

Experimental Testing and Computational Modal Analysis of Air-Inflated Drop-Stitch Fabric Structures for Marine Applications

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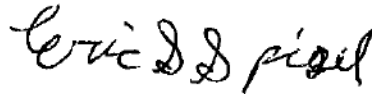
PREFACE

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14. ABSTRACT
<p>The U. S. Navy seeks to develop the capability to rapidly deploy marine structures. Surface-based inflatable structures including rigid inflatable boats, inflatable causeways and bridging, and launch and recovery systems provide unique solutions for temporary structures used during sea-based missions. Specifically, the Navy seeks to develop inflatable structures using shapes other than the typical cylindrical beams, arches, and spheres that are in service today. Air-inflated drop-stitch fabric panels enable the formation of lightweight inflatable structures that are suitable for structural applications requiring flat shapes. Unlike conventional metallic structures that buckle and fracture when they are exposed to overloaded conditions, air-inflated structures provide a failsafe mechanism during overload conditions: they wrinkle and collapse without damage to the fabric and regain their design shape and structural performance when the overload is removed.</p> <p>Design standards, however, are virtually nonexistent for inflatable structures involving shapes constructed of spheres, beams, arches, and most recently flat panels using three-dimensional woven drop-stitch panels. Predictive performance tools (analytical and numerical) for static and dynamic applications lag behind those for conventional structures, particularly with respect to the influence of inflation pressure on dynamic response. This research establishes the validity of physics-based models using the Ideal Gas Law as an equation of state to predict the natural frequencies and corresponding mode shapes of air-inflated drop-stitch fabric panels as functions of inflation pressure ranging from 5.0 to 30.0 psig. Both numerical and experimental methods were pursued; the results of laboratory modal experiments were used to validate the numerical models. Predicted and experimental natural frequencies and mode shapes were compared, and excellent correlation was observed.</p>

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LIST OF ABBREVIATIONS AND ACRONYMS

3-D	Three-Dimensional
FEM	Finite Element Method
FRF	Frequency Response Function
FSI	Fluid-Structure Interaction
kN	Kilonewton
ksi	Kilopounds per Square Inch
MDOF	Multiple Degree of Freedom
MPa	Megapascal
SDOF	Single Degree of Freedom

LIST OF SPECIAL NOMENCLATURE

a	Fluid Property Coefficient
b	Fluid Property Coefficient
c	Fluid Property Coefficient
C	Damping Constant
C_g	Pressure-Volume Constant
d	Fluid Property Coefficient
e	Fluid Property Coefficient
E	Modulus of Elasticity
$E_{internal}$	Internal Energy
E_{strain}	Strain Energy
$E_{kinetic}$	Kinetic Energy
$E_{dissipative}$	Dissipative Energy
$F(t)$	Force on Mass/Spring/Damper System
h	Drop-Stitch Panel Height
K	Spring Constant
L_o	Drop-Stitch Panel Length
M	Mass
n	Ratio of Specific Heats
P	Fluid Pressure
r	Drop-Stitch Panel Side-Wall Radius
R	Universal Gas Constant
T	Fluid Temperature
t_{skin}	Drop-Stitch Panel Skin Thickness
V	Fluid Volume
w_o	Drop-Stitch Panel Width
x	Position of Mass
ρ	Density
ω	Natural Frequency of Vibration

EXPERIMENTAL TESTING AND COMPUTATIONAL MODAL ANALYSIS OF AIR-INFLATED DROP-STITCH FABRIC STRUCTURES FOR MARINE APPLICATIONS

1. INTRODUCTION

An objective of the U.S. Navy is to develop the capability to rapidly deploy marine structures. Surface-based inflatable structures—including rigid inflatable boats, inflatable causeways and bridging, and launch and recovery systems—provide unique solutions for temporary structures during sea-based missions. Until recently, the Navy’s performance specifications for inflatable structures required minimal weight and stowage volume, rapid deployability, and temporary rigidity; solutions were limited to inflatable structures constructed of flexible materials in the form of cylindrical beams, arches, and spheres.

For the new generation of inflatable structures, the Navy seeks to develop inflatable structures that use shapes other than the aforementioned that are in service today. Air-inflated drop-stitch fabric panels, also known as spacer fabrics, allow inflatable structures to be formed that are suitable for structural applications requiring flat shapes. Like other inflatable shapes, air-inflated drop-stitch panels provide a failsafe mechanism during overload conditions: they wrinkle and collapse—without damaging the fabric. When the overload is removed, the structure regains its design shape and structural performance. Conventional metal structures buckle and fracture when they are exposed to overloaded conditions.

The problem is that, for all practical purposes, there are no design standards for inflatable structures involving shapes constructed of spheres, beams, arches, and, most recently, flat panels using three-dimensional woven drop-stitch preforms. Predictive performance tools (analytical and numerical) for static applications lag significantly behind those for conventional structures. Nonlinear system behaviors (material and geometric), thermomechanical coupling, and fluid-structure interactions (FSIs) pose significant challenges when existing design tools are applied to inflatable structures. This gap is further exacerbated for dynamic applications because inflatable structures exhibit pressure-dependent natural frequencies and mode shapes. The design of surface-based structures must consider operational sea-state frequencies and wave periods to prevent the onset of structural instabilities (wrinkling, buckling) and loss of load-carrying capacities.

The research documented in this report establishes the validity of physics-based models using the Ideal Gas Law as an equation of state to predict the natural frequencies and corresponding mode shapes of air-inflated drop-stitch fabric panels as functions of inflation pressure. Numerical and experimental methods were pursued; the results of laboratory modal experiments were used to validate the numerical models. Predicted and experimental natural frequencies and mode shapes were compared, and excellent correlation was observed.

