NASA/TM–2018-219826

Demonstration of Probabilistic Sensitivity Analyses Tools on the Structural Response of a Representative Inflatable Space Structure

Karen H. Lyle and Thomas C. Jones
Langley Research Center, Hampton, Virginia

April 2018

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM–2018-219826

Demonstration of Probabilistic Sensitivity Analyses Tools on the Structural Response of a Representative Inflatable Space Structure

Karen H. Lyle and Thomas C. Jones
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

April 2018

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Abstract

This work provides an initial step toward demonstrating a probabilistic numerical simulation capability to support trade studies and the development of a certification plan for inflatable space habitats. This study concentrates on interpreting the results from probabilistic analysis and numerical simulation tools to identify parameter sensitivities for a novel inflatable airlock concept, specifically the Non-Axisymmetric Inflatable Pressure Structure (NAIPS) that was designed and tested under NASA's Minimalistic Advanced Softgoods Hatch (MASH) Program. A brief overview of the finite element model is provided along with the probabilistic sensitivity analysis approach. The sensitivity studies required a model that was numerically stable and efficient enough that hundreds of simulations could be completed in the allotted time. Therefore, the existing full model was simplified by: extracting a quarter symmetry section of the dome; focusing on a single inflation pressure; and replacing the non-linear material stress-strain curves with linear, isotropic materials defined by elastic moduli. Responses of interest include the sensitivity of various structural component loads to material properties, cord lengths, inflation pressure and friction. Multiple sensitivity studies were completed and three are reported here. The first study focused on utilizing wide input parameter ranges to provide an opportunity to assess numerical robustness. The next two studies narrowed the parameter ranges to enable focus on understanding uncertainty at a fixed operating condition. The completion of the sensitivity studies improved understanding of the interdependence of multiple inputs on the responses. In addition, numerical stability of the simulations over wide parameter ranges, shows the feasibility of incorporating uncertainty-based methods in the design and certification of inflatable space habitats. With the experience and trust gained, it is anticipated that these same methods will be applied to nonlinear, orthotropic models in the future.

Introduction

High-reliability, inflatable space structures are in demand for a number of applications due to their efficient packaging and light weight. Traditionally, evaluations of design concepts and concept validation have been performed through testing because of the limited analysis capability for soft-goods structures. However, recent advances in simulation capability and numerical computing speed have enabled simulations of a wide range of aerospace applications. Examples where numerical simulations were utilized in soft-goods applications include: inflatable habitats such as the Bigelow Expandable Activity Module (BEAM)[1,2]; atmospheric decelerators such as the Hypersonic Inflatable Aerodynamic Decelerator (HIAD)[3,4]; attenuation systems such as the Orion Crew Module Airbag Landing System[5,6]; and aerospace recovery systems[7].

Complementary to the advances in structural computational capabilities has been the implementation of probabilistic methods and establishment of standards for verification and validation of numerical simulations. Several technical societies and agencies are developing standards for documenting the uncertainty of responses to variations in input parameters. Examples include: The AIAA Guide for the Verification and Validation of Computational Fluid

Dynamics Simulations[8]; NASA's Standard for Models and Simulations[9]; and Sandia National Laboratories' Predictive Capability Maturity Model for Computational Modeling and Simulation[10]. Additional examples of aerospace applications incorporating probabilistic methods are provided in Refs. 11 and 12.

Sensitivity analyses are performed for a number of reasons. A prime example is to identify, in a quantitative manner, the variables that are controlling the response uncertainty. With this knowledge, designers can direct resources to reduce uncertainties in point-designs, as well as to utilize the results to efficiently modify designs to improve performance. Sensitivity analyses can also be used for variable screening purposes, i.e., to down-select from a large list of parameters to those variables that will be incorporated into future analyses. A review of many sensitivity methods and applications can be found in Ref. 13. Probabilistic Analysis (PA) methods can be used to support sensitivity studies in a number of phases of design. For example, parameter variations can be selected based on expected parameter deviations from the as-built system. In addition, PA tools can be used to conduct parametric studies where the uncertainty model description represents a design space, as opposed to an uncertainty space. In general, for probabilistic analyses sophisticated methods may be required to optimally use the results from a relatively small number of simulations. The choice of method is dependent on the number of uncertain parameters, the number and types of responses, the simulation execution time, and the physics of the application.

As NASA continues to explore the use of inflatables for a variety of applications, development of a certification plan for human-rated inflatable space structures is critical[14]. A novel inflatable airlock concept, specifically the Non-Axisymmetric Inflatable Pressure Structure (NAIPS) developed under the Minimalistic Advanced Softgoods Hatch (MASH) Program[15,16], is the application focus of this report, see Figure 1 for a photograph of the engineering development unit (EDU). The NAIPS structural analysis problem represents several design challenges, including: 1) the lack of formal design approaches to address such soft-goods hatch concepts; and 2) modeling the behavior of complex structural responses that include uncertainty in soft goods material properties and transfer of loads through multiple paths and different soft-goods elements. Fortunately, the detailed computational tools needed to analyze the structural response of such systems are becoming sufficiently mature to adequately model the response of these complex structures. Additionally, it is now feasible to complete the numerous nonlinear transient dynamic simulations that are critical to support verification of the design in a reasonable amount of time.

The purpose of the work reported here is to describe the demonstration of a probabilistic numerical simulation capability to support trade studies and development of a certification plan for inflatable habitats. This study concentrates on the demonstration of probabilistic analysis tools to identify parameter sensitivities by: focusing on the NAIPS modeling effort to understand design sensitivities and mitigate modeling instabilities; and building on PA tools developed for other types of structural applications. Responses of interest include the cord loads and fabric line-loads as well as the geometric shape of the lobes. This paper begins with a brief overview of the finite element model (FEM) and the probabilistic sensitivity analysis approach, followed by a discussion of the results. Within the discussion of the results, parameter sensitivities and variation of component loads are provided. Finally, concluding remarks provide general comments about the approach and findings.

Description of Inflatable Hatch Concept

NAIPS is an inflatable airlock and softhatch concept that consists of high-specific strength Vectran fabric material constrained by a network of braided Vectran cords, see Figure 1. The concept dimensions were selected to provide adequate room for two astronauts to don and doff their space suits as they transfer between the pressurized spacecraft and the vacuum of space. The design utilizes the ability to transfer the internal pressure load applied to the woven fabric to the cords, which are then capable of carrying the majority of the load. Additionally, the design takes advantage of the low-stress areas in the lobes of each end dome perpendicular to the dome radial (or meridional) cords. These low stress regions enable inclusion of one or more lightweight softhatch openings, analogous to a zipper. Mechanical property tests were performed on the fabric and the cords to obtain load-strain properties. It should be noted that the woven fabric and braided cords undergo large displacements at the onset of loading, due to material strain and to decrimping and untwisting of the yarns. In addition, the load-strain behavior changes as the materials are cyclically loaded. Prior to this analysis effort, experiments were conducted to acquire structural response data for a representative, full-scale point design. Additional details about the EDU design, test data and early simulation results were provided in Ref. 16.

Description of Analyses

Finite Element Model (FEM)

The sensitivity studies required a model that was numerically stable and efficient enough that hundreds of simulations could be completed in the allotted time. Therefore, the existing full model was simplified by: extracting a quarter symmetry section of the dome; focusing on a single inflation pressure; and replacing the non-linear material stress-strain curves with linear, isotropic materials defined by elastic moduli. The simplified FEM contained 10,056 nodes, with 8,960 fully-integrated shell elements and 1,072 2-noded beam elements. The numerical simulations were executed in LS-Dyna[17], a commercial, general-purpose, nonlinear, transient-dynamic, finite element code.

