Modeling of Global BEAM Structure for Evaluation of MMOD Impacts to Support Development of a Health Monitoring System

Karen H. Lyle
Langley Research Center, Hampton, Virginia

Gregory J. Vassilakos
Analytical Mechanics Associates, Hampton, Virginia

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:
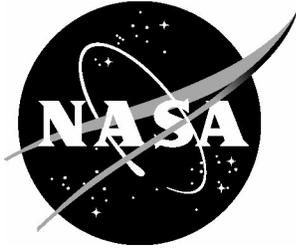
- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compila-tions of significant scientific and technical data and information deemed to be of continuing 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

Modeling of Global BEAM Structure for Evaluation of MMOD Impacts to Support Development of a Health Monitoring System

Karen H. Lyle
Langley Research Center, Hampton, Virginia

Gregory J. Vassilakos
Analytical Mechanics Associates

Abstract

This report summarizes the initial modeling of the global response of the Bigelow Expandable Activity Module (BEAM) to micrometeorite and orbital debris (MMOD) impacts using a structural, nonlinear, transient dynamic, finite element code. These models complement the on-orbit deployment of the Distributed Impact Detection System (DIDS) to support structural health monitoring studies. Two global models were developed. The first focused exclusively on impacts on the soft-goods (fabric-envelop) portion of BEAM. The second incorporates the bulkhead to support understanding of bulkhead impacts. These models were exercised for random impact locations and responses monitored at the on-orbit sensor locations. The report concludes with areas for future study.

1. Introduction

Micrometeorite and Orbital Debris (MMOD) impacts are a common threat for human and robotic spacecraft traveling in low earth orbit, see Ref [1]. Design approaches for protecting spacecraft against MMOD impacts that degrade performance or cause catastrophic destruction have been studied extensively, see Ref. [2]. Flexible spacecraft structural components present a particularly challenging structure to protect. A human-rated space habitat demonstration module has been fabricated utilizing the design approach documented in a US Patent, see Refs. [3 and 4]. This demonstration module has been designated the Bigelow Expandable Activity Module (BEAM), which will be attached to the International Space Station (ISS) as illustrated in Figure 1, see Ref. [5].

A number of numerical methods and associated hardware testing for damage detection for MMOD type impacts have been documented in the literature, see Ref. [6-12]. Historically, hypervelocity testing has been conducted to determine MMOD impact performance. Hypervelocity testing is very expensive and is only feasible for shields in the latter phases of design. Therefore, advancement of analytical methods is important to develop protection against MMOD impacts for novel structures in the early trade study and design phases.

Complementary to advances in soft-goods design and fabrication is progress in the development of numerical simulation tools for complex structural systems. For example, simulations can incorporate structural aspects such as geometrically accurate models and advanced material models that include nonlinear stress-strain behaviors, woven fabrics, and inflation. This was demonstrated for the Orion Landing System – Advanced Development Project, where the spacecraft landing system effectively incorporated modeling of fabric airbags (soft-goods) in the early

design process, see Refs. [13 and 14]. Additional simulations incorporating structural members with fabrics can be found in Refs. [15-17].

The focus here is the global dispersion of responses, due to localized excitations at varying locations for structures, where the primary, load-bearing structure is composed of tensioned fabric materials. The simulations presented here complement the on-orbit deployment of the Distributed Impact Detection System (DIDS) structural health monitoring system, see Refs. [18-20], on BEAM. This report documents the model development and sample responses for MMOD impact on the BEAM structure. First, the impact models will be described. This will be followed by numerical results. The report concludes with areas identified for future studies.

2.0 Numerical models

Three NASTRAN finite element models were provided by the project, see Ref. [21]. These models represented the BEAM structure in various states and were designated as "Packed", "Deflated", and "Inflated". The Inflated Model, see Figure 2, was selected as the basis for developing the transient models utilized for the results reported here. Specifically, two transient-dynamic, finite element models were developed to assess the global transient dynamic responses. These models, denoted as the "Soft-Goods" and the "Bulkhead" models, will be described in following two sections. Both models were executed in LS-DYNA, a commercial, nonlinear, transient dynamic finite element simulation tool, see Ref. [22].

2.1 Soft-Goods Model

For the Soft-Goods Model, only the portion of the Inflated Model representing the restraint-layer and shield were retained, see Figure 3(a). The Inflated Model parts not incorporated in the Soft-Goods Model are shown in Figure 3(b). The Soft-Goods Model contained 12,101 nodes and 11,040 4-node shell elements. For this configuration, the nodes attaching the restraint-layer to the Adapter and Passive Common Berthing Mechanism were fully restrained in translation. The nodes attaching the Soft-Goods to the bulkhead were constrained to behave like a rigid body. Concentrated masses were located at the bulkhead interface nodes to equally distribute the bulkhead mass.