2. DROP-STITCH FABRICS

Drop-stitch fabrics are examples of three-dimensional (3-D) woven fabric preforms (see figure 1); they consist of two skins that are simultaneously woven and spaced apart by a distance governed by the length of the drop yarns. The skins consist of a base fabric that is plain-woven using two orthogonal yarn directions (warp and weft directions) and a second warp yarn family to construct the drop yarns. The weft direction corresponds to the width direction and is limited by the size of the loom beam. The warp direction, which is in the weaving direction, is virtually unlimited in length. The drop yarns, a second family of warp yarns woven within the skins, are periodically dropped from one skin to the other; this weave pattern is repeated in an alternating manner as shown in figure 1. To maintain an airtight membrane, the skins are made impermeable by laminating layers of an elastomeric material, such as rubber or urethane, to fully contain a volume of air.

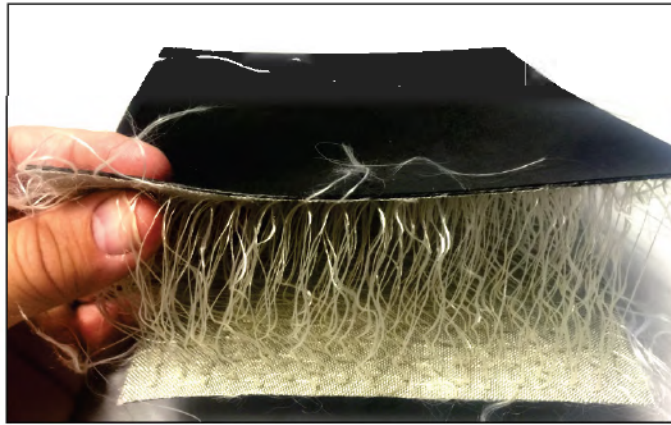


Figure 1. Example of a Drop-Stitch Fabric with Laminated Rubber Skins

During inflation of a drop-stitch panel, several phenomena occur: (1) the air volume increases with inflation pressure, (2) the skins become biaxially pretensioned, and (3) the drop yarns extend to their tensioned length and restrict the panel to generating a flat inflated shape. The pretensioned skins and drop yarns produce the stiffness necessary for the inflated panel to resist axial, bending, shear, and torsion loads. Load-carrying capacities and the stability of inflatable drop-stitch panels depend on a number of factors such as panel shapes, fabric architectures, and material properties. Nonlinear behaviors are often observed in the load-carrying performance. Drop-stitch panels exhibit similar load-carrying characteristics to those of sandwich panels in which the pressurized air volume acts as the foam or honeycomb core to provide shear stiffness. The drop-stitch panel skins support the primary resistance to bending loads.

To date, most research on inflatable fabric structures has focused on beam and arch-like structures with cylindrical cross sections using analytical, numerical, and experimental methods;¹⁻⁸ moreover, modal analyses have been limited to these shapes as well. Natural modes

of vibration for inflated beam and torus structures have been studied with both experimental and computational methods.^{9, 10} Griffith and Main determined a dependence of the frequency of vibration on the internal pressure level.¹¹ Except for the recently published findings on three- and four-point bending tests conducted on inflatable drop-stitch panels,^{12, 13, 14} very little research addresses the use of drop-stitch fabrics for use in flat inflatable structures.

As previously reported by Cavallaro, Hart, and Sadegh, the biaxial pretensions produced in the skins are functions of the inflation pressure, where increased inflation pressures produce increased pretensions.¹⁴ The pretensioned stress states increase the effective stiffnesses of the panel when it is subjected to bending and shearing loads. Both overall load-carrying capacity and the force (or moment) at which wrinkling onset occurs increase with increasing inflation pressure.

Comparing the results of Cavallaro, Hart, and Sadegh¹⁴ and those of Griffith and Main¹¹ for inflated fabric structures reveals that the pressure influence on the bending and shearing stiffnesses affects the natural frequencies of vibration of the drop-stitch panels. Natural frequencies and the accompanying mode shapes play a large role in the stability of the system when it is exposed to harmonic excitation, be it from cyclical loading on the structure or base excitation during operation. Understanding and controlling the natural frequencies and mode shapes of inflatable drop-stitch structures is critical when these structures operate in the presence of sea-state motions. In general, marine structures should be designed to avoid the generation of breathing modes when panel flatness is critical to system performance. Breathing modes in inflated drop-stitch panels are characterized by out-of-phase motions of the opposite skin surfaces. Breathing modes have the potential to produce through-thickness oscillations that can negatively affect performance, such as the ride performance and comfort levels of inflatable vessels that may be susceptible to the low-wave frequencies associated with operational sea states.

Design methods for air-inflated fabric structures constructed with drop-stitch panels can be improved through the combined use of computational and experimental mechanics. Computational methods include both numerical and analytical methods. The numerical finite element method (FEM) has been used for air-inflated fabric structures, and analytical solutions have also been developed. Experimental mechanics, including material property characterization tests, are necessary to provide mechanical behaviors of the constituent materials. Inflatable structures can be modeled prior to construction of physical prototypes such that the typical build-test-build cycle of prototype design can be minimized. With experimentally validated virtual design tools that accurately simulate the behavior of inflatable drop-stitch structures, their vibrational and dynamic responses can be predicted.