The simplifications reduced the simulation runtime by an order of magnitude. In fact, the model simplifications enabled hundreds of simulations to be completed in less than a week. The FEM representation of the NAIPS dome section, with symmetry boundary conditions identified, is shown in Figure 2. The model is composed of an isotropic, linear-elastic fabric constrained by a network of 11 linear-elastic radial cords attached to a loop (or axial) cord. It should be noted that the dimensions of this model represent a larger version than the tested EDU configuration. Nonetheless, the model was sufficient to refine the modeling approach for numerical stability over wide parameter ranges as well as to understand the overall responses' sensitivities to several variables.

At the start of the simulations, the article is deflated and flattened (Figure 2a), and the radial cords are sized to match the radius of the dome, where the initial length for each simulation was 111 in. These cords were then shortened numerically during inflation, through the inclusion of thermal loading applied to elements at each end of the radial cords, where they attach to the loop cord. A negative temperature change is applied to the 2-noded beam elements, referred to here as "thermal elements" to contract them. To retain the axisymmetric behavior, all of the radial cords are shortened to the same length.

The model includes some key features worth mentioning here. To minimize confusion about the modeling details, the LS-Dyna keywords have been included.

- Contact definitions are crucial to the simulations by enabling transfer of loads between the parts. All of the contacts are penalty-based, where the friction and penalty-force stiffness scale factors can be varied. The modeling capabilities implemented to represent the physics of the cord-to-fabric and fabric-to-fabric interaction are:
    - *contact _single_surface: This contact was implemented to prevent inter-penetration between the fabric surfaces.
    - *contact_ nodes_to_surface: This contact was implemented to prevent the loop cord from penetrating the fabric.
    - *contact_guided_cable: This contact was implemented to replicate the slipping of the radial cords through the guide loops on the fabric. More generally, this is a sliding contact that was developed to guide elements through a list of nodes. For this model, the list of nodes for each cord is a line of radial nodes on the fabric. Each radial cable has a unique list of nodes that it must pass through. The contact friction for these contacts has been allowed to vary in the probabilistic analysis.
- The material models have been selected to replicate the behavior of the woven fabric and braided cord materials.
    - *mat_fabric: The dome fabric material is represented by a special membrane element specially formulated for fabric materials undergoing large deformations.
    - *mat_cable_discrete_beam: The cord materials are represented with elastic beam elements in which no compression force is allowed to develop.
    - *mat_add_thermal_expansion: This capability enables thermal loads to be applied to specified elements.
- Both a pressure load and a thermal load are applied as described below, with the normalized profiles shown in Figure 3.
    - *load_pressure: The pressure load (or inflation pressure) is applied to the fabric inner surface and linearly increased from zero to a prescribed value over the time range from 0 to 0.3 seconds. The simulations are executed until 0.4 s to allow the loads to reach equilibrium and mitigate dynamic effects.
    - *load_thermal: A linear temperature decrease is applied to the thermal elements from 0 to 0.15 seconds. The intent of this thermal load is to decrease the effective length of the radial cords. The thermal elements are sufficiently stiff in tension such that they do not substantially change in length after 0.15 s. As noted earlier, the thermal elements are a numerical feature that enables inclusion of cords of varying lengths.

Numerical stability of the model was enhanced by modifying details of the contact definitions. In general, the contacts are incorporated to: prevent penetration of one part through another; or enable sliding of one part over another. For this application, much of the numerical instability stemmed from conflicts between the "*contact_guided_cable" with other contacts. This issue was mitigated by removing the radial card parts from the more general "*contact_nodes_to_surface". In addition, the SSFAC (stiffness scale factor) was reduced by an order of magnitude to prevent nonphysical large restoring forces that would cause individual nodes to have unrealistically large accelerations. The modifications to the contact definitions were based on user-experience and a trial-and-error approach, since numerical instabilities are usually problem dependent.

The simulation computational time ranged from 1 to 2 hours using 8 processors to compute the 0.4-second responses. Unlike most applications using an explicit, transient analysis, only the end-state results, and not the time-varying responses, were of interest. It should be noted that responses of interest were absent of noticeable oscillations and behaved like a steady-state response from 0.3 to 0.4 s. Figure 4 contains a schematic of the inflated model with the primary responses identified. The following results for each simulation were saved: loads for each of the 11 radial cords (P_{RC}); loads at 3 locations along the loop cord (P_{LC}); and the radial and tangential line-loads (N_R and N_T, respectively) computed from the elemental stresses of representative elements near the equator for each of the 10 lobes.

Two derived responses were also examined to enhance understanding of the structural behaviors for more general applications. The Shape-Ratio (SR) is defined by the ratio of the distances provided in Figure 5. In an optimal configuration, as SR approaches 1.0, then the fabric line-loads would be approaching a minimum where the hatch opening is located near a radial cord. SR=1.0 is the point with the smallest radius of curvature for the given number of cords. In addition, the ratio of the tangential to radial fabric line-loads (FR= N_T/ N_R) provides non-dimensionalized insight about the relative trends in the fabric behavior.

Additional results such as the kinetic, internal, sliding, and damping energies were also retained for each simulation. This data was utilized for diagnostic purposes, if needed. For example, if the simulations are terminating prematurely, the energies of parts can provide insights as to the portion of the model that requires increased scrutiny. As a reminder, only the end-state responses extracted at 0.4s were of interest for the current studies.

<u>Sensitivity Analysis</u>

A probabilistic approach was employed for the sensitivity analyses. Although there are many techniques that can create adequate sampling of the parameter space for a probabilistic analysis, Halton-Leap deterministic sampling was chosen for this study[17]. The Halton-Leap method creates uncorrelated, multi-dimensional, uniformly distributed values between 0 and 1, which are then converted to engineering values. A total of 6 parameters were varied to demonstrate probabilistic analysis approaches. Material properties were varied by allowing the elastic moduli of the radial cord (E_{RC}), the dome fabric (E_F), and the loop cord (E_{LC}) to change. Geometric parameters were varied through changes in the radial cord length (L_{RC}). Operating parameters were varied through changes in the inflation pressure, and the contact friction between the dome fabric and the radial cords.

There are a number of methods for computing sensitivities and ranking variables. These include local gradient-based methods[19], and global techniques[20,21]. For inflated fabric structures, the global correlation method used here has proven to be acceptable for understanding the importance of variables, even under large deformations and nonlinear stress-strain behaviors[12]. Concurrent with the sensitivity computations, the cross-plotting of input-to-response can provide additional insight about the physics. As with all studies, the project's required accuracy or adequacy needs are critical to determining whether a simple correlation approach completed in less than a second is adequate. If a correlation approach is not sufficient, then more sophisticated approaches incorporating surrogate models and global sensitivity methods, such as Sobol[21], may be needed.

Often constraints on time, combined with the long executions of explicit simulations, result in a limited number of runs for a probabilistic analysis. Such applications require the generation of a surrogate model that can be quickly interrogated. Luckily, the short simulation times for the simplified model meant that surrogate models (and their added uncertainties) were not needed for the sensitivity studies presented here. Variable rankings are but one aspect of a probabilistic analysis. Fortunately, once a set of simulations has been completed, surrogate models can be further utilized in the design process.

The normalized correlations were computed by first calculating the magnitude of the correlations (denoted as $|r_i|_j$) between each of the uncertain variables (i) and each of the responses (j). For a particular response, say the radial cord load, each of the coefficients, $|r_i|_{Radial}$, was then divided by the sum, $R_{Radial}=\sum_i |r_i|_{Radial}$, to normalize the uncertainty of a particular response to a total of 1. For the number of samples in these probabilistic analyses, coefficients less than 0.25 are not considered significantly different from 0. However, no effort was made to account for insignificant values in the results.