The Soft-Goods were assigned fabric material properties. This fabric material model implemented in LS-DYNA was originally developed for automotive airbag applications. Specifically, the fabric material model is based on an existing composite material model, however it is only valid for membrane elements. For these simulations, the shell elements were 0.254 cm thick, with nominal material properties of elastic modulus=8.96×10^{10} dyne/cm^2; shear modulus=3.48×10^{10}

dyne/cm^2; Poisson's ratio=0.3; and density=11.58 g/cm^3. These properties were derived based on information provided in Ref. [21] as well as private communications between the authors and project engineers. To improve numerical stability, this material model supports inclusion of a liner that allows for small compressive loads. The liner for this application is set to 2% of the restraint layer thickness, with the same material properties and a liner damping of 5% critical.

The total mass of the Soft-Goods Model is 1,468 kg, distributed as 756 kg for the restraint layer, 358 kg for the bulkhead, and 354 kg for the adapter and berthing mechanism. The inflation pressure is implemented by slowly ramping up the pressure on the interior surfaces of the elements over 1 second to a nominal value of 1.048x10^6 dyne/cm^2. Simultaneously, a nodal load is applied in the axial direction to the nodes attached to the bulkhead interface to represent the interior pressure acting on the bulkhead. Following the inflation load ramp, the impact was approximated by a 0.002s triangular force pulse applied to a single node. The transient dynamic simulations executed using the Soft-Goods Model were completed in less than 10 minutes.

2.2 Bulkhead Model
For impacts on the bulkhead, additional parts were incorporated into the Soft-Goods Model. The full model and a cross-section are shown in Figure 4. The remainder of the bulkhead structure was a direct translation of the NASTRAN model, including the linear-elastic material properties assigned. Transmission of the impact energy across the Soft-Goods/bulkhead interface was severely attenuated. For that reason, the bulkhead model was only used to simulate bulkhead impacts, with attention paid to the bulkhead acceleration responses at the DIDS locations also shown on the figure. The transient dynamic simulations executed using the Bulkhead Model required over 4 hours.

3.0 Results
3.1 Modal Comparison of Inflated and Soft-Goods Models
The global vibration modes of the Soft-Goods Model were evaluated to understand the implication of significantly simplifying the Inflated Model mesh. Specifically, a comparison of the first three modes for three different models is provided in Figure 5. The first column represents the modes of the full Inflated Model when executed in NASTRAN. The second column represents the modes of the NASTRAN model for the Soft-Goods portion only. The third column represents the modes of the Soft-Goods LS-DYNA Model. There is less than 3% difference between the NASTRAN and LS-DYNA Soft-Goods Models. The Inflated Model modes are 5% lower for the first two bending modes with a 26% difference for the third or bouncing mode. This level of

agreement was considered sufficient to continue use of the Soft-Goods Model for studies of impacts that focus on the restraint layer responses.

3.2 Soft-Goods Model Studies

A number of studies were completed using the Soft-Goods Model to further understand the implication of some of the modeling unknowns on the acceleration responses. The results are presented as resultant acceleration contours with the excitation node located at the center. The first parameter studied is the effect of the internal pressure, see Figure 6, which directly relates to the restraint layer tension. In this case, the baseline is the design condition, with half and double inflation pressures also simulated. In the figure, the resultant accelerations are plotted for 3 times, namely, 0.01, 0.02, and 0.03 seconds after the simulated impact. The wave propagation increases with pressure and therefore tension as would be expected. In addition, the uniform internal pressure produces faster wave speeds in the circumferential direction when compared to the axial direction due to higher fabric tension in the circumferential direction. Next, the impact of the elastic modulus on the response was studied, see Figure 7. Little effect of the variation in elastic modulus was observed on the resultant acceleration.

3.3 Simulated DIDS responses using Soft-Goods Model

This section illustrates the method that will be used to generate a response library to support on-orbit assessments. A companion report describes the component model and contains additional information about through-the-thickness modes. Nodes at the locations of the on-orbit DIDS accelerometers on the Soft-Goods Model were identified, see Figure 8. Ten random nodes were excited to approximate MMOD impacts. Four of the impulse locations were selected for more detailed study, see Figure 9. Sample acceleration DIDS time history results for an excitation at each location are provided in Figure 10. The Time-of-Arrival of an array of signals can be utilized for identification of impact location. The Time-of-Arrival for this demonstration was computed as when the acceleration amplitude was greater than 0.01 g. For the selected excitation locations, the Time-of-Arrival was plotted against the geodesic distance from the impulse point for each of the DIDS sensor locations, see Figure 11. The geodesic distance was approximated using a cylinder of 127.7 cm radius. The cylinder was selected because the geodesic length is a readily-programmed closed form expression. When the arrival threshold of the acceleration amplitude was increased from 0.01 g, the correlation coefficient of the time of arrival versus geodesic distance was substantially less than 1. The average wave speed computed from these results is 901 m/s. This process can be expanded to generate a large response library. In addition, acceleration history results can be used to support development of DIDS impact location identification.