3. INFLATION MECHANICS

To understand the stiffening effects due to inflation pressure on the natural frequencies and vibration modes of drop-stitch panels, the distribution of skin and drop yarn pretensions must be determined. Furthermore, the influence of panel mass, size, aspect ratio, and structural supports are fundamentally important. The pressure-volume relationship for a closed volume of air can be treated in accordance with the Ideal Gas Law, which is given by:

$$PV = RT, \quad (1)$$

where P is the absolute pressure, V is the volume of air, R is the ideal gas constant, and T is the absolute temperature in Kelvin. For a polytropic thermodynamic process¹⁵ on an ideal gas confined in a closed volume, the pressure-volume relationship for the compression cycle (see figure 2) can be described by:

$$PV^n = C_g, \quad (2)$$

where $C_g = \text{constant}$ and $n = \text{ratio of specific heats}$ ($n = 1.4$ for air).

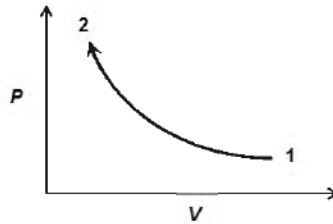


Figure 2. Compression Cycle for a Gas from State 1 to State 2

Therefore, two states of a compression (or expansion) process within a system can be described by

$$P_1V_1^n = P_2V_2^n. \quad (3)$$

FSIs occur when the enclosed air experiences pressure and volume changes resulting from mechanical or thermal loading. Inflation causes tensile strains to develop in the membrane material, which will, for a closed system, contribute to finite volume increases. This type of fluid-structure coupling—unique to inflated structures—is a source of nonlinear behavior and increases the complexity of the governing mechanics. When FSIs are considered, air compressibility must be included in the energy balance. In addition to the strain energy developed in the membrane materials, the thermodynamic work done on the air, known as PV -work, must be accounted for.

The idealized form of the energy balance for an air-inflated fabric structure is

$$\int Fd\delta = \Delta E_{internal} = \Delta E_{strain} + \Delta E_{kinetic} + \Delta E_{dissipative} + \Delta \int PdV + \Delta \int VdP, \quad (4)$$

where F is an externally applied force, δ is the deflection at point of loading, $E_{internal}$ is the internal energy of the system, E_{strain} is the sum of the elastic (recoverable) and plastic (irrecoverable) strain energies, $E_{kinetic}$ is the kinetic energy of the system mass, and $E_{dissipative}$ is the dissipated energy through damping and viscous effects. The Δ symbol is used to denote differences between inflated and loaded states.

4. DROP-STITCH PANEL GEOMETRY

The current air-inflated drop-stitch panel geometry is a nominally flat, enclosed volume with semi-cylindrical edges (see figure 3). The overall panel length L_o , the overall panel width w_o , and the overall panel thickness h are defined as shown in figure 3. The edges have a radius r equal to $h/2$. The thickness of the skins t_{skin} was 2.43 mm (0.096 in.). The drop yarns were assumed to be uniformly distributed and were further assumed to possess extensional stiffness only. If the drop yarns are compressed, they do not contribute any compressive reaction forces. Note that, in fabricating drop-stitch panels of the geometry described in this report, drop yarns within the vicinity of the rounded edges were considered to be nonparticipatory because their length was longer than the distance between the two drop-stitch panel faces. Total mass of the drop-stitch panel was 10 kg (22 lb).

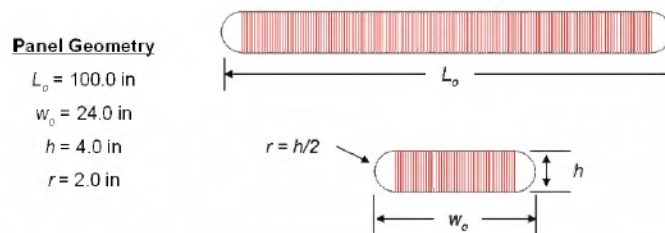


Figure 3. Geometry and Loading Parameters for Inflatable Drop-Stitch Panel

The drop-stitch skins were constructed of a plain-woven polyester fabric laminated with rubber layers on each surface. The warp, weft, and drop yarns were all constructed of the same polyester fibers. Figure 4 shows the base and laminated fabric construction details. The reinforcing effects of rubber coatings on woven fabrics were investigated using experimental methods by Farboodmanesh et al.¹⁶

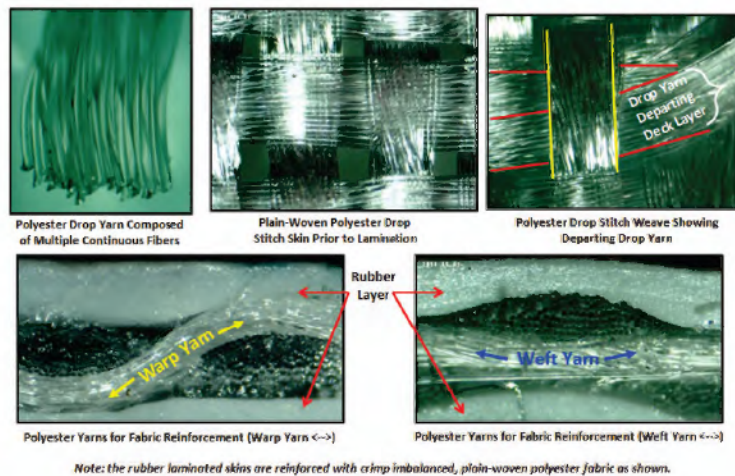


Figure 4. Construction Details of Rubber-Laminated, Polyester Fabric-Reinforced Drop-Stitch Skins

5. EXPERIMENTAL TESTING

The natural frequencies and vibration modes of drop-stitch panels were experimentally determined at the Structural Dynamics and Acoustic Systems Laboratory at the University of Massachusetts Lowell. Drop-stitch panels were inflated to an internal pressure ranging from 5.0 to 30.0 psig and were subjected to harmonic shaker excitations. Motions in the panel were recorded by laser vibrometry at a series of locations covering both the front and back faces. Because of the noncontact nature of the system, laser vibrometry is ideally suited for lightweight and flexible structures. This method was previously used in measuring natural frequencies of vibration for membrane structures.¹⁷ With proper signal processing of the displacements at each measured point, overall mode shapes and vibration frequencies can be determined.