Description of Results

Preliminary Results

A number of Matlab[22] scripts were written to automate the simulation execution and data reduction. As noted previously, the model was simplified to remove as much asymmetrical behavior as possible. Responses provided are based on the mean values, unless otherwise noted. Thus "radial cord load" (P_{RC}) refers to the mean load computed from the values from all 11 cords. Likewise, fabric line-loads (N_R and N_T) are an average of the 10 lobes, and loop cord load (P_{LC}) is an average of 3 locations along the axial loop cord. To identify numerically unstable simulations, the Normalized-Scatter (NS) or the ratio of the standard-deviation (σ) over the mean (μ), i.e., NS=σ/μ, were evaluated. First the NS for the radial cord loads for each simulation was computed based on the radial cord loads of all 11 cords. This ratio for the radial cord loads was compared to 0.03 (or 3% scatter). Similarly, the NS of the 3 loop loads and the NS for both of the fabric line-loads were compared to 0.03. Because of the axisymmetrical behavior of this model, the ideal NS would be identically 0. If any of these ratios was greater than 0.03, then the simulation was removed from the probabilistic analysis population data set. Often, the ratios were substantially less than 0.03. The attention to numerical stability up front meant that the number of numerically unstable simulations was minimized.

For the probabilistic studies, only one element in each of the 10 lobes was extracted to serve as a representative response for the sensitivity analysis. However, it should be noted, the spatial distribution of the line-loads within one lobe was not necessarily uniform. To illustrate this behavior, the spatial variation of the line-loads in both the radial and tangential direction for one lobe of a representative simulation are shown in Figure 6. The lower left subplot shows that there is very little variation in N_R or N_T as one traverses radially along the center of the lobe. On the other hand, the variation in N_R for elements that span the lobe in the circumferential direction is large, while the variation in N_T remained relatively small. The radial line-load, $N_{R,}$ approaches zero at the lobe-cord boundaries where the cords are carrying most of the load. It should be noted that except at the edges of the lobes, N_T is substantially less than N_R due to the much smaller radius of curvature of the lobe versus the dome.

Sensitivity Results

Table I provides the parameters that were varied for the 3 probabilistic analyses, designated as Sets A, B, and C, that are examined in this paper. The three sets represent a progression of uncertainty ranges, which illustrate different uses for the sensitivity results. Set A has large parameter ranges such as those that might be used for evaluation of a concept trade studies. Performing analyses over these large variable ranges also provided an opportunity to assess the numerical robustness of the model and mitigate numerical instabilities through management of computational parameters. In this case, the elastic modulus of the loop cord (E_{LC}) was kept constant. Set B is focused on smaller parameter ranges that might be used for model calibration to a specific test condition. Set C represents a probabilistic sensitivity analysis that is more focused on large variations in the radial cord lengths (L_{RC}), while maintaining modest ranges of uncertainties in the other parameters.

For each of the analyses, a similar set of results is provided. First, the sensitivity ranking of the responses to the variables will be provided in a bar chart form. Next, the primary and derived responses will be cross-plotted against a single variable that dominated the sensitivity calculation shown in the respective bar chart. These types of cross-plotting results are particularly useful when implementing PA in a new application to gain confidence in the sensitivity results. As the correlation is a simplistic quantity, there is a possibility that it may not be adequate for certain applications.

Set A: Design parameter space example

Set A sensitivity results are shown in Figure 7 for each of the primary and derived responses. Reviewing the parameter ranges shown in Table I: the elastic moduli ranges for the fabric (E_F) and the radial cord (E_{RC}) were more than an order of magnitude; the length of the radial cord (L_{RC}) was shortened 3 to 7 inches from the original length of 111 in; the pressure was varied from the working pressure of 15 psi to twice the working pressure; and the contact friction was varied a small amount. (It was found that varying the contact friction increased the NS of responses, while not substantially impacting the sensitivity results). These results show that the pressure variable dominates the sensitivity of the cord loads (P_{RC} and P_{LC}) and tangential line-load (N_T). Interestingly, the computations show that the fabric radial line-load, N_R, has significant contributions to the uncertainty from several variables. To look at this more closely, the various responses have been plotted as a function of pressure, see Figure 8. Verifying the sensitivity trends shown in Figure 7, three of the 4 responses (subplots a, b, and d) show a strong and nearly linear dependence on pressure. The data from the fabric radial line-load, N_R, show substantial scatter although an increase with pressure is evident. The data in subplot (c) validates that the N_R is significantly sensitive to more variables than just the inflation pressure. No discernable impact of the pressure was evident on either of the derived ratios, see Figure 9. This would be anticipated since the dominant parameter, Pressure, has been essentially nullified.

Set B: Model calibration parameter space example

In contrast to the variable ranges chosen for Set A, the ranges for the Set B example were chosen to represent typical test set-points. In this case, the test would be focused on a single operational pressure, rather than a range. The parameter ranges for the material properties were modified to better reflect the ranges corresponding to the measured material load-strain behavior and variability. At fabrication, the cord length is measured, however, the cordage experiences very large strains during the initial loading phase. In addition, as the cord and structure are repeatedly loaded and unloaded, the braided cord "zero"-strain shifts. In reality, the measured strains in an inflated structure are often "zeroed" at an inflation pressure greater than zero. Thus, significant uncertainty exists in the effective radial cord length.

Parameter sensitivity results for Set B are shown in Figure 10. For this Set, the cord length seems to be a primary driver with minimal difference in rankings for the various responses. For this reason, the related graphs in Figures 11 and 12 show the effect of radial cord length (L_{RC}) on the responses. A strong monotonic variable-to-response relationship is evident, but scatter about the trend exists. For the radial cord load (P_{RC}), as the cord length increases, the cord load decreases (subplot a). Similarly, the loop cord loads (P_{LC}) decrease with increasing radial cord length (subplot b). Looking at the results in subplot (c), as the radial cord length increases, the fabric radial line-load (N_R) increases. These results show that as the radial cord loads increase, the fabric is taking less load in the radial direction. The tangential line-load (N_T) follows the same trend as the cords (subplot d). Turning to the derived ratio results, Figure 12, as the radial cord lengthens, the SR shows a strong linear relationship, while the FR decreases.

Set C: Targeted design space example

Set C was designed to explore the sensitivity of the responses as the Shape-Ratio (SR) approaches 1.0. Specifically, the radial cord length for Set C was shortened substantially when compared to the simulations executed for Set B, while the other parameter ranges were similar to those for Set B. In addition, preliminary single parameter studies had shown that the cord loads reach a maximum as the radial cords are shortened.

As might be expected from the preliminary single parameter study, the sensitivity results shown in Figure 13 differ than those for Set B. Specifically, for Set C the uncertainty of the fabric modulus (E_F) becomes more important. With the exception of N_R, the uncertainty for the responses is composed of several contributors. As in Set A, the sensitivity of N_R is fundamentally different from the other three responses. The length and modulus of the radial cord are the dominant contributors to the uncertainty for N_R.

Based on the sensitivity results for $N_{R,}$ the responses were plotted against the radial cord length (L_{RC}), see at Figure 14. As the radial cords are shortened, the radial and loop cord loads reach a maximum near 102 inches, which is 9 inches shorter than the starting length. The radial line-load, N_R decreases substantially until 102 inches, at which point additional shortening produces small decreases in the line-load. The tangential line-load, N_T, continues to decrease as the cord shortens, but only varied 4 lb./in over the range. The SR decreases nearly linearly as the cord shortens. Numerical instabilities emanating from the *contact_guided_cable prohibited the continuation of the automated executions for shorter cords, at this time.

Concluding Remarks

The purpose of the work reported here is to describe the demonstration of a probabilistic numerical simulation capability to support trade studies and development of a certification plan for inflatable habitats. This study concentrates on the demonstration of probabilistic analysis tools to identify parameter sensitivities by: focusing on the NAIPS modeling effort to understand design sensitivities and mitigate modeling instabilities; and building on PA tools developed for other types of structural applications. Responses of interest include the cord loads and fabric line-loads as well as the non-dimensional quantities related to lobe shape and fabric line-loads. This paper discusses a global sensitivity analysis approach for evaluation of the structural response of NAIPS. The simulation of the response of the NAIPS structure to pressure loading was automated with a combination of Matlab scripts and LS-Dyna simulations. The global sensitivity of the component loads was computed using a correlation-based metric.

