine a span-to-rise ratio and then select the best beam-column. However, a uniformly deep honeycomb shell structure might be better suited to resist such a combined bending and compressive load in this situation as shown in Fig. 5b, due to its superior buckling stiffness.

Double-skin ribbed shell: In order to combine the advantage of the partially circular section and remove the disadvantages of sandwich construction, another possible alternative was considered. If the honeycomb

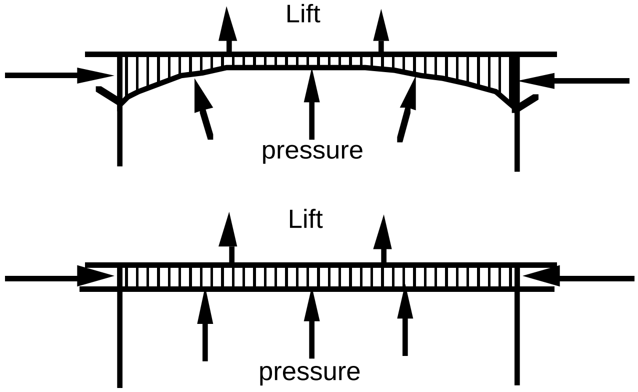
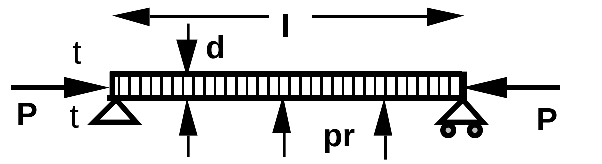


Fig. 5. Idealized loading on upper-section of a a) vaulted shell; and b) uniform depth shell fuselage.

core could be replaced with stiffening ribs and properly spaced to prevent local buckling, then this configuration would be significantly lighter. Such construction is much like a double-skin pressure bulkhead of a tanker ship, and could be well suited to prevent fatigue crack propagation and increase buckling rigidity. In addition, in case of an inner-skin pressure leak, the double skin vaulted shell concept could be designed to be fail safe, because it would act like a suspension bridge, where the outer aerodynamic skin would take the pressure load, which would be transmitted through the ribs to put the inner vaulted-skin in tension, like a catenary. However, fabrication and splicing of such a structure could be a major problem for both conventional and composite construction. This double skin ribbed shell concept was analyzed for both the vaulted- and flat- shell configurations and compared with the sandwich concept results.

<u>Other problem areas</u>: There are several other problem areas which became apparent during this analysis. If the end of the fuselage is terminated at the wing front or rear spar, the spars must also be designed to withstand both pressure and bending. The most outboard section where the unpressurized outer wing is attached, appeared to be a highly stressed critical structure. Thus stresses at the wing-fuselage and wing-spar junction could be a major problem. Of course, other issues like local crippling, damage tolerance, crack propagation, splicing, moisture egress, corrosion, cut-out, fabrication and maintenance should also be addressed.

<u>Two-dimensional beam-column analysis</u>: Some initial sizing, load, stress and deflection data can be obtained using the analytical nonlinear beam-column solution[3] for a simplified configuration of the cabin roof shown in the sketch, where P is axial load, pr is normal cabin pressure, l is column length, t is thickness of face skin,



and d is depth of honeycomb core. Assuming that the bending area moment of inertia of the sandwich beam with core depth d, and width w is given by $I=2tw(d/2)^2$, the critical bucking load P_{cr} for simply-supported boundary condition is given by $P_{cr}=\pi^2 EI/l^2$. Defining $\mu=(\pi/2)(P/P_{cr})^{0.5}$, the maximum deflection, bending moment and bending stress at mid span are given by

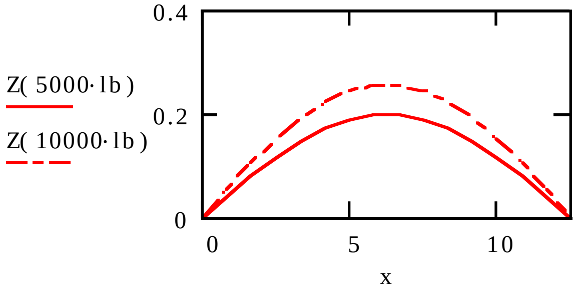
$$z_{\max} = \frac{5pr.l^4}{384EI}\frac{12(2\sec\mu - 2 - \mu^2)}{5\mu^4}$$

$$M_{\max} = \frac{pr.l^2}{8} + \frac{5pr.l^4}{384EI}\frac{12(2\sec\mu - 2 - \mu^2)}{5\mu^4}P$$

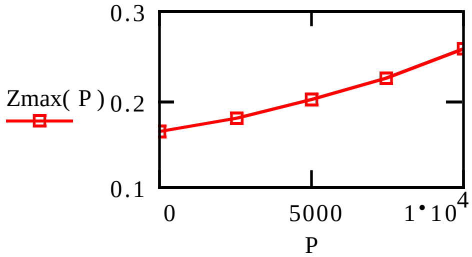
and

$$\sigma_{\max} = M_{\max}\frac{d}{2I} \text{ where } \mu = \frac{\pi}{2}\sqrt{\frac{P}{P_{cr}}}$$

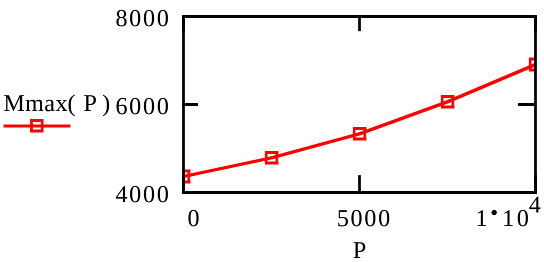
Note that the expressions are singular at $P=P_{cr}$. Using a core depth of d=10 inches, face skin thickness of t=1/8 inch, Young's modulus of $E=10\times10^6$ psi, beam length of l=150 inches, transverse pressure of pr=18.6 pounds per square inch (psi), the mid-span deflection Z_{max}, deflection shape Z, mid-span bending moment M_{max} and bending stress σ_{max} were computed and plotted in Fig. 6 as a function of axial load P from 1 to 5000 pounds, for a simply-supported beam of unit width. The plot of deflection Z_{max} and stress σ_{max} indicate that when the axial load P is 5000 pounds per inch, mid-span deflection Z_{max}=0.2 feet, and the maximum bending stress σ_{max}=51450 psi. Although the buckling load ratio P/P_{cr}=0.182, the nonlinear in-plane effect of additional bending moment caused by the deflection and axial compressive load is to produce 23 percent higher stress compared to the linear value of 41850 psi due to the transverse pressure load. If the depth of the beam is 5 inches and P=5000 lb/inch, then P/P_{cr} is 0.73, Z_{max} is 2.42 ft and σ_{max} is 316,000 psi. If the depth of the beam is 5 inches and P=1000 lb/inch, then P/P_{cr} is 0.146, Z_{max} is 0.766 ft and σ_{max} is 98,410 psi. These simple calculations provide a basic idea of sizing for a typical composite material with Young's modulus of $E=10\times10^6$ psi and yield stress of 50000 psi.