5.1 MODAL THEORY

When a mechanical structure is subjected to an impulse or harmonic force excitation, the structure exhibits a vibrational response that is dependent on its stiffness and mass distribution. Air-inflated drop-stitch structures are complex, multiple degree-of-freedom (MDOF) systems with nonlinear characteristics. For such complicated systems, it is a better approach to treat this MDOF as a weighted series of linear single degree-of-freedom (SDOF) systems that are superimposed. For an SDOF system, such as the lumped mass attached to a spring-damper system (see figure 5), the equation of motion of the mass is

$$M \ddot{x} + C \dot{x} + Kx = F(t). \quad (5)$$

where M is the mass, C is the damping coefficient, K is the spring stiffness, and $F(t)$ is the force applied to the system.

For an undamped system ($C = 0$), the primary frequency of vibration becomes:

$$\omega = \sqrt{\frac{k}{m}}. \quad (6)$$

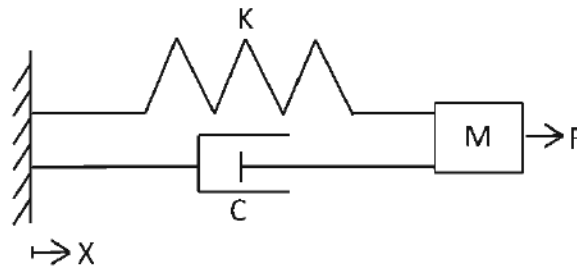


Figure 5. Single Degree-of-Freedom Mass-Spring-Damper System

Drop-stitch panels, however, have multiple sources of damping that must be considered. Furthermore, the complex structure of drop-stitch panels is better approximated as a continuum structure, rather than a system of discrete components. In this MDOF system, the equations of motion can be assessed in matrix form:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\}. \quad (7)$$

Transforming equation (7) into the Laplace domain allows efficient manipulation of the differential equations and produces:

$$[[M]s^2 + [C]s + [K]]\{X(s)\} = \{F(s)\}. \quad (8)$$

The mass, damping, and stiffness terms can be grouped into the transfer function matrix $[B(s)]$, which directly relates the input matrix to the output matrix, defined as $\{X(s)\}$ and $\{F(s)\}$ respectively:

$$[B(s)]\{X(s)\} = \{F(s)\}. \quad (9)$$

The inverse of the transfer function matrix $[B(s)]$ gives the system transfer matrix $[H(s)]$, which can then be written in terms of the poles and residues of a system in partial fraction form:

$$[B(s)]^{-1} = \frac{\{X(s)\}}{\{F(s)\}} = [H(s)] = \sum_{k=1}^m \frac{[A_k]}{(s-p_k)} + \frac{[A_k^*]}{(s-p_k^*)}. \quad (10)$$

Reverting from the Laplace domain to the frequency domain, with $s=j\omega$, the resulting function $[H(j\omega)]$ is called the frequency response function (FRF):

$$[H(j\omega)] = \sum_{k=1}^m \frac{[A_k]}{(j\omega-p_k)} + \frac{[A_k^*]}{(j\omega-p_k^*)}. \quad (11)$$

The FRF consists of SDOF systems summed over all the modes of the complete system. The Laplace domain transfer function can now be evaluated for a given system pole and can be broken down, through singular-value-decomposition techniques, to give:

$$[H(s)]_{s=p_k} = \{u_k\} \frac{q_k}{s-p_k} \{u_k\}^T. \quad (12)$$

Considering all the modes of the system yields:

$$[H(s)] = \sum_{k=1}^m \frac{q_k \{u_k\} \{u_k\}^T}{(s-p_k)} + \frac{q_k \{u_k^*\} \{u_k^*\}^T}{(s-p_k^*)}. \quad (13)$$

From this form, a relationship between the residue matrix and the mode shapes of the system can be written. The FRF is decomposed into a summation of a set of SDOF frequency responses (see figure 6). When this partial fraction form is used, mode shapes and poles can be estimated through curve fitting with a least-squares-error approach.

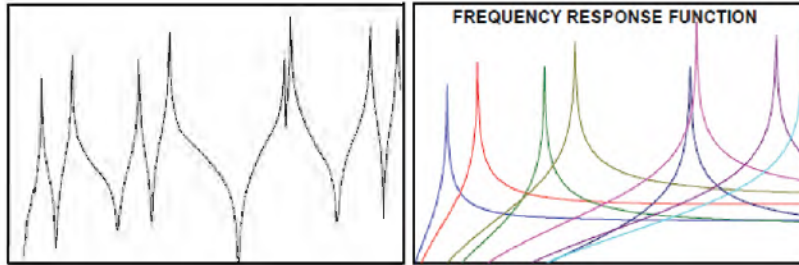


Figure 6. Decomposition of the Freedom Frequency Response into a Series of Single Degree-of-Freedom Frequency Responses

5.2 TEST SETUP

Figure 7 shows the drop-stitch panel in its testing configuration. The panel was hung from the ceiling using bungee cords to best represent an unconstrained boundary condition. A harmonic excitation shaker from MB Dynamics using pseudo-random signals was used for each pressure configuration. The shaker was located at the bottom-right side of the front face. A laser vibrometer from Polytec Inc. measured the motion of a grid of response points over the two panel faces. These grid points are highlighted in blue in figure 7. The back side was covered by 65 grid points; the front (shaker) side was covered by 63 points.