<u>3.4 Simulated DIDS responses using Bulkhead Model</u>

Less is known about soft-goods modeling and propagation of impacts as compared to MMOD impacts on solid, metallic structures, see Ref. [2]. Therefore, the focus thus far has centered on the simulated soft-goods impacts and responses. Nonetheless, sample responses for an impact on the bulkhead have been included. For the case illustrated in Figure 12, the excitation is a node less than 4 inches from sensor D4. The proximity of the excitation to D4 is so small that accurate Time-of-Arrival estimates are difficult to determine. Locations D1 and D2 are equidistant from the excitation node with D3 significantly farther. The comparison of Time-of-Arrival versus geodesic distance is shown in Figure 13. In this case, the wave propagation speed is 2258 m/s.

4. Summary

Two global structural models of the on-orbit BEAM were generated and transient dynamic simulations of pseudo-MMOD impacts were completed. The model development supported understanding of MMOD impacts for Soft-Goods structures and specifically focused on restraint layer accelerations that would be measured by the on-orbit Distributed Impact Detection System (DIDS) to be deployed on BEAM. Considerable uncertainty exists as to the value for the elastic modulus of the restraint-layer. Fortunately, the parameters studies showed that the acceleration responses are nearly insensitive to the elastic modulus. However, the dispersive wave speeds for the acceleration responses are significantly dependent on the inflation pressures. The tension in the restraint-layer straps is directly related to the inflation pressure.

Time histories at the restraint layer response locations were recorded for simulated impacts at randomly selected nodal locations on the Soft-Goods. Plots of Time-of-Arrival versus geodesic distance for multiple excitations indicated a wave speed of 901 m/s.

A number of modeling and measurement concerns have been identified for future effort:
1. Incorporate a more realistic representation of the through-the-thickness Soft-Goods structure and impact physics utilizing results from Local BEAM Model studies, such as:
   a. Retain the current simple Soft-Goods Model and utilize a refined Local BEAM restraint-layer response.
   b. Map the complex transmission path of an MMOD impact through multiple layers and foam spacers.

2. Generate simulation data to multiple random impacts:
    a. Provide a library of response spanning a broad range of impact locations and severities.
    b. Provide sample signals to support DIDS data processing.

5. References

1. Anderson, B. M.(Editor): Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development. NASA TM-1994-4527, June 1994.
2. Christiansen, E. L., et al: Handbook for Designing MMOD Protection. NASA TM-2009-214785, June 2009.
3. Bigelow, Orbital Debris Shield, US Patent 7,2004460 B2, April 2007.
4. Bigelow, Orbital Debris Shield, US Patent Application Publication, US2005/0284986 A1. December 2005.
5. Website: http://en.wikipedia.org/wiki/Bigelow_Expandable_Activity_Module.
6. Chintalapudi, et al: Structural Damage Detection and Localization Using NETSHM. 2006.
7. Welty, N., et al: Computational Methodology to Predict Satellite System-Level Effects from Impacts of Untrackable Space Debris. 62nd International Astronautical Congress, Cape Town, ZA, 2011.
8. Iyer, K. A. , et al: Use of Hydrocode Modeling to Develop Advanced MMOD Shielding Designs. IEEE, 2012.
9. Shafer, F. and Janovsky, R.: Impact Sensor Network for Detection of Hypervelocity Impacts on Spacecraft. ACTA Astronautica Vol 61, 2007, pp. 901-911.
10. Melkonyan, A.; Akopian, D.; and Chen C. L. P.: A Sensor Placement Measure for Impact Detection in Structural Health Monitoring. IEEE International Conference on Systems, Man, and Cybernetics, San Antonio TX October 2009.
11. Pavarin, D. et al: Acceleration Fields Induced by Hypervelocity Impacts on Spacecraft Structures. International Journal of Impact Engineering. Vol 33, 2006, pp. 580-591.
12. Inter-Agency Space Debris Coordination Committee: Sensor Systems to Detect Impacts on Spacecraft. IADC-08-03. Version 2.1. April 2013.
13. 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.
14. 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.

15. 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.

16. Tanner, C. L.; Cruz, J. R.; Braun, R. D.: Structural Verification and Modeling of a Tension Cone Inflatable Aerodynamic Decelerator. Proceedings of the 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA Paper No. 2010-2830, Orlando FL, April 12-15, 2010.

17. Lyle, K. H.: Preliminary Structural Sensitivity Study of Hypersonic Inflatable Aerodynamic Decelerator Using Probabilistic Methods. NASA TM-2014-218290, July 2014.