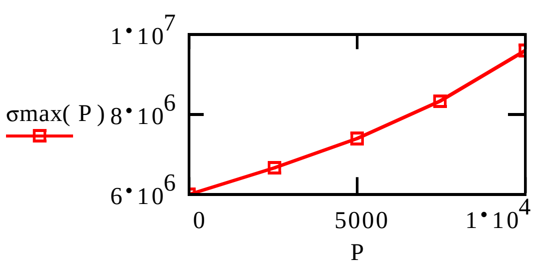
a) Beam deflection shape (feet) vs. P (lb)



b) Mid Span deflection (feet) vs. P (lb)



c) Mid span bending moment (ft-lb) vs. P (lb)



d) Mid-span bending stress (psf) vs. P (lb)

Fig. 6. Beam deflection shape Z, mid-span deflection Z_{max}, bending moment M_{max} and bending stress σ_{max} variation with axial compressive load P.

For a typical face skin thickness of 1/8 inch, the 150 inches long simply-supported beam depth must be about 10 inches, to sustain a compressive load of 5000 lb/inch and transverse pressure of 18.6 psi. A simply-supported beam which is 5 inches deep can barely sustain a compressive load of 1000 lb/inch when the transverse pressure is 18.6 psi. This idealized study indicates that a 5-inch deep honeycomb beam may not be adequate. Hence, in the 3-D finite element analysis to be described next, a conservative 10-inches deep shell construction was considered, although for actual boundary condition and fully stressed design, the depth could be between 5 and 10 inches.

3. Structural configurations

Since the structural details of the entire wing-fuselage combination are usually not known in the conceptual design stage, the comparison study was accomplished by first analyzing two simple configurations, which represented an outer bay of the wing-fuselage combination shown in Figs. 3 and 4. The cross sections of the fuselage bay for the two proposed structural configurations, namely a) uniform depth flat shell, and b) vaulted shallow cylindrical shell are shown in Fig. 7. For each of these configurations, both the c) honeycomb sandwich shell, and d) stiffened double-skin shell structural constructions were investigated.

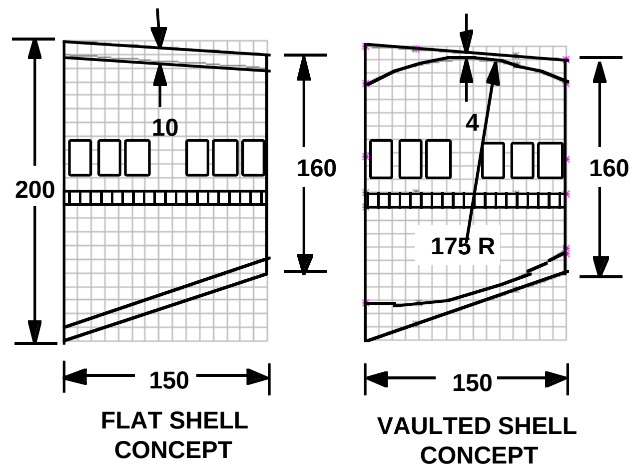


Fig. 7. Cross sections of a) Uniform-depth flat shell, and b) Vaulted shell fuselage concepts.

<u>Sandwich Shell</u>: All dimensions shown in Fig. 3 were typical for a six-passenger abreast, single-aisle fuselage bay, but otherwise arbitrary. Based on the 2-D beam-column analysis in section 2, the flat sandwich shells were assumed to have uniform core depth of 10 inches, with 1/8 inch thick composite face skins. The vaulted cylindrical shells were assumed to have a radius of 175 inches and the center was placed such that the core thickness varied between 20 inches at the cabin side wall to 4 inches at mid-cabin roof. This provided approximately the same core volume as a uniform 10-inch depth flat honeycomb sandwich shell.

<u>Pressure Bearing Spars</u>: The fuselage bay is assumed to have a trapezoidal planform with its ends at the front and rear main spar of the swept flying wing. Therefore, the front and rear spars must also carry the cabin pressure load. The pressure-bearing part of the spar were assumed to have a sandwich structure with a 10-inch thick honeycomb core and 1/8 inch thick face skin. Although the mid-deck floor carries only passenger

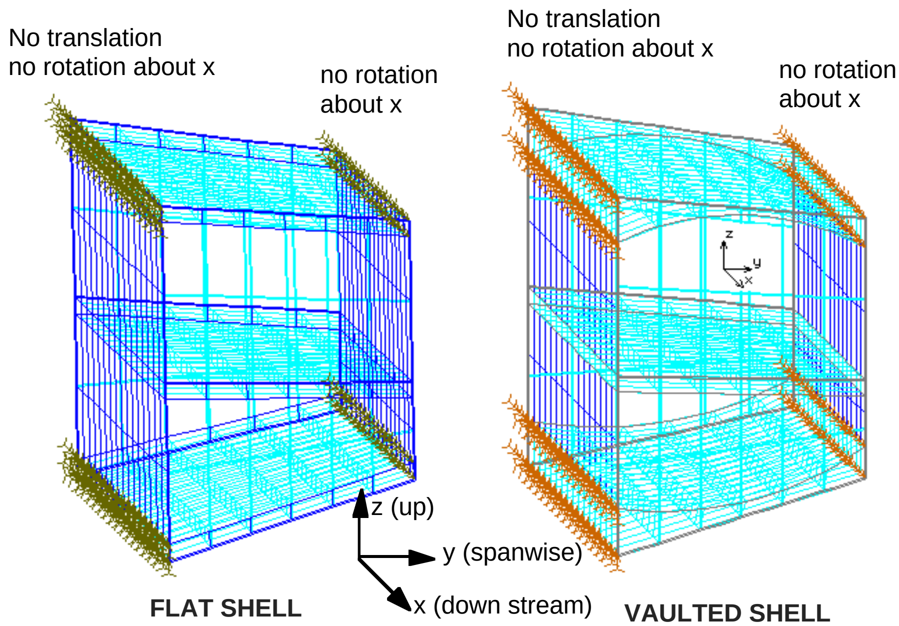


Fig. 8. Clamped boundary conditions and 1340 element 16x6x7 mesh description.

load and could have a conventional stiffened plate construction, they were assumed to have the same uniform 10-inch deep honeycomb sandwich construction like the pressure bearing spars, for a uniform conservative design.