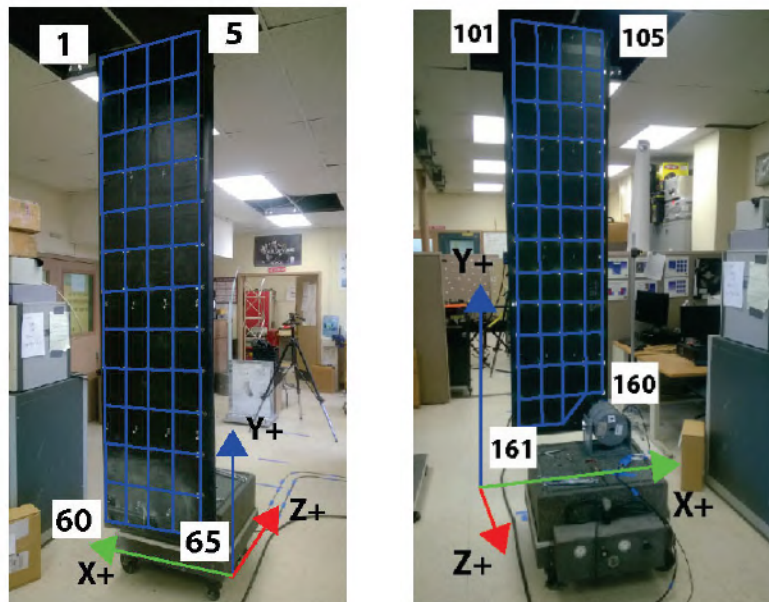


Figure 7. Back (Left) and Front (Right) Faces of the Drop-Stitch Panel in the Testing Configuration (blue grid represents the data acquisition points)

Tests were conducted at six different pressure levels in 5-psi increments (5.0 to 30.0 psig). Experimental FRFs were collected for all grid point locations for each inflation pressure. The vibration response of each grid point in the time domain was converted to the frequency domain using the fast Fourier transform algorithm, then analyzed to formulate the FRFs. The primary modes of vibration were tracked using the modal assurance criteria. Testing parameters are shown in table 1.

Table 1. Experimental Test Parameters

Parameter	
Spectral Lines	800
Bandwidth Hz	100
Frequency Resolution Hz	0.125
Measurement Duration s	8.00

5.3 TEST RESULTS

Several of the first lower order mode shapes and frequencies of vibration were extracted from testing at each inflation pressure (see table 2). These mode shapes of interest were the first three bending modes along the long axis of the panel, the first three torsion modes along the same long axis, and one bending mode along the short axis. No breathing modes were recorded for this panel at the considered inflation pressures. As inflation pressure increased, the frequency of vibration for a given mode shape increased as expected. A graphical representation of the data in table 2 is provided in figure 8.

Table 2. Natural Frequencies of Each Mode Shape of Interest at Different Inflation Pressures

Mode	Frequency (Hz) for Each Inflation Pressure					
	5 psi	10 psi	15 psi	20 psi	25 psi	30 psi
First Bending	12.8	14.4	15	15.7	16.4	17.0
First Torsion	13.5	13.8	14.7	15.3	15.9	16.4
Second Bending	22.1	28.2	30.2	32.3	34.5	36.0
Second Torsion	25.4	30.0	32.0	33.3	34.8	35.9
Third Bending	29.1	39.3	44.1	48.4	52.5	55.8
Third Torsion	36.1	44.7	49.2	52.3	55.2	57.4

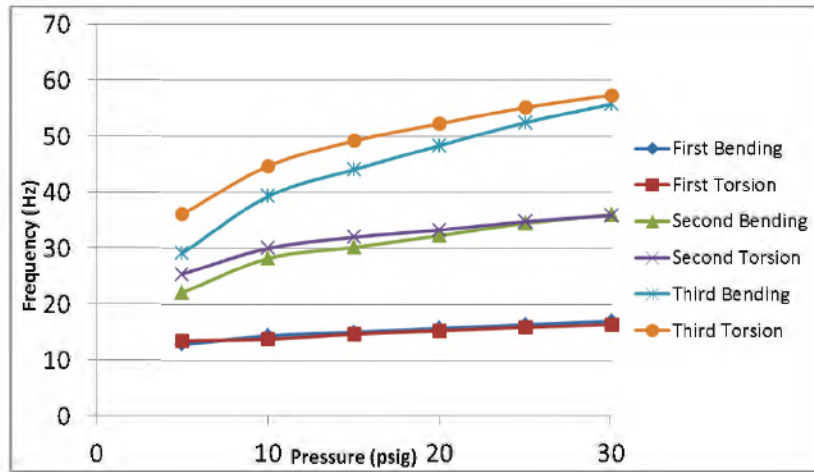


Figure 8. Natural Frequency (Hz) versus Pressure (psi) of Drop-Stitch Panels during Experimental Testing

Each mode shape increased nonlinearly in frequency with increasing inflation pressure. Because the mass of air within the drop-stitch panel was negligible for vibration characterization purposes, the changes in frequency with respect to inflation pressure were attributed to the increased fabric/yarn pretensions. Progressively higher pretension stresses in the fabric skins produced higher skin stiffnesses.