18. Tian, J.; and Madaras, E. I.: An Amplitude-Based Estimation Method for International Space Station (ISS) Leak Detection and Localization Using Acoustic Sensor Networks, NASA TM-2009-215948. November 2009.

19. Wilson, W. C.; Coffey, N. C.; and Madaras, E. I.: Leak Detection and Location Technology Assessment for Aerospace Applications. NASA 2008-215347. September 2008.

20. Prosser, W. H.; and Madaras, E. I.: Distributed Impact Detector System (DIDS) Health Monitoring System Evaluation. NASA TM-2010-216694/NASA NESC-RP-07-035, May 2010.

21. Prock, B.: Overview of BEAM Intermediate Dynamics Models. Project Presentation, April 2014.

22. *LS-DYNA Keyword User's Manual*, Version 971, July 27, 2012 (revision: 1617).
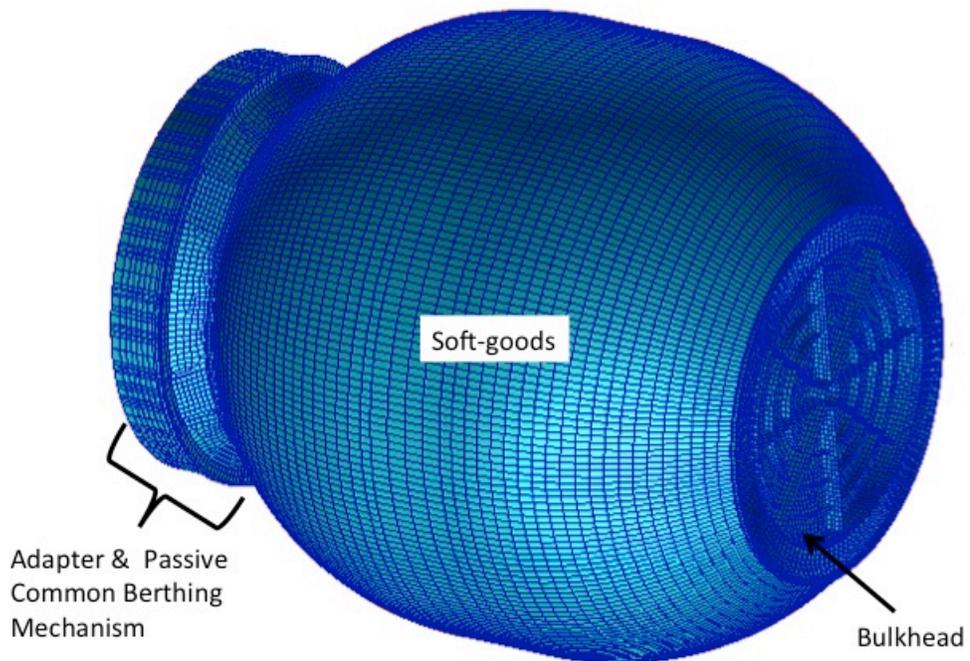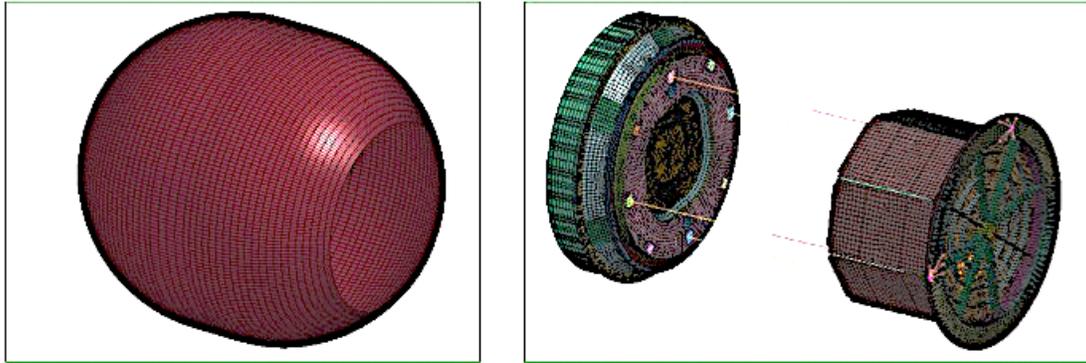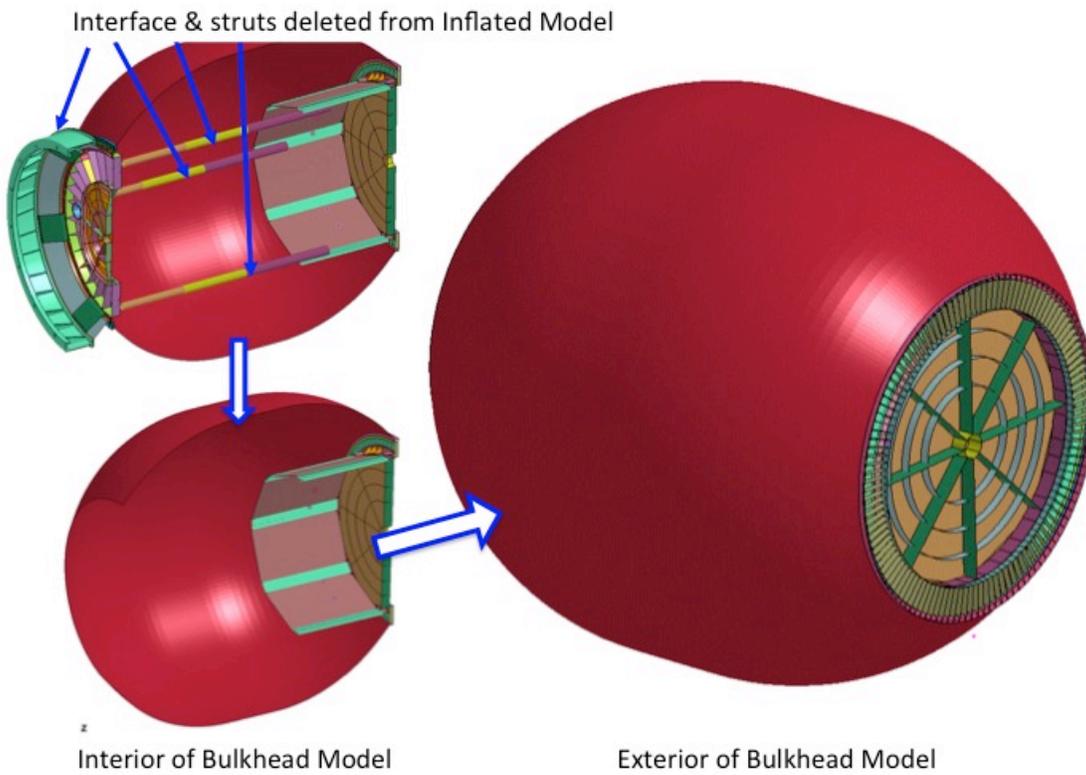
Figure 1. Graphic representation of BEAM attached to ISS.