Simply-supported boundary conditions: Initially simply-supported boundary conditions were analyzed for an isolated section, in order to evaluate their effects. The fuselage section was assumed to be simply supported at cabin top and bottom edge at inboard side but were unrestrained at the outboard side. This boundary condition may be realistic for the flat shell concept shown in Fig. 4, where the T-junctions between cabins may not have sufficient rigidity in rotation. However, as a part of the overall flexible wing, the outboard section side generally translates upward with very small rotation. Thus in later analysis, partially clamped boundary conditions were used as described next.

Clamped boundary conditions: The simply-supported nodes at the cabin top and bottom edge at inboard sides were restrained from rotation about chordwise direction, as shown in Fig. 8. The corresponding nodes at the outboard sides were only restrained in rotation about chordwise direction. The outboard side was otherwise free to translate. Although these two boundary condition assumptions were nonconservative, they were deliberately chosen in order to identify regions of large deflections and stresses where additional buckling analysis would be needed. Of course, the outcome of any comparison using isolated components of fuselage would be dependent on the assumed boundary conditions at the section ends. In order to resolve this issue, a combined half wing and fuselage idealized structure was modeled and analyzed using clamped boundary condition at the plane of symmetry. This will be discussed later in the paper.

Finite Element Model and Meshing: A desktop computer based finite element analysis software[2] was used primarily for its rapid interactive modeling and post processing graphic facilities. The fuselage skin surface was modeled by four node flat plate elements. The honeycomb core was modeled by 3-dimensional eight-node solid elements. Due to computer memory limitation, initially a coarse 8x4x5 mesh finite element model was used for comparative analysis of the two configurations shown in Fig. 7. Later, a less coarse 16x6x7 mesh 1340 element model as shown in the Fig. 8 was used for obtaining better stress and deflection values. However the analysis does not take into account nonlinear effects or guarantee deflection or stress convergence and should be used only for comparison purposes.

Material Properties**:** *Isotropic*. In the initial analysis, all face skins were assumed to be 1/8-inch thick isotropic graphite epoxy composite material with 96 lb/cuft density, with a Young's modulus of $E=10x10^6$ psi, and a shear modulus of $G=3x10^6$ psi. The allowable tensile stress was assumed to be 50,000 psi. The Nomex honeycomb core material was assumed to have a Young's modulus of E=20,000 psi, shear modulus of G=7000 psi, with a density of 3.1 lb/cuft. The allowable shear stress was assumed to be 70 psi.
Orthotropic. In the latter limited sizing study, a 12 percent reduced thickness skin and a light density (1.6

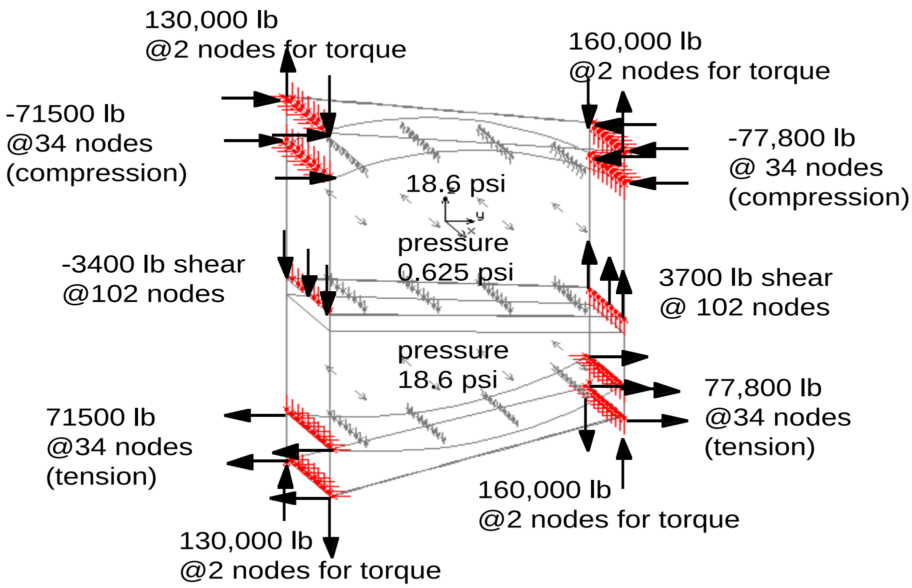


Fig. 9. Equivalent load application on element nodes of vaulted shell configuration for 16x6x7 mesh model.

lb/cuft) core honeycomb were used in an attempt to reduce the weight. The following typical orthotropic material properties were assumed for the composite sandwich skin: Young's modulus E_x=9x10^6 psi, E_y=5x10^6, G_{xy}=2x10^6 psi, Poisson's ratio ν=0.4, and allowable tensile stress of 50,000 psi. The higher modulus direction was aligned spanwise. The light aluminum honeycomb core properties were as follows: Young's modulus E_x=E_y=300 psi, E_z=30,000 psi, shear modulus G_{xy}=200 psi, G_{xz}=12,000 psi, G_{yz}=20,000 psi, Poisson's ratio ν_{xy}=0.3, ν_{xz}=ν_{yz}=0.05. The allowable stresses in compression and shear were 80 psi and 40 psi, respectively.

Loads: The critical flight condition for limit load was assumed to be a 2.5g maneuver at maximum takeoff weight. A typical bending moment, shear force and torque distribution based on elliptic spanwise loading on a swept cantilever beam were determined for the critical load case. The limit loads at the fuselage section were estimated to be: bending moment 27x10^6 ft-lb, shear load 25x10^4 lb, and torque 13x10^6 ft-lb, at the inboard side of the fuselage section. These loads were multiplied by a safety factor of 1.5 to obtain ultimate design load. For finite element analysis purposes, bending moments were converted to equivalent tension and compression forces at the upper- and lower-surface skin element nodes. The equivalent running compressive force on upper surface was close to 4000 lb/inch for a 625-inch long fuselage. The shear and torque loading were converted to equivalent forces at the appropriate element nodes. The equivalent nodal forces due to bending, shear, torque and pressure loading for the vaulted shell configuration are shown in Fig. 9. The design ultimate cabin pressure differential at cruise condition was assumed to be 18.6 psi which included all safety factors. The mid-deck floor loading at 2.5g was assumed to be 0.625 psi. The aerodynamic pressure and cavity pressure loads on the fuselage section were neglected compared to the 18.6 psi ultimate cabin pressure for the fuselage section analyses. The outside surface approximate aerodynamic pressure varying from 1.2 psi to 4 psi were included for the integrated wing-fuselage analyses.

4. Conceptual Structural Analysis

The conceptual structural analysis was executed first with an initial set of data. These results were then used to guide the next stage of analysis. The four analysis stages were as follows.

1. Analyze two concepts: a) Flat sandwich shell, and b) Vaulted sandwich shell construction, using isotropic material with 1/8th inch thick skin and heavy honeycomb core using a 8x4x5 mesh, 488 element model. Both the simply-supported and clamped boundary conditions were investigated.