With the exception of 5.0 psig, the short axis bending mode was at the highest frequency for the mode shapes of interest. At the lowest pressure of 5.0 psig, the biaxial pretension in the skins may not have been fully developed to provide sufficient stiffness for this vibration mode. With higher inflation pressures, the fully-formed inflation stress states produced a consistent order of mode shapes with increasing frequencies. Mode shapes were categorized using the laser vibrometer and are shown in figure 9 for the first three bending modes, and the first torsion mode.

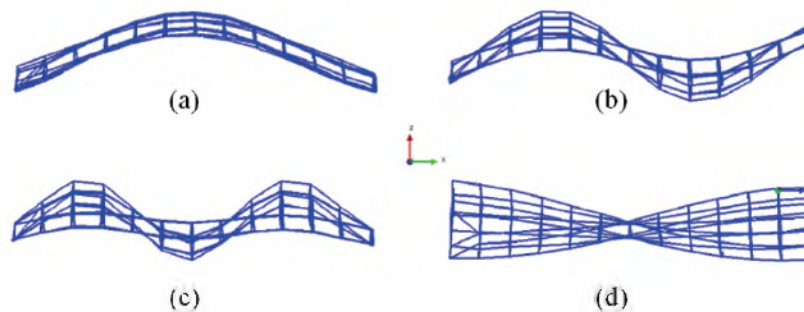


Figure 9. Mode Shapes During Experimental Test of Drop-Stitch Panels: (a) First Bending, (b) Second Bending, (c) Third Bending, (d) First Torsion

6. COMPUTATIONAL ANALYSIS

6.1 FINITE ELEMENT MODEL

To predict the natural frequencies and modes of vibration for an inflated drop-stitch panel, a computational model simulating the experimental tests was developed. A 3-D FEM was created using the explicit and standard solvers in ABAQUS.¹⁸ The model consisted of triangular membrane elements (M3D3) that represented the fabric/laminate skin structure and two-node truss elements (T3D2) representing the drop yarns. The skin elements were modeled to replicate the thickness of the test panel t_{skin} at 2.43 mm (0.096 in.) with a mesh density of 6.35 mm (0.25 in.). The density, stiffness, and dimensions of the panel skins and drop yarns were defined to reflect the weight and stiffness of the entire test panel (see table 3 for the material properties of drop-stitch panel).

Table 3. Material Properties for Finite Element Model of the Drop-Stitch Panel

Parameter	Drop Yarn	Skin
Drop Yarn Cross-Sectional Area mm ² (in. ²)	0.0167 (2.59E-5)	-
Skin Thickness mm (in.)	-	2.438 (0.096)
Elastic Modulus E MPa (ksi)	7240 (1050)	379 (55.0)
Density ρ kg/m ³ (lb/in. ³)	1187 (0.0429)	1187 (0.0429)
Length L_0 mm (in.)	-	2540 (100)
Height h mm (in.)	102 (4.00)	102 (4.00)
Width w_0 mm (in.)	-	607 (24.0)

The drop yarn elements connected matching nodes from opposite skin surfaces. The cross-sectional area of the drop yarns was 0.0167 mm² (2.59E-06 in.²), and the pitch between drop yarns was 6.35 mm (0.25 in.). The sides and ends of the panels were hemispherically shaped with a diameter equal to the distance between the flat skin surfaces h . No drop yarns were modeled in these regions because these remained slack during each of the inflation pressures considered and; therefore, could not fully straighten and develop pretension. Figure 10 shows a partial cutout at the radiused corner of the drop-stitch panel highlighting the mesh refinement with the drop yarn elements highlighted in yellow.

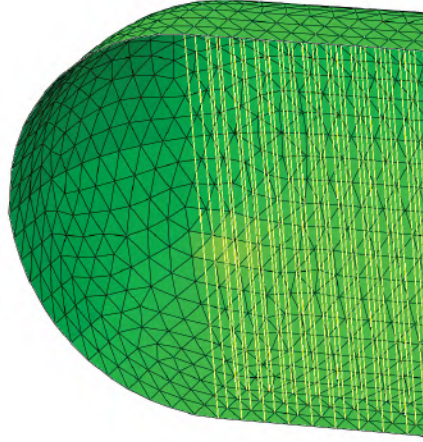


Figure 10. Cutout of the Drop-Stitch Panel Showing the Mesh Refinement and Drop-Stitch Elements

The pressurized air contained within the drop-stitch panel was simulated by the fluid cavity capability within ABAQUS. The fluid cavity pressure was defined by an additional nodal degree of freedom for a reference node within the cavity. The pressure within the cavity was assumed uniform; moreover, it was assumed that any changes in the fluid volume or air pressure occurred adiabatically. Fluid behavior was determined by the Ideal Gas Law, shown in equation (1). The universal gas constant R was 8.314 J/k-mol . The constant volume heat capacity of the fluid was determined by the Shomate equation. Coefficients for the heat capacity of air are listed in table 4.

Table 4. Material Properties for Air Cavity in Drop-Stitch Panels

Coefficient	Value
Molecular Weight	0.0289
a J/k-mol	28.1
b J/k ² -mol	0.001967
c J/k ³ -mol	4.8E-6
d J/k ⁴ -mol	-1.97E-9
e J-k/mol	0.00

6.2 TWO-STEP ANALYSIS: QUASI-STATIC INFLATION AND MODAL STEPS

The analysis was performed in two steps: (1) an initial quasi-static inflation step was performed to obtain the skin and drop yarn pretensions and volumetric deformations using ABAQUS/Explicit and (2) a second step was performed to extract the natural frequencies and mode shapes relative to the inflated states using ABAQUS/Standard.