Soft-goods

Adapter & Passive
Common Berthing
Mechanism

Bulkhead

Figure 2. NASTRAN Inflated Model.

(a) Soft-Goods Only   (b) All Parts Except Soft-Goods

Figure 3. Soft-Goods Model derived from Inflated Model.

Interface & struts deleted from Inflated Model

Interior of Bulkhead Model   Exterior of Bulkhead Model
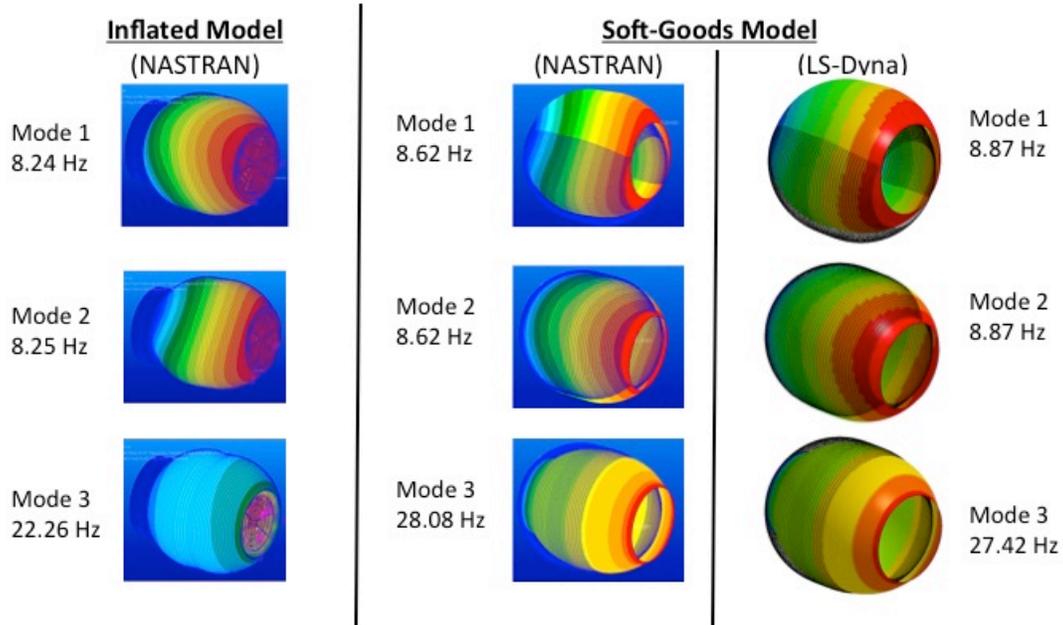
Figure 4. Schematic of Bulkhead Model.
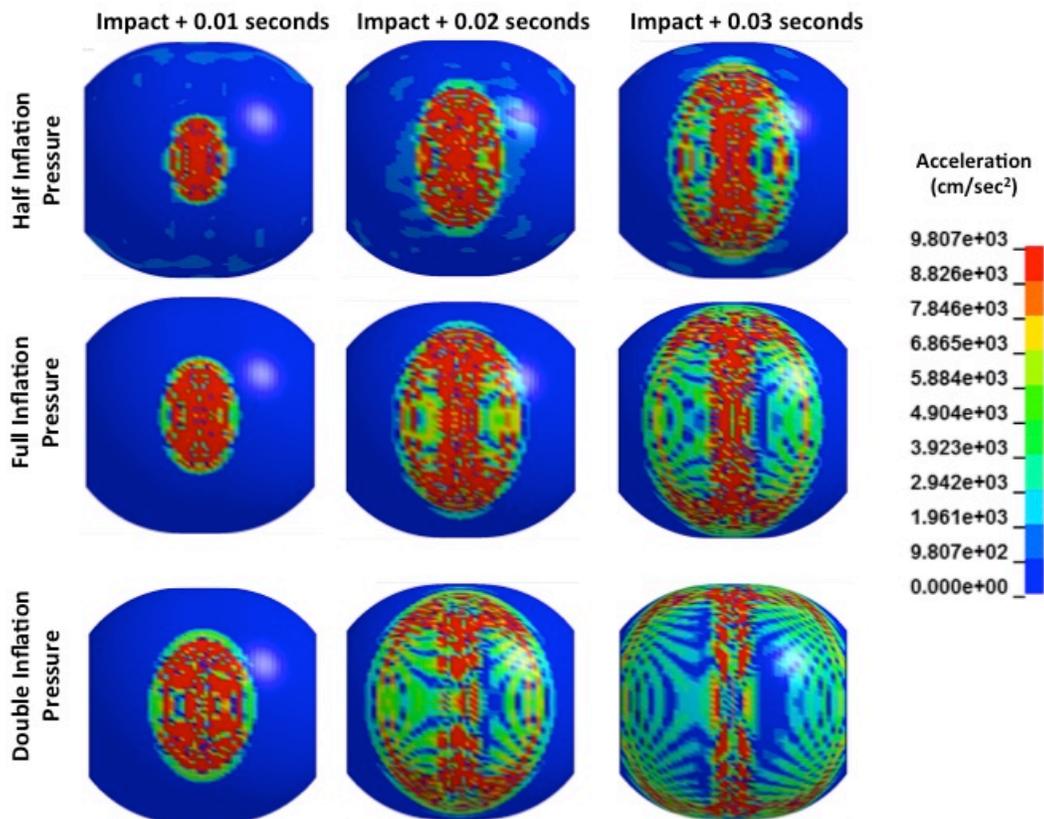
Figure 5. Comparison of first 3 free vibration modes.

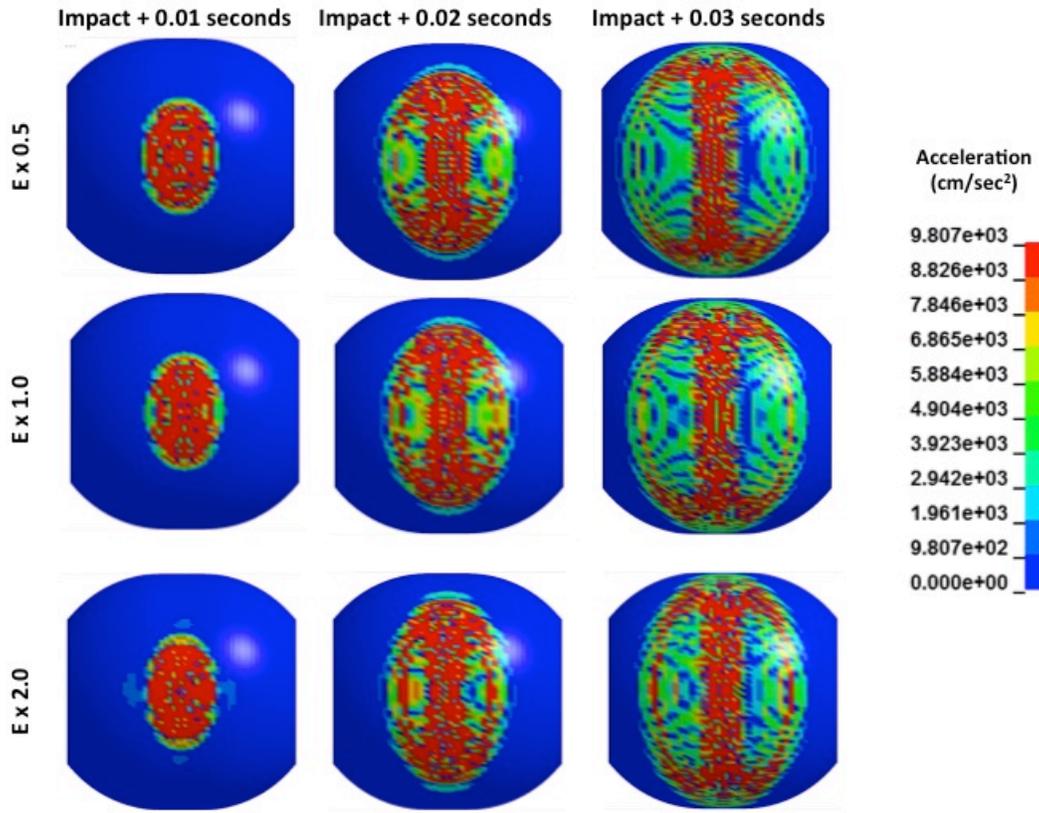Figure 6. Effect of Inflation pressure on acceleration wave for Soft-Goods Model.