2. Conduct limited sizing study, using orthotropic advanced composite face material with a 0.11 inch thick skin, light honeycomb core for the a) Flat sandwich shell, and b) Vaulted sandwich shell construction, using a 16x6x7 mesh, 1340 element model.

3. Investigate an alternate ribbed shell concept to eliminate the honeycomb for weight reduction using a) Flat double-skin ribbed shell model with 16 spanwise

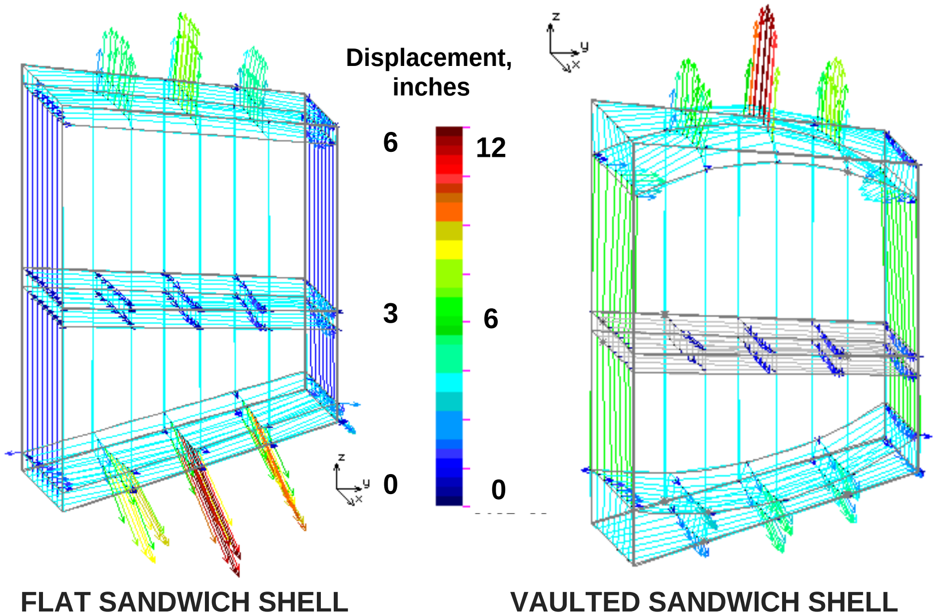


Fig. 10. Displacement vectors at maximum cabin pressure 18.6 psi at 2.5g for simply-supported boundary condition (isotropic material, heavy core, 8x4x5 mesh)

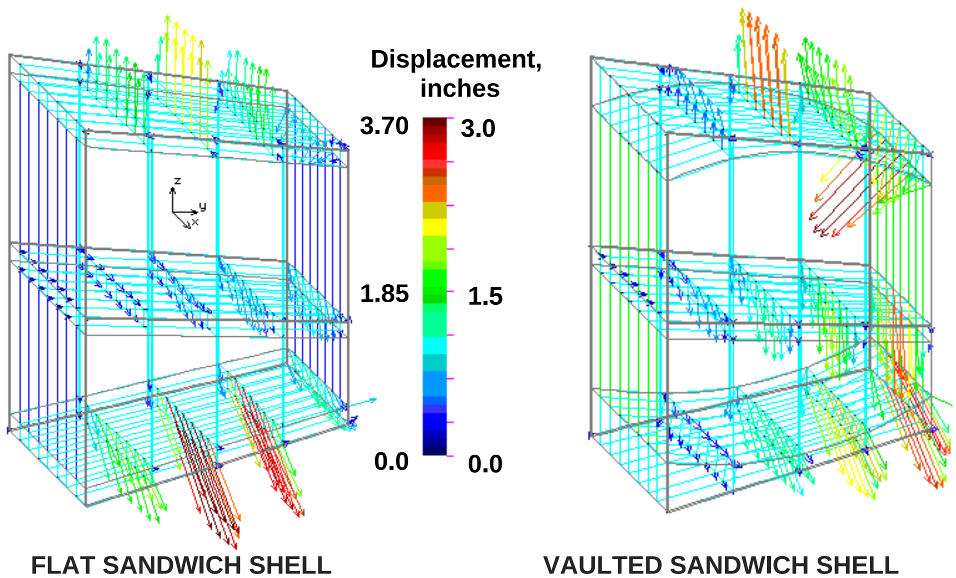


Fig. 11. Displacement vectors at maximum cabin pressure 18.6 psi at 2.5g for clamped-boundary condition (isotropic material, heavy core, 8x4x5 mesh).

and 1 chordwise rib (16x6x7 mesh), and b) Vaulted double-skin ribbed shell model with 8 spanwise and 4 chordwise ribs (8x4x5 mesh)

4. Finally, analyze a combined cantilever wing-fuselage finite element model using the vaulted double-skin ribbed shell configuration with pressurized fuselage inside flying wing and a basic outer-wing structure.

The resultant displacements from the stage 1 analysis using isotropic material properties, heavy honeycomb core, and 8x4x5 meshing are shown in Figs. 10 and 11. The displacements of the two structural configurations are shown in Fig. 10 for the simply-supported boundary condition. The deflections at the mid-cabin roof of the flat sandwich shell are consistent with the earlier 2-D analysis. The deflections for the vaulted sandwich shell are, in general, almost twice for the same load.

The displacements for the clamped boundary condition (Fig. 8) are shown in Fig. 11, which indicate that the effect of clamped boundary condition is much more

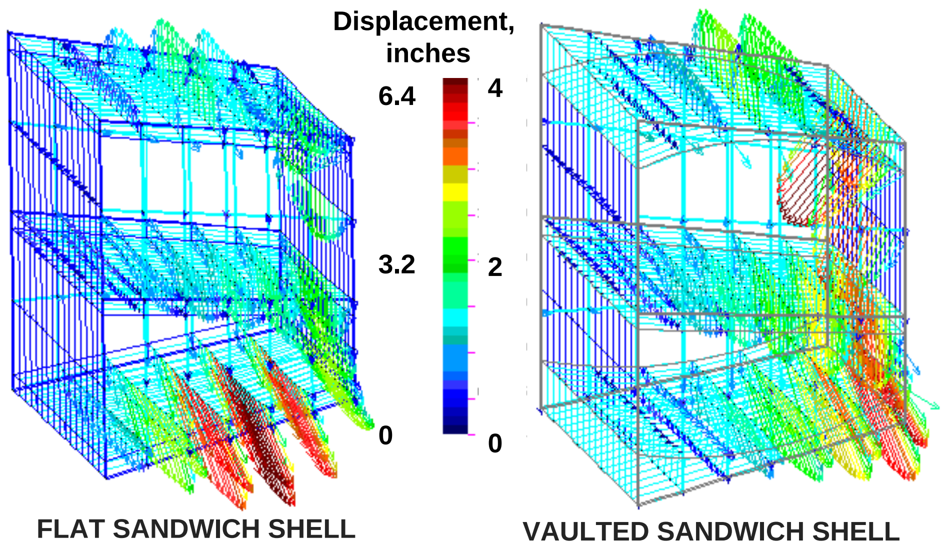


Fig. 12. Displacement vectors at maximum cabin pressure 18.6 psi at 2.5g (orthotropic material, light core, clamped boundary condition, 16x6x7 mesh).