6.2.1 Quasi-Static Inflation Step

For the inflation step, boundary conditions were applied to simulate the panel resting on a combined pin/roller support, allowing in-plane and transverse deformations. The pressure degree of freedom at the reference node corresponding to the fluid cavity was increased from 0.0 psig to a range of 5.0 to 30.0 psig, over a span of 0.5 second. This time span was selected for purposes of computational efficiency only. As pressure was exerted on the inner surfaces of the panel, a developed shape was achieved, with stresses distributed in such a way that static equilibrium was reached and volume changes occurred in accordance with the Ideal Gas Law. Figure 11 shows the maximum principal stress contours for the drop-stitch panel at 20-psi inflation.

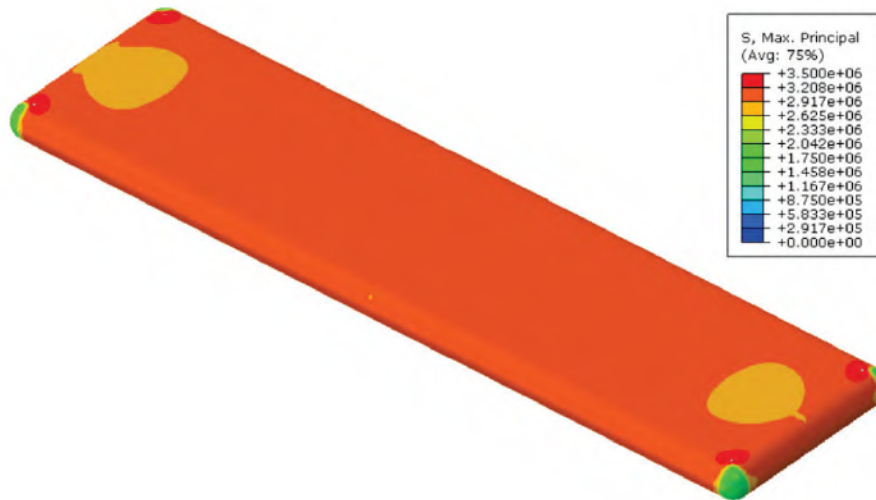


Figure 11. Maximum Principal Stress (in Pa) of the Drop-Stitch Panel Skin at 20-psi Inflation Pressure

A uniform distribution of maximum principal stress can be seen across the top and bottom faces of the drop-stitch panels while stress reductions occurred at the curved corners of the panel where the drop yarns ended. The drop yarn elements maintained the flat panel profile and prevented the skins from otherwise expanding into a cylindrical shape. The maximum principal stress in the skin was 3.5 MPa (508 psi), which corresponds to a skin force/width of 8.53 kN/m (48.7 lb/in.). The maximum principal stress in the drop yarns was 370 MPa (54.7 ksi), giving a force of 6.17 N (1.39 lb) per drop yarn. Figure 12 plots the maximum principal stress at a central point on the drop-stitch face as a function of inflation pressure. Maximum principal stress was observed to increase linearly with respect to increasing inflation pressure.

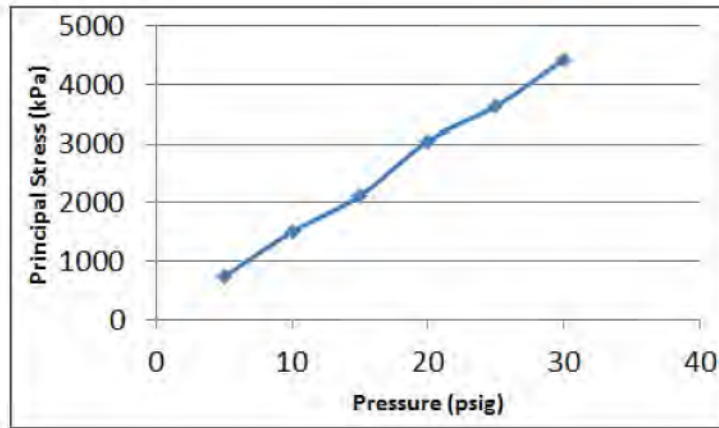


Figure 12. Maximum Principal Stress of the Drop-Stitch Panel Skin as a Function of Inflation Pressure

6.2.2 Modal Step

Data from the inflation step, including deformations, volume changes, and stress states, were transferred from ABAQUS/Explicit to ABAQUS/Standard by using the *IMPORT command for use as initial conditions in the modal step. The current air pressure and volume in the fluid cavity were held constant to simulate a closed system. Any changes in volume attributed to vibration deformation were inversely proportional to changes in the applied fluid pressure and temperature, according to the Ideal Gas Law.

To mirror the boundary conditions present in the modal testing, the FEM was allowed to move freely in all directions. The first 20 natural frequencies of vibration up to a maximum frequency of 500 Hz were analyzed using the Lanczos solver. The corresponding frequencies obtained included the first three bending modes and one torsion mode as shown in figure 13. These modes were consistent for all inflation pressures considered and, as with the experimental testing, did not exhibit any breathing modes. The deformations were enhanced to accentuate the panel mode shapes. The bending modes of vibration induced rotations about the axis parallel to the panel width; whereas the torsion mode of vibration was twisted about the panel’s longitudinal axis.