A preliminary model was substantially simplified to reduce computation time while retaining important behaviors. Specifically, an axisymmetrical model of the NAIPS dome was derived from a full model. This symmetry model kept features, such as using thermal loads to shorten cords and the special contact available in LS-Dyna for guiding cables on surfaces. It is understood that the current modeling of the materials as linear-elastic and isotropic are simplifying approximations. However, these approximations are reasonable and are not anticipated to significantly impact the assessment of parameter importance. These simplifications enabled hundreds of simulations to be completed on a typical engineering workstation.

In summary:

- A complex FEM was significantly simplified to reduce the computation time, while retaining the key structural behaviors and also improving numerical stability. These changes enabled implementation of probabilistic methods through the automated executions of hundreds of simulations and subsequent data reduction. Completion of the studies supported: an improved understanding of the potential for interdependence of the response to multiple inputs; and a demonstration of this type of approach before proceeding to more complex models requiring substantially longer execution times.
- The focus of the report was a series of probabilistic sensitivity analyses. Completion of the analyses demonstrated the feasibility of automated simulations that were numerically stable for parameter ranges that spanned an order of magnitude. The broad range of sensitivity results showed that care must be exercised when identifying responses of interest, uncertain parameters and parameter ranges. Most notably, the sensitivity results for the fabric radial line-load (N_R), was substantially different than those for the cords or the fabric tangential line-load.
- The work performed for this paper demonstrated the feasibility of utilizing probabilistic sensitivity analyses for these types of applications. Future work will focus on: 1) incorporation of orthotropic fabric and nonlinear load-strain property curves for the fabric and cords, as well as inclusion of the NAIPS mid-body fabric and cords; 2) correlations with existing EDU test results through refinement of dimensions and/or scaling existing simulation results; and 3) expansion of the PA tools to better support a broader range of design concepts; and certification with test-validated analysis

Acknowledgements

The authors would like to recognize the contributions of Mr. Alberto Makino (NASA Ames Research Center), who provided the preliminary model.

References

1. Lyle, K. H. and Vassilakos, G. J.: Modeling of Global BEAM Structure for Evaluation of MMOD Impacts to Support Development of a Health Monitoring System. NASA/TM-2015-218984. November 2015.
2. Lyle, K. H. and Vassilakos, G. J.: Modeling of Local l BEAM Structure for Evaluation of MMOD Impacts to Support Development of a Health Monitoring System. NASA/TM-2015-218985. November 2015.
3. Lindell, M. C., Hughes, S. J., Dixon, M, and Willey, C. E.: Structural Analysis and Testing of the Inflatable Re-entry Vehicle Experiment (IRVE). Proceedings of the 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA Paper No. 2006-1699, Newport RI, 1-4 May 2006.
4. Lyle, K. H.: Comparison of Analysis with Test for Static Loading of Two Hypersonic Inflatable Aerodynamic Decelerator Concepts. NASA TM-2015-218778, July 2015.
5. Timmers, R. B.; Hardy, R. C.; and Welch, J. V.: Modeling and Simulation of the Second-Generation Orion Crew Module Air Bag Landing System. Proceeding of the 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, AIAA Paper No. 2009-2921, Seattle WA, May 4-7, 2009.
6. Tutt, B.; Johnson, R. K.; and Lyle, K.: Development of an Airbag Landing System for the Orion Crew Module. Proceedings of the 10th International LS-Dyna Users Conference, Dearborn MI, June 8-10, 2008.
7. Tutt, B. A.; and Taylor, A. P.: Applications of LS-Dyna to Structural Problems Related to Recovery Systems and Other Fabric Structures. Proceedings of the 7th International LS-Dyna Users Conference, Dearborn MI, May 19-21, 2002.
8. Guide for the Verification and Validation of Computational Fluid Dynamics Simulations. AIAA Publication AIAA G-077-1998, 1998, Reston VA.
9. NASA Standard for Models and Simulations. NASA Publication NASA-STD-7009, 2006.
10. Sandia National Laboratories Predictive Capability Maturity Model for Computational Modeling and Simulation. Sandia Publication SAND-2007-5948, 2007.
11. Horta, L. G., Reaves, M. C., Jackson, K. E., Annett, M. S. Little, J. D.: Fuselage Impact Testing and Simulation: A Model Calibration Exercise. Proceedings of the IMAC-XXII A Conference and Exposition on Structural Dynamics, Orlando FL, February 2014.
12. Lyle, K. H.: Preliminary Structural Sensitivity Study of Hypersonic Inflatable Aerodynamic Decelerator Using Probabilistic Methods. NASA TM-2014-218290, July 2014.
13. Iooss B., Lemaître P. (2015) A Review on Global Sensitivity Analysis Methods. In: Dellino G., Meloni C. (eds) Uncertainty Management in Simulation-Optimization of Complex Systems. Operations Research/Computer Science Interfaces Series, vol 59. Springer, Boston, MA
14. Jones, T. C.: Structural Certification of Human-Related Inflatable Space Structures. 2018 IEEE Aerospace Conference, 3-10 March 2018, Big Sky MT.
15. Doggett, W. R., Jones, T. C., Watson, J. J., Warren, J. E., Makino, A., Selig, M., and Mikulas, M. M., "Non-Axisymmetric Inflatable Pressure Structure (NAIPS) Concept that Enables Mass Efficient Packageable Pressure Vessels with Openings," 3rd AIAA Spacecraft Structures Conference, 2016 AIAA SciTech Forum and Exposition, AIAA Paper 2016-1475.
16. Jones, T. C., Doggett, W. R., Warren, J. E., Watson, J. J., Shariff, K. I., Makino, A., and Yount, B. C.: Non-Axisymmetric Inflatable Pressure Structure (NAIPS) Full-Scale Pressure Test. 4th

AIAA Spacecraft Structures Conference/AIAA SciTech Forum, AIAA Paper 2017-0854, 9-13 January 2017, Grapevine TX.

17. *LS-Dyna Keyword User's Manual*, Version 971, July 27, 2012 (revision: 1617).
18. Halton, J.H.: On the Efficiency of Certain Quasi-Random Sequences of Points in Evaluating Multi-Dimensional Integrals. *Numerische Mathematik*, Vol. 2, 1960, pp. 84–90.
19. Saltelli, A.; Chan, K.; Scott, E. M.: *Sensitivity Analysis*. Chichester, England: John Wiley and Sons, 2000
20. Helton, J. C. and Davis, F. J.: Illustration of Sampling-Based Methods for Uncertainty and Sensitivity Analysis, *Risk Analysis*, Vol 22, No. 3, 2002 pp 591-622.
21. Sobol, I. M., *et al*: Estimating Approximation Error When Fixing Unessential Factors in Global Sensitivity Analysls. *Reliability Engineering and Safety*, Vol. 92, 2007, pp. 957-960.
22. Matlab Release 2015b, The MathWorks, Inc., Natick, Massachusetts, United States.

Table I. Parameter Ranges for Uncertainty Studies.