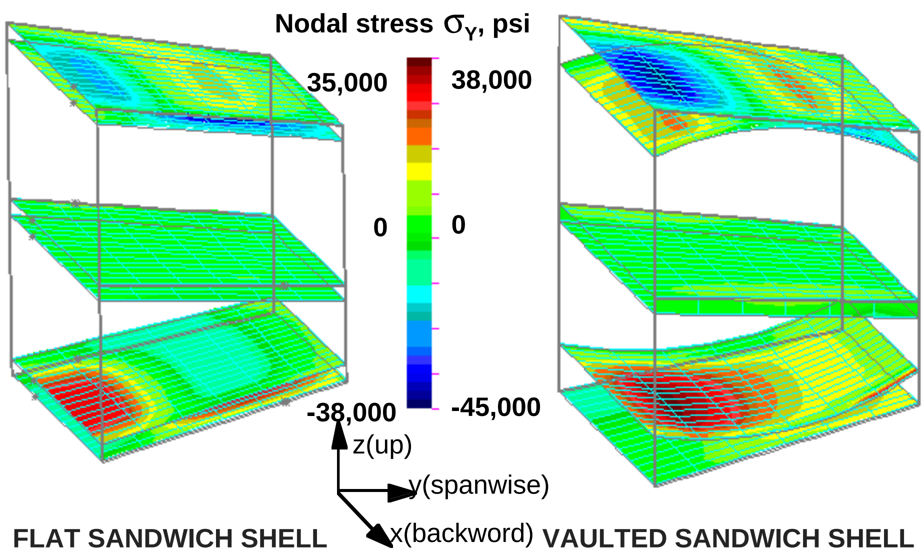


Fig. 13 Sandwich shell skin element nodal stress σ_Y at maximum cabin pressure 18.6 psi at 2.5g (orthotropic material, light core, clamped boundary condition, 16x6x7 mesh, 0.11 inch skin thickness)

significant for the vaulted shell compared to the flat shell due to the beneficial effect of the curvature. The deflections now are of the same order for both the cases with the deflections for the flat shell being 20% percent higher. For the flat sandwich shell, the maximum deflections were at the mid-cabin roof due to pressure, while for the vaulted shell concept, beam-column type compression loading caused significant deformation at the free end. This confirms that for this structural size, the uniform deep honeycomb sandwich shell is probably the better of the two concepts under combined in-plane compression and normal pressure load.

Light aluminum honeycomb**:** In stage 2, a limited sizing study using a thinner face material and a lighter aluminum honeycomb with 1.6 lb/cuft density was conducted. In this stage, the orthotropic composite material properties were used. Using the same 8x4x5 mesh 488 element model, the vaulted shell model maximum deflections with light core were generally 10 to 15 percent higher that those obtained with heavy core in stage 1, but the total weight of the structure was reduced by about 30 percent. The results using a 16x6x7 mesh, 1340 element model and light aluminum core for both the concepts were computed next. The deflection vectors and stresses are shown in Figs. 12

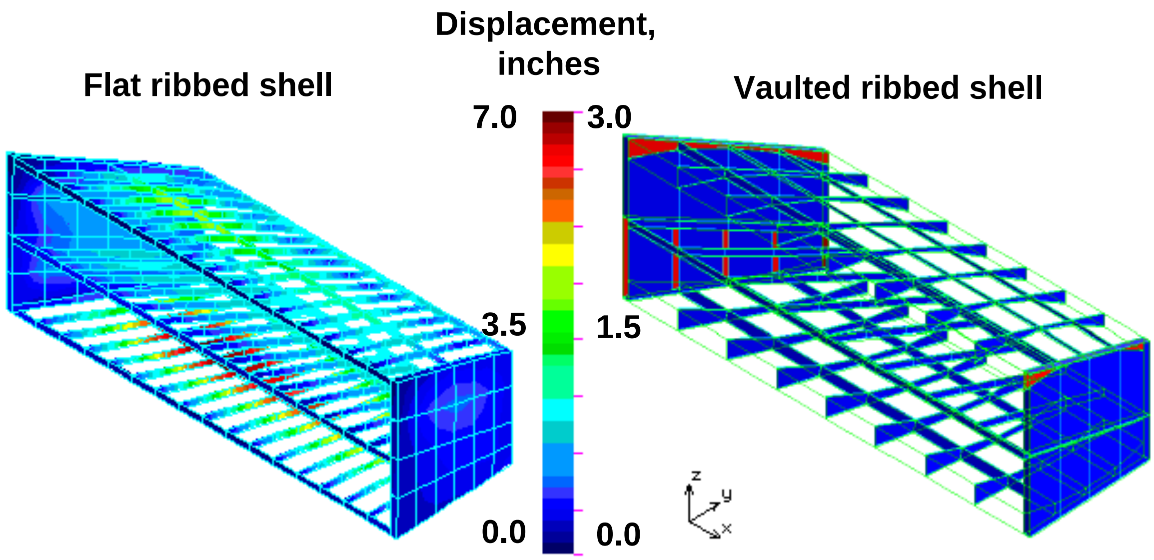


Fig. 14. Flat and vaulted double skin ribbed shell displacement at maximum cabin pressure 18.6 psi at 2.5g (clamped boundary condition).

and 13. Figure 12 indicates that deflections were generally were 25 percent higher than the case shown in Fig. 11. Although this was partially due to the meshing change, the higher deflections and stresses indicate that the light core may not be adequate, particularly for the vaulted shell. The maximum deflections at mid cabin were significant for both the concepts indicating that the long cabin would need additional stiffening at the middle. Light aluminum core is also not suitable due to handling and local crippling problems.

The membrane stress distribution at the element nodes in the spanwise y direction σ_y for the flat and vaulted sandwich shell are compared in Fig. 13. The outer top skins are seen to be in compression and the lower vaulted interior skins are in tension. Fig. 13 indicated that stress values were maximum at the clamped beam root as expected, and were significantly higher for the vaulted shell concept. Core shear stress and stress resultants exceeded corresponding ultimate stresses at several places. Although the stress values of such a course mesh are generally not fully reliable, they provide a good estimate of the general stress level expected. This again confirms that for the assumed structural size, the uniformly deep honeycomb sandwich shell is relatively more efficient than the vaulted shell concept under combined in-plane compression and normal pressure load, although this conclusion was initially counter intuitive. However neither concept offered any distinctive weight advantage, since a heavier core would be necessary for operational and safety considerations.