Figure 7. Effect of elastic modulus on acceleration response for Soft-Goods Model.
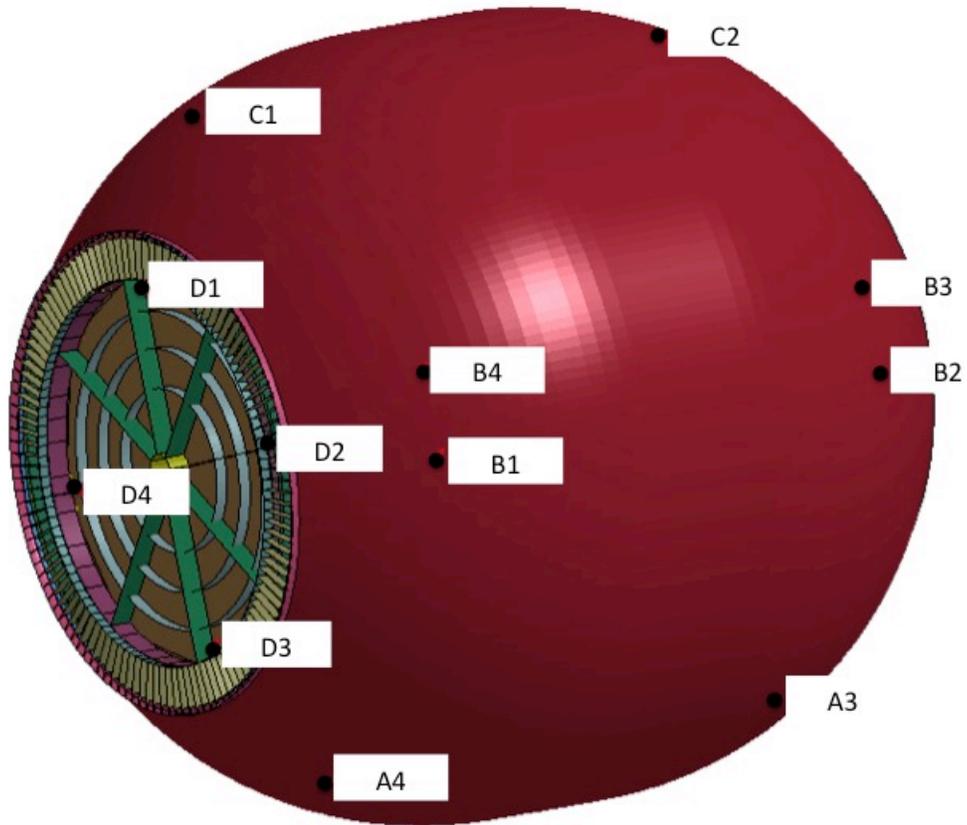
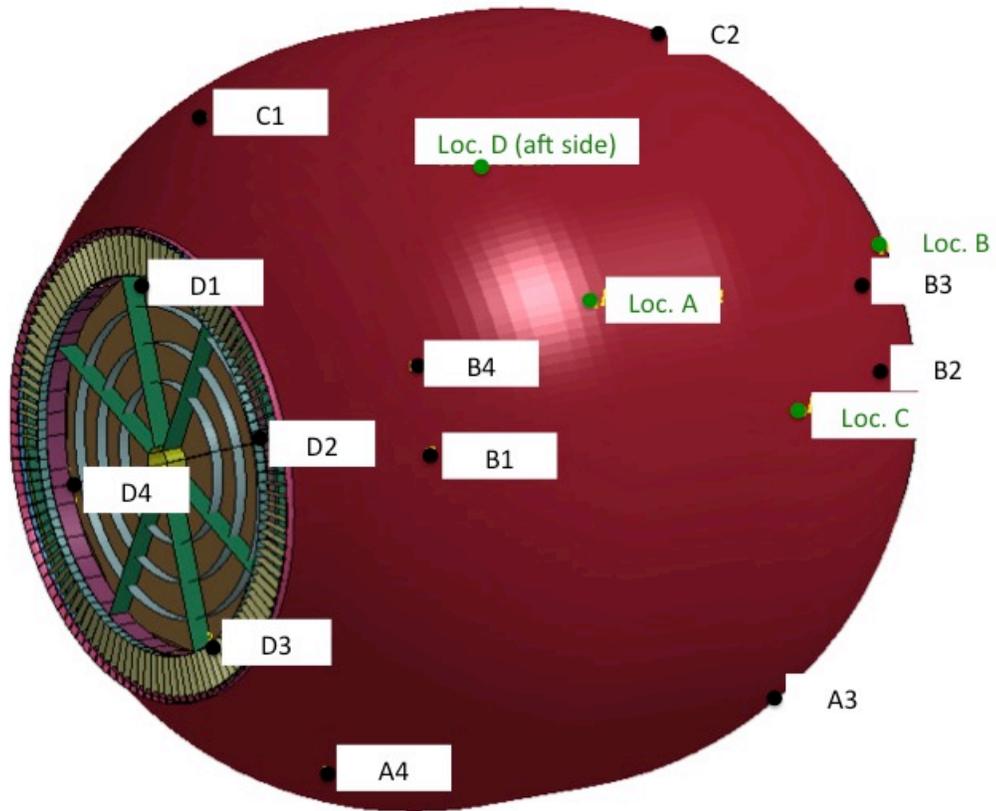Figure 8. DIDS accelerometer locations.