Set	No. of Sims	E_{RC}, psi		E_F, psi		E_{LC}, psi		L_{RC}, in		Pressure, psi		Friction	
		Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
A	53	2e5	8e6	5e4	2e6	3.5e5	3.5e5	104.1	108.6	10	30	0	0.01
B	47	2e5	8e5	1e6	1.6e6	3e5	1e6	105.2	108.6	15	15.4	0	0.02
C	182	5e5	1e6	1e6	1.6e6	3e5	5e5	98.3	106.4	15	15.4	0	0.05

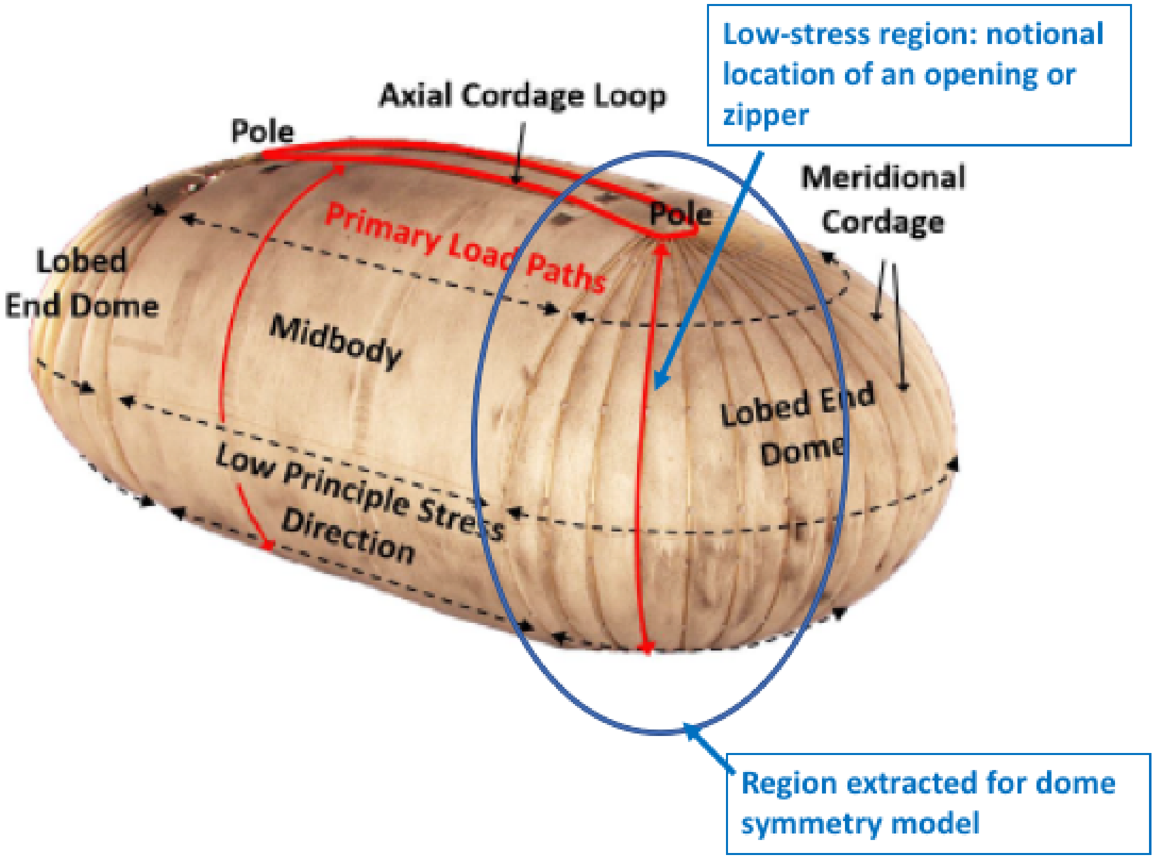
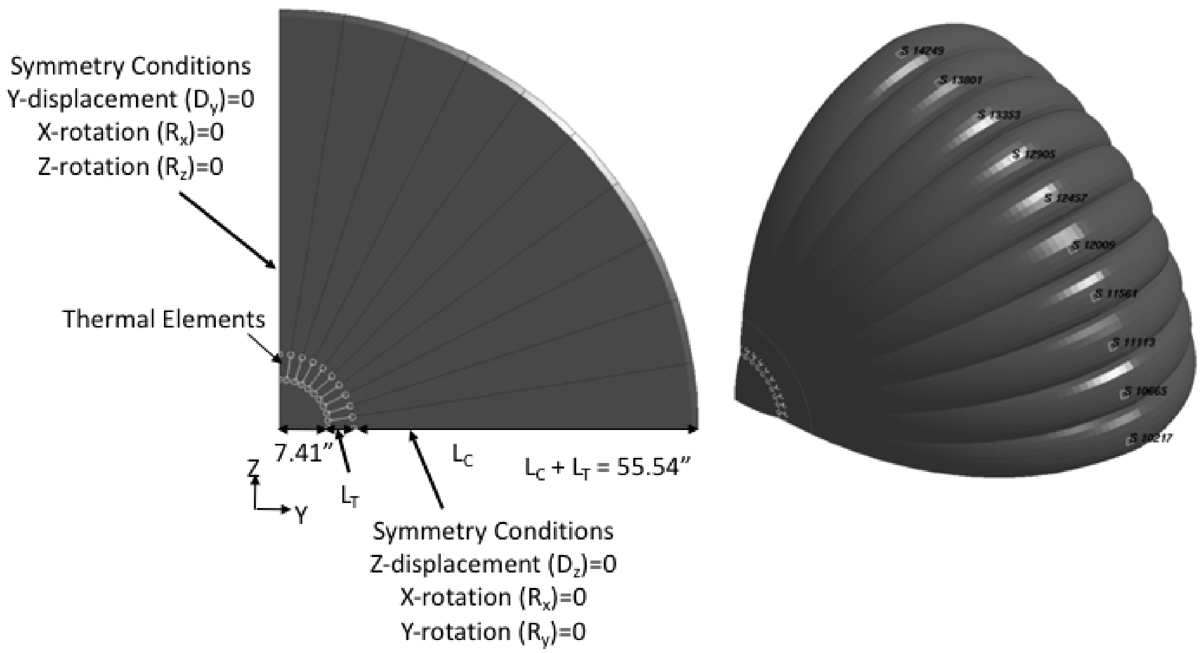


Figure 1. Photograph of inflated NAIPS test article[16].



(a) Initial State with Boundary Conditions (b) Nominal Inflated State

Figure 2. Schematic of dome FEM. *(D=displacement and R=rotation)*

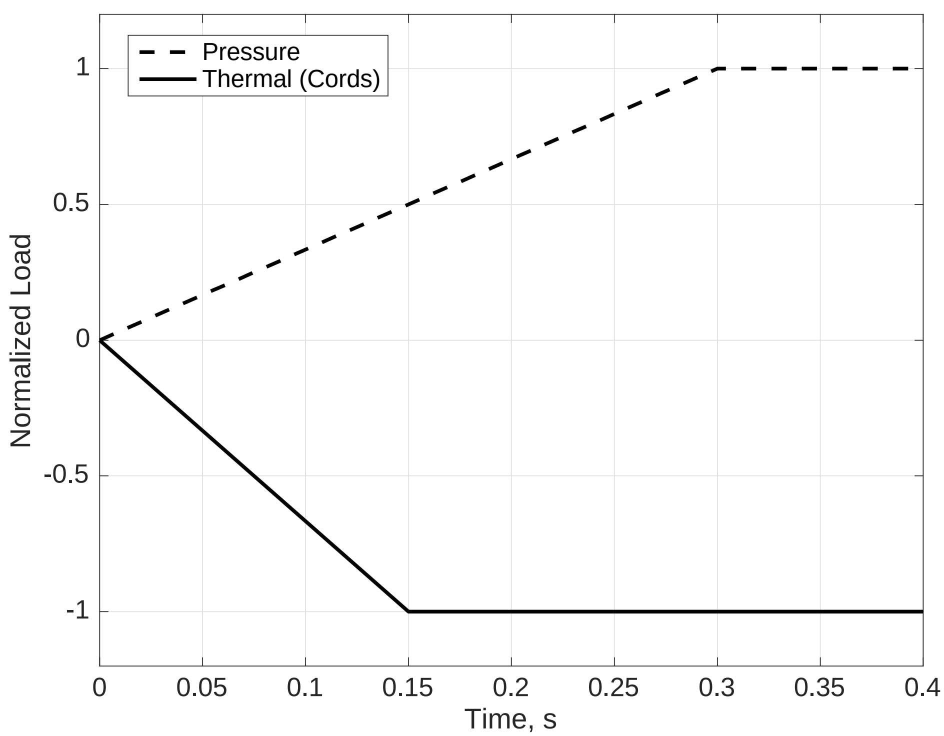


Figure 3. Non-dimensional loading profiles.