5. Double-skin Ribbed Shell

Since neither the vaulted sandwich shell concept nor the flat sandwich shell concept offered any distinctive weight advantage, the flat shell concept could be a better choice due to its simplicity for fabrication. However, from an operational view point, any honeycomb core in primary flight structure is usually avoided by aerospace industry and Navy due to debonding, local crippling, moisture egress, crack propagation and inspection problems. So in stage 3, as discussed earlier, the "double-skin ribbed shell," concept was studied to further reduce the structural weight of the pressurized wing-fuselage. In this concept, the honeycomb core was replaced by spanwise and chordwise ribs, much like a double-skin pressure bulkhead, as shown in Fig. 14. All ribs were modeled by 0.11 inches thick flat plate elements. The pressurized front and rear spar were modeled as before with a 10-inch thick core solid elements and 0.11 inches thick face skin plate elements.

Initial results of the ribbed-shell concept structural analysis are shown in Figs. 14 and 15, for the same critical 2.5g maneuver load condition and maximum 18.6 psi design cabin pressure. The deflections and stresses of the double-skin ribbed shell concept were generally lower or similar to those for the corresponding honeycomb sandwich shell concept. The stresses of the vaulted ribbed shell concept were generally lower than those of the flat ribbed shell concept. Fig. 15 shows the ribbed shell skin element nodal stress σ_y distribution. The maximum stress values were within allowable limits and significantly lower than those with honeycomb composite sandwich construction.

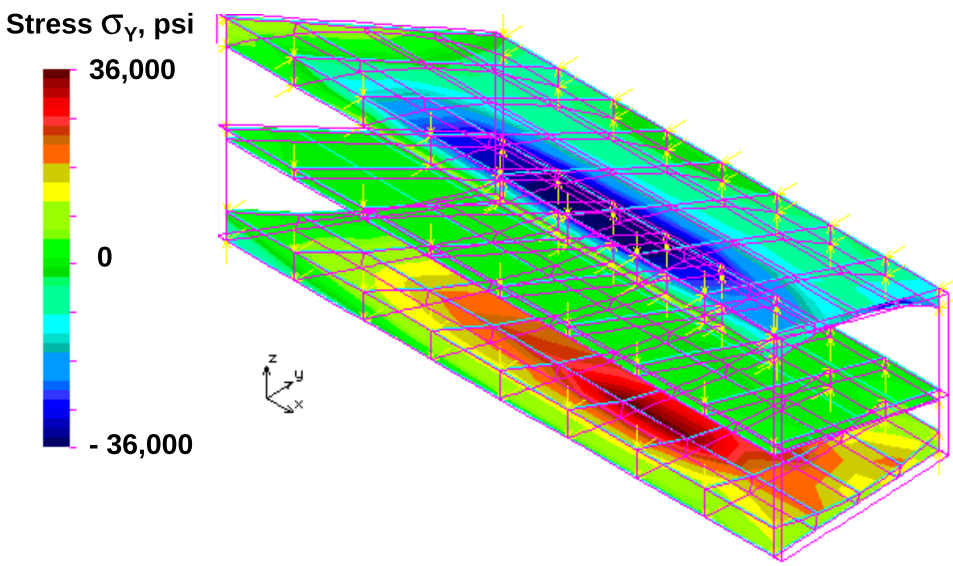


Fig. 15. Vaulted ribbed-shell skin element nodal stress σ_y at maximum cabin pressure 18.6 psi at 2.5g (clamped boundary condition).

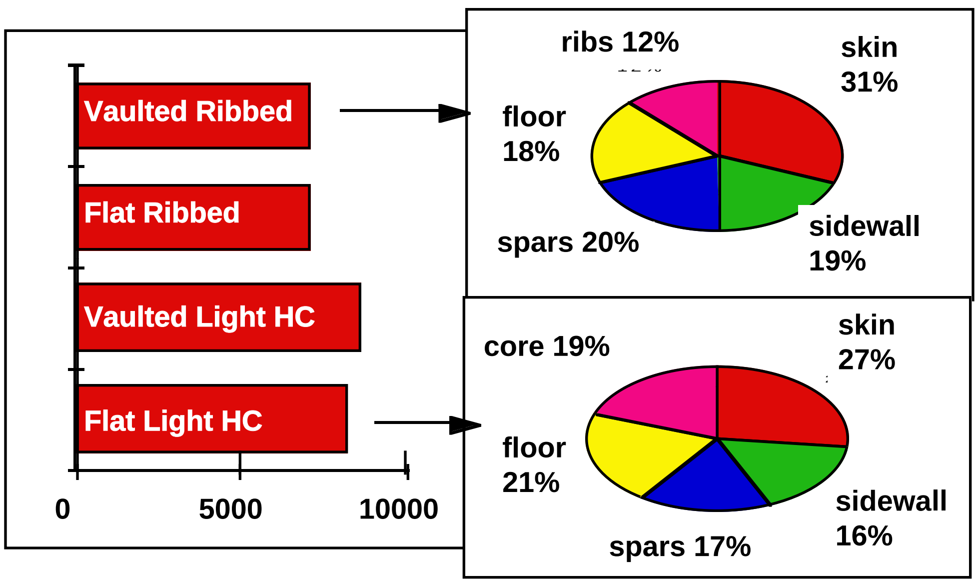


Fig. 16. Fuselage section structural weight comparison.

Weight comparison: Figure 16 shows a bar-chart comparison of weight in pounds from all four concept finite element models as well as component weight breakdown pie charts of the flat shell with light honeycomb core and double-skin ribbed shell concepts. The actual manufactured weights are conservatively estimated at twice the idealized FEM weight, in order to account for the joints, splices, fasteners and adhesives. These results indicate that the vaulted ribbed-shell concept could offer a 10 to 15 percent weight advantage over the uniform depth honeycomb sandwich concepts with comparable level of stress and deflection at the critical 2.5g maneuver load condition and maximum 18.6 psi design cabin pressure. Since the skin and the side walls comprise 45 to 50 percent of the total weight, additional weight savings could be achieved by a fully stressed design and optimization. However, many manufacturing issues remain to be resolved for both cases.