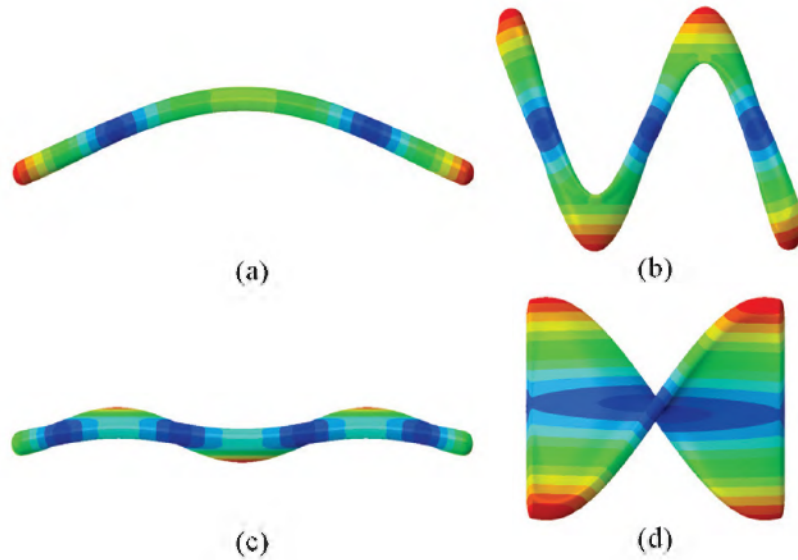


Figure 13. Modes of Vibration for the Drop-Stitch Panels: (a) First Bending Mode, (b) Second Bending Mode, (c) Third Bending Mode, (d) Torsion Mode

Figure 14 shows the frequencies of these four vibration modes for each inflation pressure along with the corresponding experimental results (reported in figure 8). As the inflation pressure and pretension stresses in the drop-stitch panel increased, the natural frequencies of vibration increased. The stiffening effect was more pronounced at higher frequency modes, particularly for the third mode of bending. A high degree of correlation between the predicted and experimental frequencies was achieved, with an average correlation of 0.98. The numerical results were consistently 2 to 3 Hz below the experimental results, suggesting that either the effective stiffness or mass distributions of the drop-stitch panel were underestimated by the model.

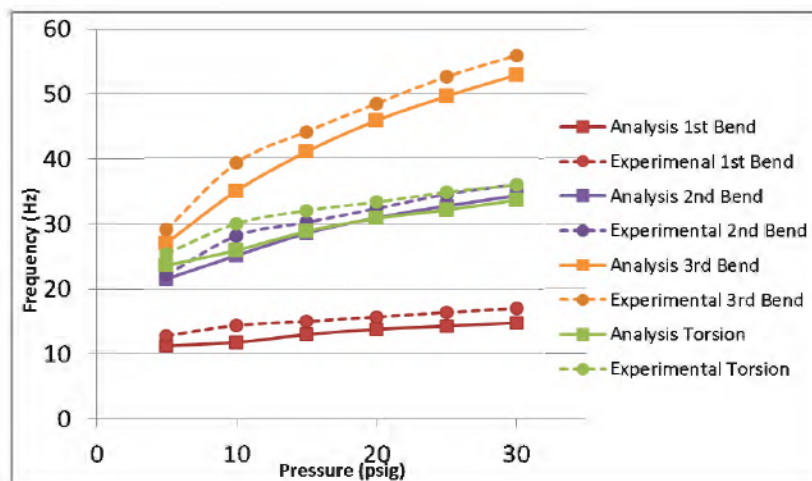


Figure 14. Comparison of Frequencies of Vibration: Analytical Results and Experimental Tests

7. SUMMARY AND CONCLUSIONS

The pressure-dependent frequencies of vibration of inflatable drop-stitch panels were investigated through combined numerical and experimental methods. Primary mode shapes of interest and their corresponding natural frequencies of vibration were determined and compared between the two methods. Modal testing of a drop-stitch panel was performed by loosely supporting the panel from the ceiling and subjecting it to a harmonic shaker. Natural frequencies and mode shapes were recorded using a laser vibrometer.

The influence of inflation pressure on the natural frequencies and mode shapes of drop-stitch panels was investigated using the finite element analysis method; the predicted responses were compared to the experimental results. The numerical method, utilizing both ABAQUS/Explicit and ABAQUS/Standard, accounted for pressure and volume changes due to inflation and panel pretension stresses. Two sequential, numerical steps, a quasi-static inflation step followed by a modal step, were utilized to replicate the experimental tests.

A strong dependence of inflation pressure on the natural frequencies was observed over the range of 5.0 to 30.0 psig. As inflation pressure increased the natural frequencies increased nonlinearly, especially at the lower inflation pressures. Breathing modes were not observed in the experimental nor the computational results for the panel dimensions and inflations pressures used. Excellent correlation of the natural frequencies and modes of vibration was obtained for the range of inflation pressures considered. However, the numerical predictions consistently underestimated the natural frequencies by 2 to 3 Hz. This underestimation was attributed to inaccuracies in mass distribution or possible nonlinearities resulting from the elasticity of the rubber coatings used on the skins. Numerical, rather than analytical, solutions are most appropriate when nonlinearities due to geometric behavior (large deflections, large strains, and large rotations) and material behavior are present. Such solutions can readily incorporate complex material models that account for hyperelastic behaviors using strain energy potentials, as reported by Ogden¹⁹ and Marlow,²⁰ to more accurately characterize the material stiffness over the range of considered inflation pressures. Such material models may produce more accurate comparisons between experimental and numerical analyses.

It is concluded from the results of this investigation that the design of inflatable structures constructed from drop-stitch panels is possible through the use of computational methods. Inflatable drop-stitch panels can be numerically modeled to accurately predict their pressure-dependent behaviors, including vibrational and dynamic responses.

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