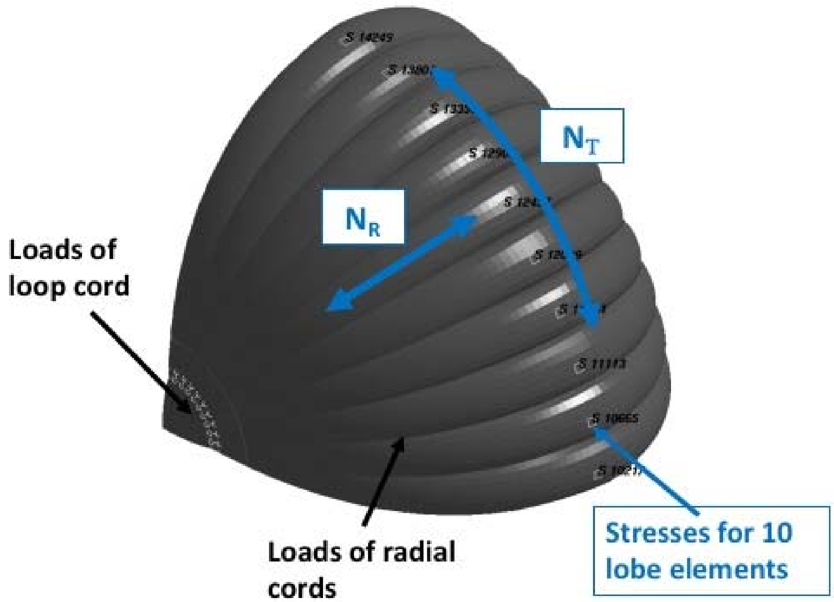


Figure 4. Primary responses of interest.

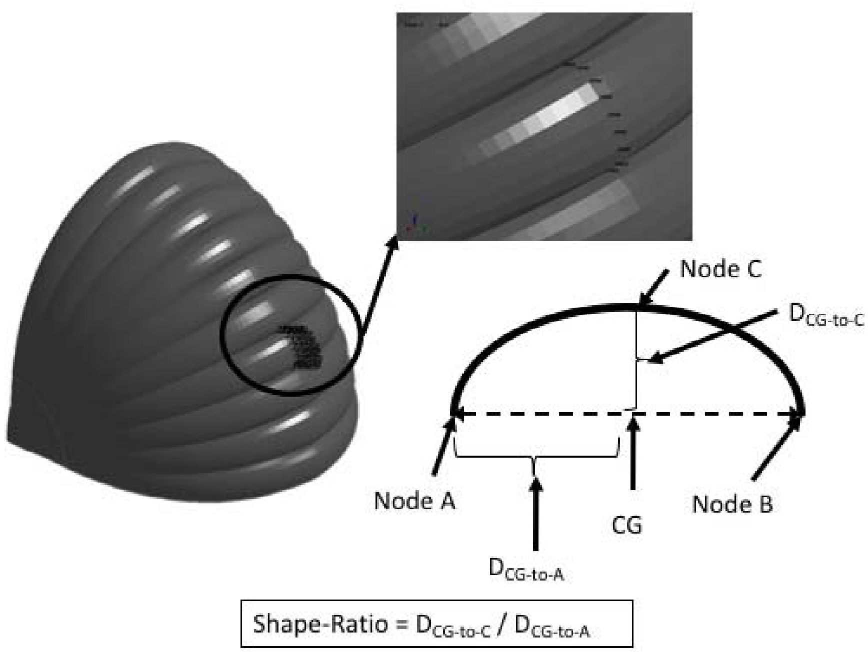


Figure 5. Derivation of Shape-Ratio (SR) response.

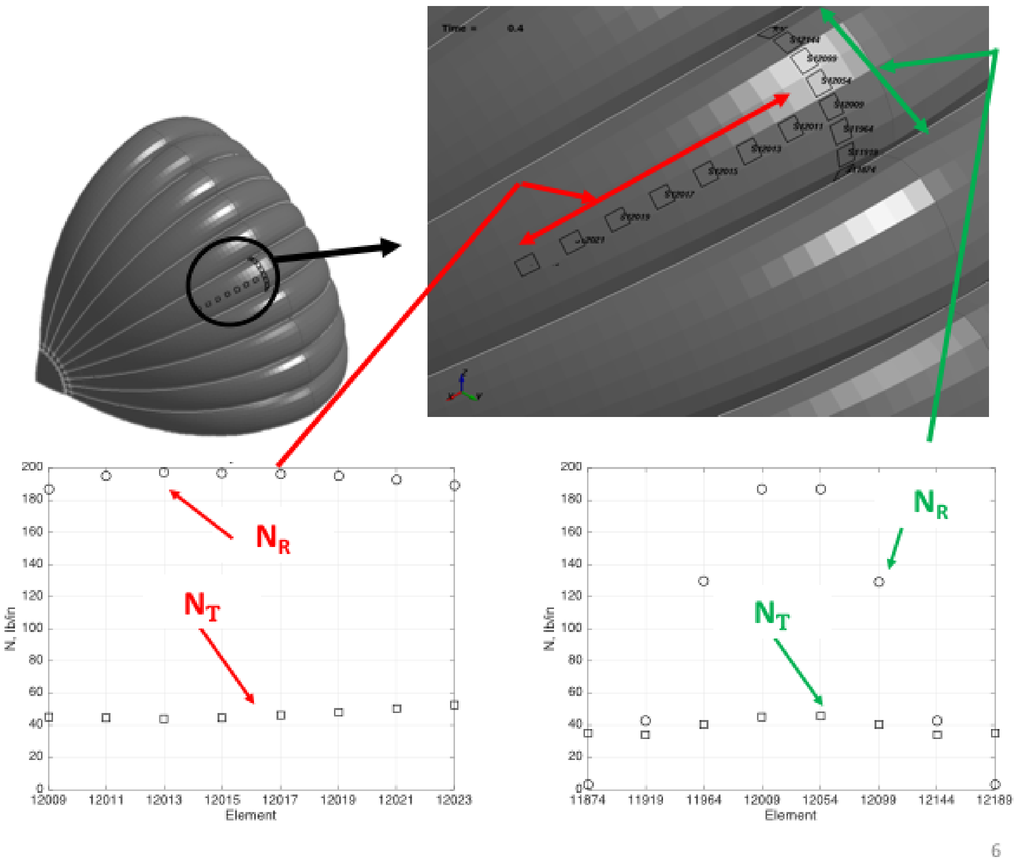


Figure 6. Spatial variation of line-loads across a representative lobe.