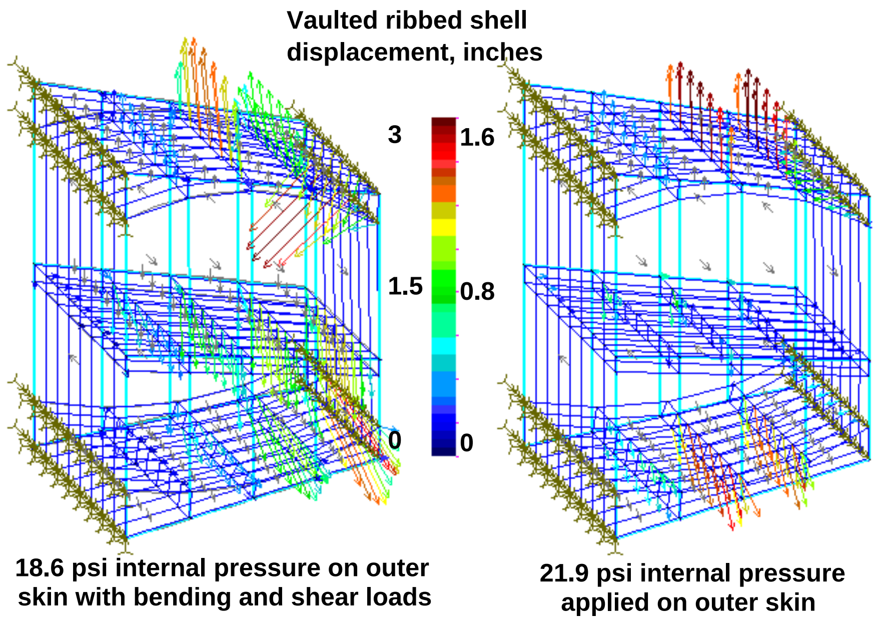


Fig. 17. Deflections due to two load cases where the pressure loads are applied to the outer skin of the vaulted ribbed shell to simulate inner skin pressure leak.

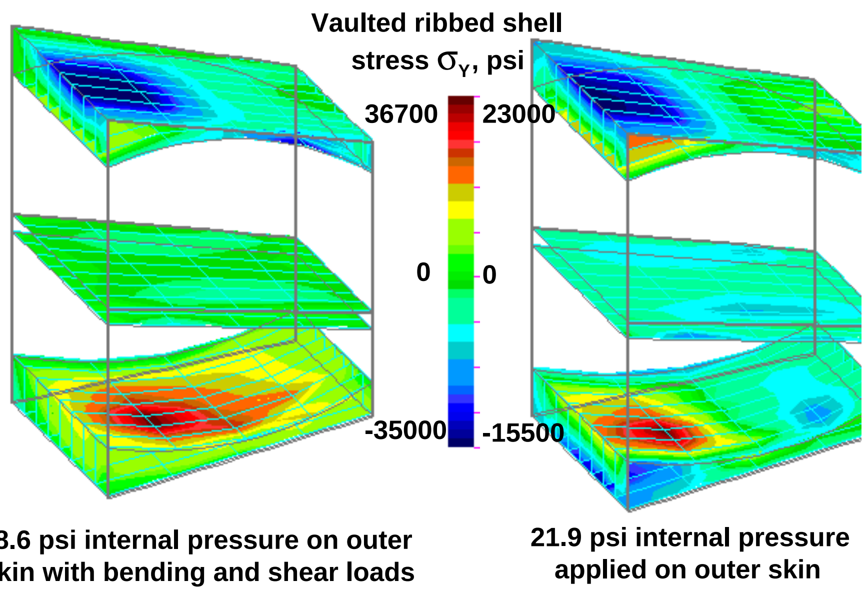


Fig. 18. Membrane stresses σ_Y due to two load cases where the pressure loads are applied to the outer skin of the vaulted ribbed shell.

<u>Suspension bridge concept and fail-safe design</u>: With the deep sandwich concept, in case of an inner skin puncture, the outer skin of the sandwich may not be able to withstand the pressure load and debond from the core, resulting in a failure. However, in case of an inner skin puncture, the double skin vaulted shell concept could be designed to be fail-safe, because it would act like a suspension bridge. The pressure on the outer skin would be transmitted through the ribs, to put the inner vaulted skin in tension, like a catenary. In order to test the fail safe feature of the double-skin shell concept, additional results were obtained by applying the 18.6 psi pressure load to the outer skin, for the 2.5g maneuver load case. A second load case in which 21.9 psi internal pressure is applied to the outer skin at sea level, without any bending load, was also analyzed to understand the effect of internal pressure only. These results are presented in Figs. 17 and 18. Note that this analysis used a 8x4x5 coarse mesh.

Fig. 17 shows the resultant displacement vectors for the two load cases, which indicates that in case of a inner skin pressure leak, the outer skin can take the pressure with same efficiency with the same level of deflection. Fig. 18 shows the membrane stress distribution on the skin in the spanwise direction for the two load cases. Note that the inner skin is mostly in tension and the outer skin is in compression. Figures 17 and 18 indicate that about 50 percent of the deflections and stresses can be attributed to pressure load and the rest to compression load. Since the bending loads and boundary conditions for the isolated fuselage bay analyses did not represent the actual condition, the integrated conceptual wing-fuselage was modeled and analyzed next for the vaulted double-skin ribbed shell concept.

ribs, inner and outer skins are assumed to be 0.125 inches thick. The skin of the outer wing and spar is assumed to have a 0.25 inches equivalent thickness to account for the effect of stringers and longirons. The number of outer wing ribs were chosen arbitrarily to be 25. The four bay fuselage section bays were subjected to a 18.6 psi internal ultimate pressure load. The mid-deck floor passenger load distribution was assumed to be 0.625 psi. Pressure load was not applied to the front and rear spar, since they were modeled only as flat plates. A typical upward elliptic lift distribution for a total elliptic lift load of 980,000 lb was applied to the upper skin. This represented half wing symmetric load distribution at 2.5g maneuver condition. Preliminary deflection and stress distribution are shown in Figs. 19 and 20.

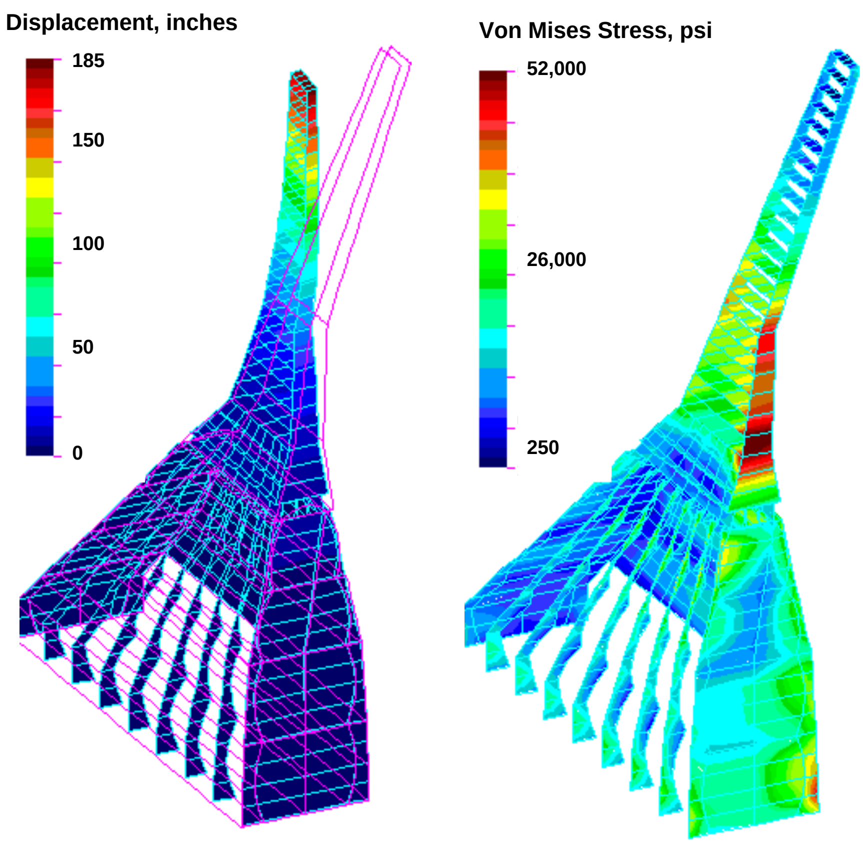


Fig. 19. Ribbed fuselage-wing displacement and Von-Mises stress distribution at 18.6 psi internal pressure and elliptic lift load at 2.5g maneuver condition.

Fig. 19 shows the ribbed fuselage-wing resultant displacement and Von-Mises stresses, when the lift load is applied to the top outer skin. It indicates that the stresses at the pressurized cabin area are well within the allowable limits. The wing tip deflection is close to 185 inches. The maximum stresses occur between the kink region of the rear spar, where the outer wing begins. With the assumed ultimate loads , mesh density and material properties, the stresses at the rear spar kink region exceeded allowable limits by 10 percent. This is a critical region and needs detailed analysis and design. Large stresses also occurred at the wing fuselage junction when the outer-most cabin ended as a flat surface. The stress was reduced substantially when the flat surface was replaced by a continuous cylindrical surface as shown in Figs. 3 and 19 with a mid-chord stiffener. Unstiffened mid-deck floors also show large deflection due to ultimate passenger load.

Figure 20 shows the side view of deformed shape and rear spar stresses on the top figure. The bottom figure shows the corresponding situation when the inner skin of the pressurized fuselage section has a pressure leak, and the internal 18.6 psi pressure is applied to the outer skin. The lift load is divided equally between upper and lower outer skin. The stresses and deflections at the fuselage region and outer wing basically remained at the same level. This demonstrated the fail-safe feature of the vaulted double-skin shell concept.

6. Wing-fuselage analysis

In view of the encouraging results in stage 3, for the vaulted double-skin shell concept, the integrated pressurized wing-body-fuselage was modeled with composite vaulted double-skin construction with deep spanwise and chordwise ribs for finite element analysis and weight estimation. Cantilever boundary conditions were assumed at the airplane symmetry line edges. All

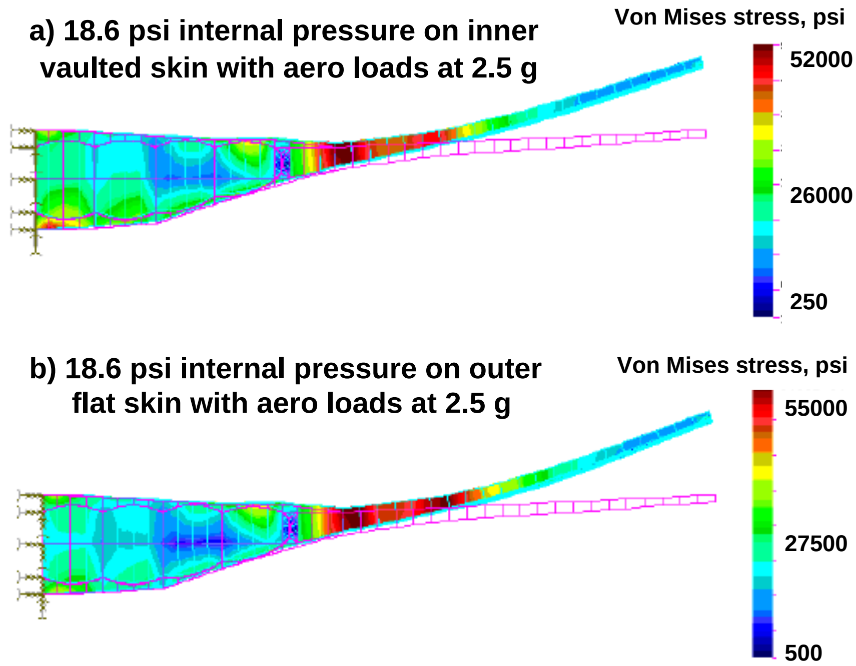


Fig. 20. Deformation and Von-Mises stress distribution with 18.6 psi internal pressure applied to, a) inner skin, and b) outer skin of the vaulted ribbed shell to simulate leak in the pressurized fuselage section (elliptic lift load at 2.5g maneuver).

7. Concluding remarks

A structural concepts study of non-circular pressurized fuselage configurations was presented for flying wing applications. Initial sizing, load, deflection and stress data were obtained using analytical nonlinear beam-column solution for a simplified configuration of the cabin roof. For a fixed set of geometry and representative critical loading condition, a vaulted sandwich shell concept and a flat sandwich shell concept were analyzed next using a coarse mesh finite element analysis. Since, neither of the concepts offered any distinctive advantage, the flat shell sandwich concept was considered to be a better choice due to its simplicity and fabrication advantage. However, for any metal-composite honeycomb concept, practical issues like local crippling, damage tolerance, crack propagation, splicing, moisture egress, corrosion, cut-out, fabrication and maintenance, also need to be addressed.

Additional structural systems studies indicated that the structural weight may be significantly reduced by replacing the honeycomb core of the sandwich shell by spanwise and chordwise ribs, much like a double skin pressure bulkhead. This double-skin ribbed-shell concept was analyzed for both the vaulted and flat shell configurations and compared with the sandwich concept results. The results indicate that a double-skin vaulted ribbed-shell concept could offer significant weight advantage over a flat ribbed-shell concept as well as the both the honeycomb sandwich concepts with similar levels of stresses and deflections. However, manufacturing and fabrication problems of ribbed double-skin shell structure need to be resolved for both conventional and composite construction.

The vaulted double-skin ribbed-shell concept was also analyzed for an integrated wing-fuselage finite element model. This concept appeared to be most promising and was demonstrated to have an additional fail-safe feature in case of an inner skin pressure leak. In such a situation this configuration operates much like a suspension bridge to transfer transverse pressure load into tension. The fuselage region where the pressurized section ends and outer wing begins and the outer wing region between the wing kinks were considered to be critically loaded areas which would need detailed analysis and design. From the stress distribution pattern, it was apparent that a nonlinear buckling analysis as well as an optimized fully stress design would be necessary for resizing in order to achieve additional weight advantage.

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