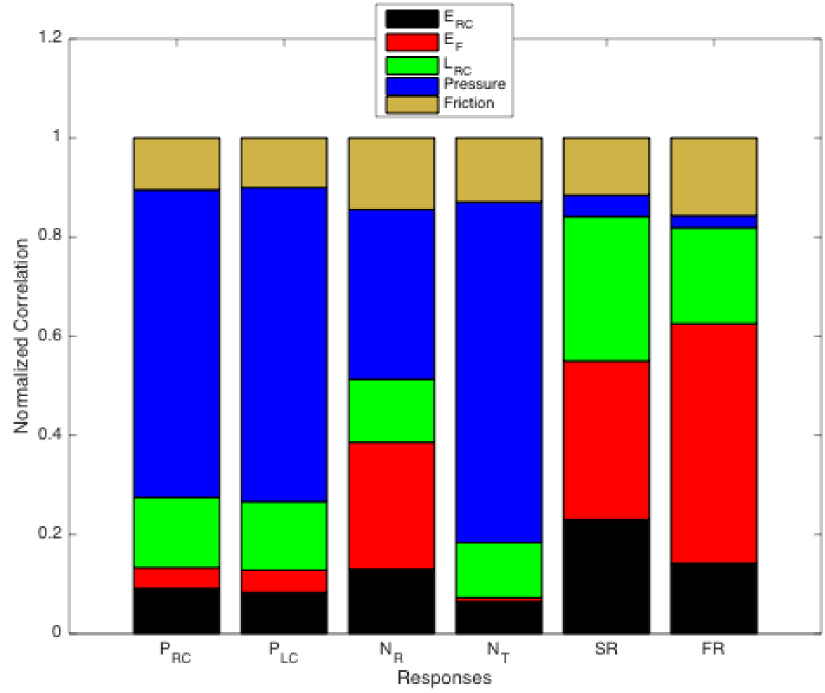


Figure 7. Sensitivity results for Set A.

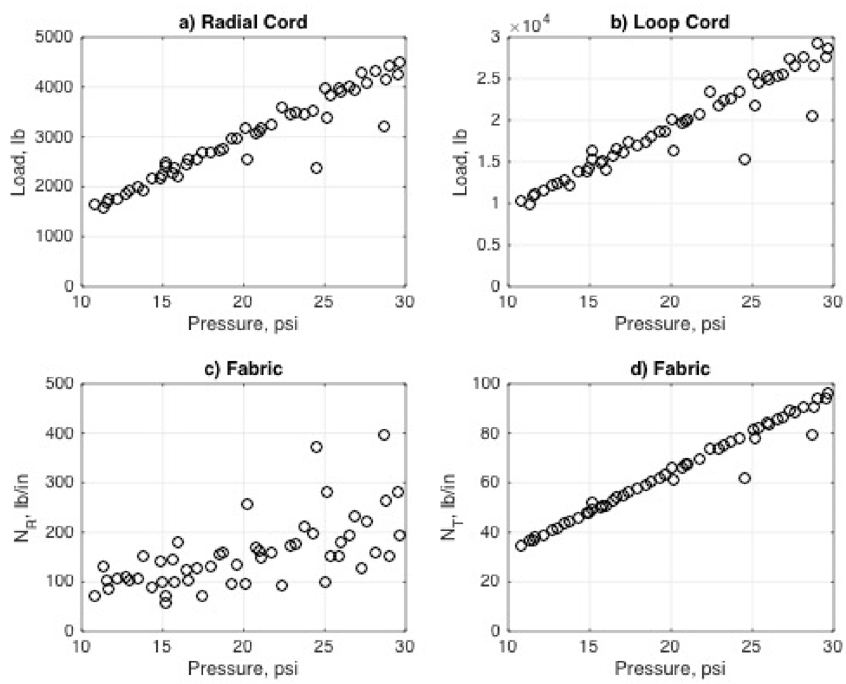


Figure 8. Primary responses vs inflation pressure for Set A.

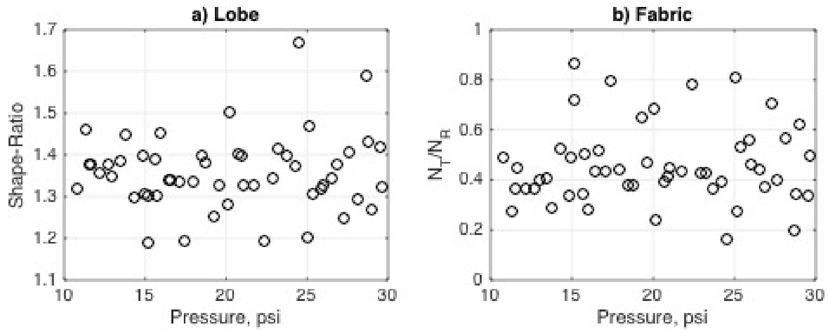


Figure 9. Derived responses vs pressure for Set A.

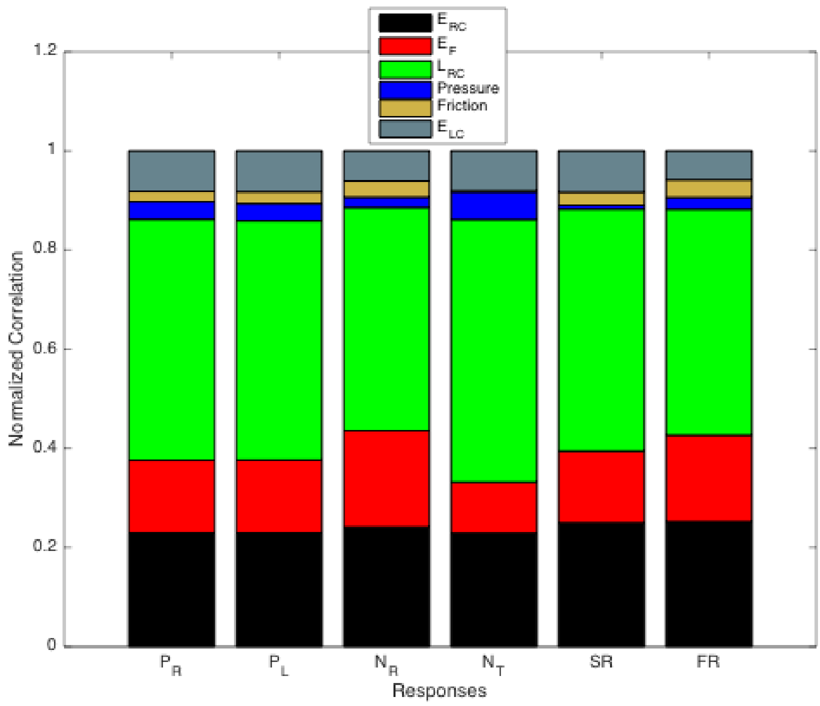


Figure 10. Sensitivity results for Set B.

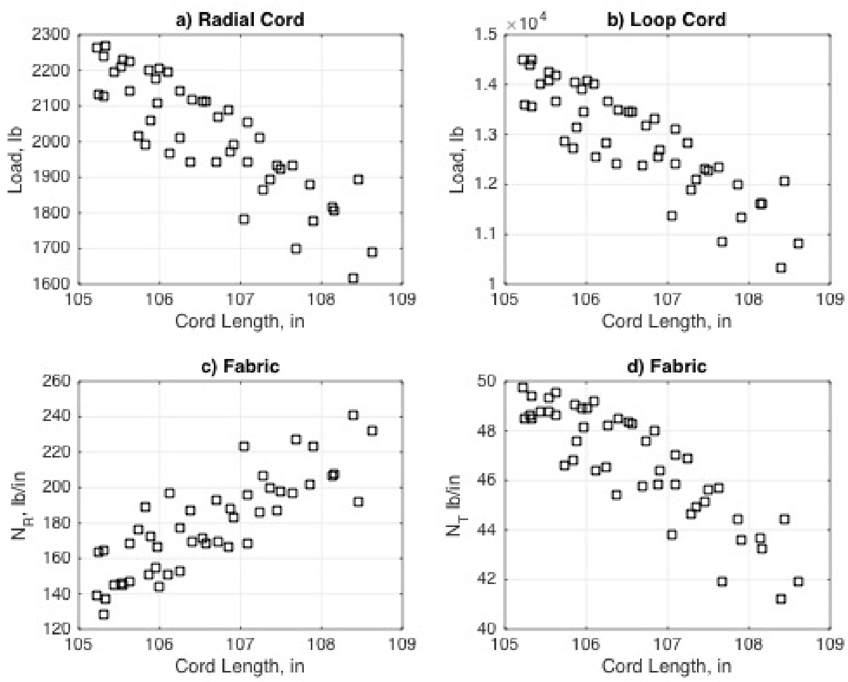


Figure 11. Primary responses vs radial cord length for Sets B.

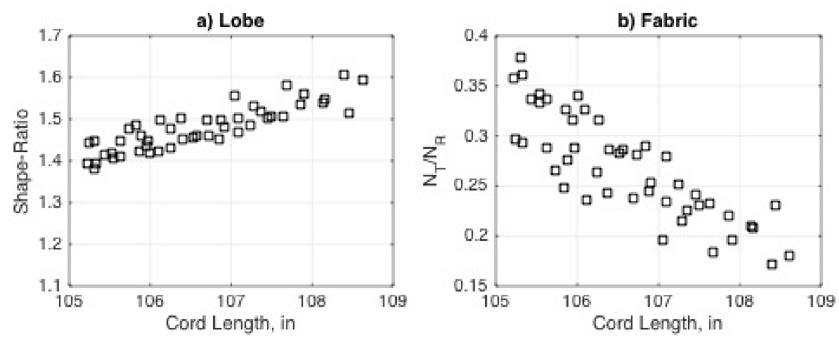


Figure 12. Derived responses vs radial cord length for Sets B.

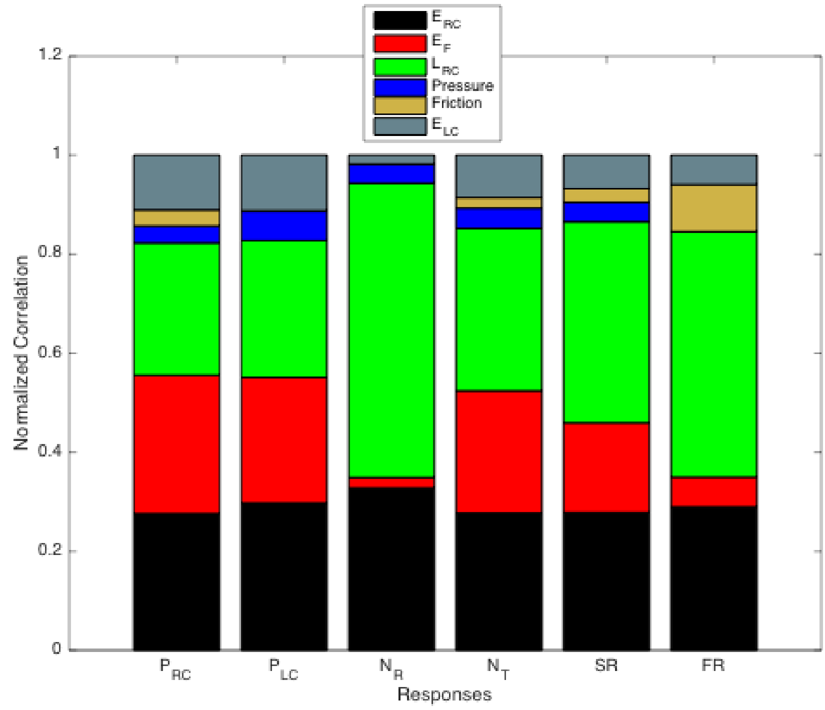


Figure 13. Sensitivity results for Set C.

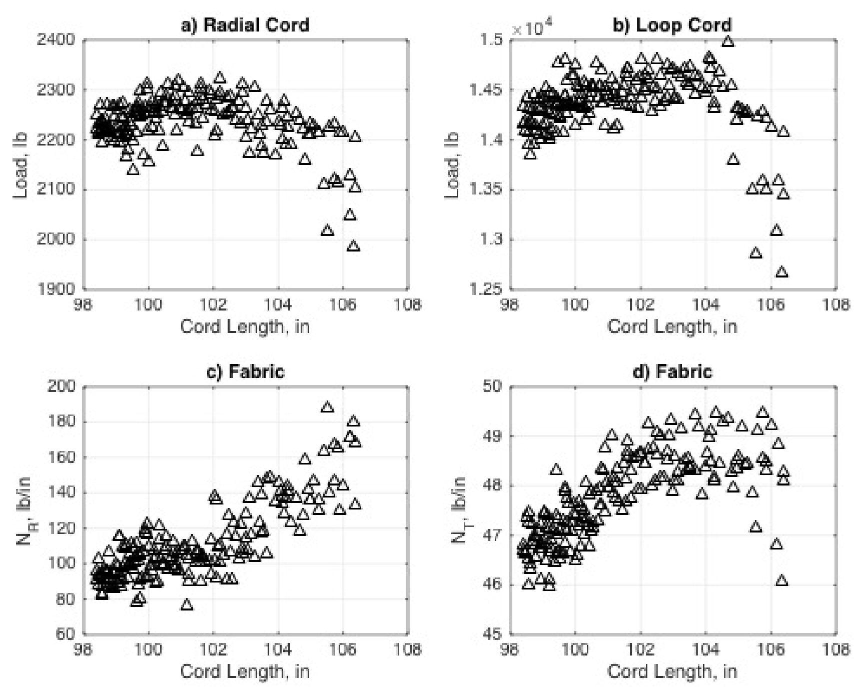


Figure 14. Primary responses vs radial cord length for Set C.

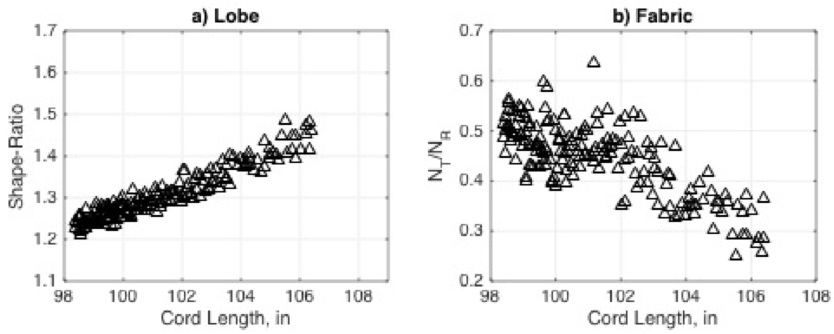


Figure 15. Derived responses vs radial cord length for Set C.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
1-04-2018

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Demonstration of Probabilistic Sensitivity Analyses Tools on the Structural Response of a Representative Inflatable Space Structure

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lyle, Karen H.; Jones, Thomas C.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
089407.01.23

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-20925

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA-TM-2018-219826

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified
Subject Category 39
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This work provides an initial step toward demonstrating a probabilistic numerical simulation capability to support trade studies and the development of a certification plan for inflatable space habitats. This study concentrates on interpreting the results from probabilistic analysis and numerical simulation tools to identify parameter sensitivities for a novel inflatable airlock concept, specifically the Non-Axisymmetric Inflatable Pressure Structure (NAIPS) that was designed and tested under NASA's Minimalistic Advanced Softgoods Hatch (MASH) Program. A brief overview of the finite element model is provided along with the probabilistic sensitivity analysis approach. The sensitivity studies required a model that was numerically stable and efficient enough that hundreds of simulations could be completed in the allotted time. Therefore, the existing full model was simplified by: extracting a quarter symmetry section of the dome; focusing on a single inflation pressure; and replacing the non-linear material stress-strain curves with linear, isotropic materials defined by elastic moduli. Responses of interest include the sensitivity of various structural component loads to material properties, cord lengths, inflation pressure and friction. Multiple sensitivity studies were completed and three are reported here. The first study focused on utilizing wide input parameter ranges to provide an opportunity to assess numerical robustness. The next two studies narrowed the parameter ranges to enable focus on understanding uncertainty at a fixed operating condition.

15. SUBJECT TERMS
Inflatable space Structures; Probabilistic Analysis; Softgoods; Structural Analysis

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	25	STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)* (757) 864-9658

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18