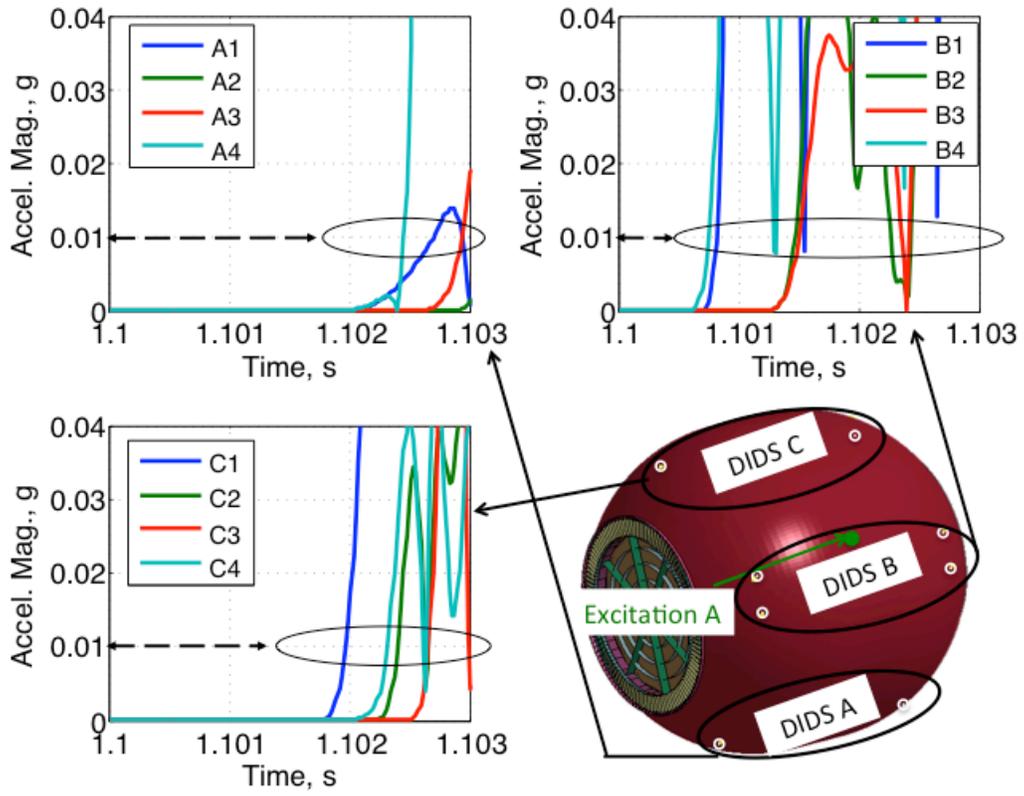Figure 9. DIDS acceleration locations along with nodal excitation locations shown in green.

Figure 10. Sample time histories for Soft-Goods impulse at the Soft-Goods DIDS sensor locations.
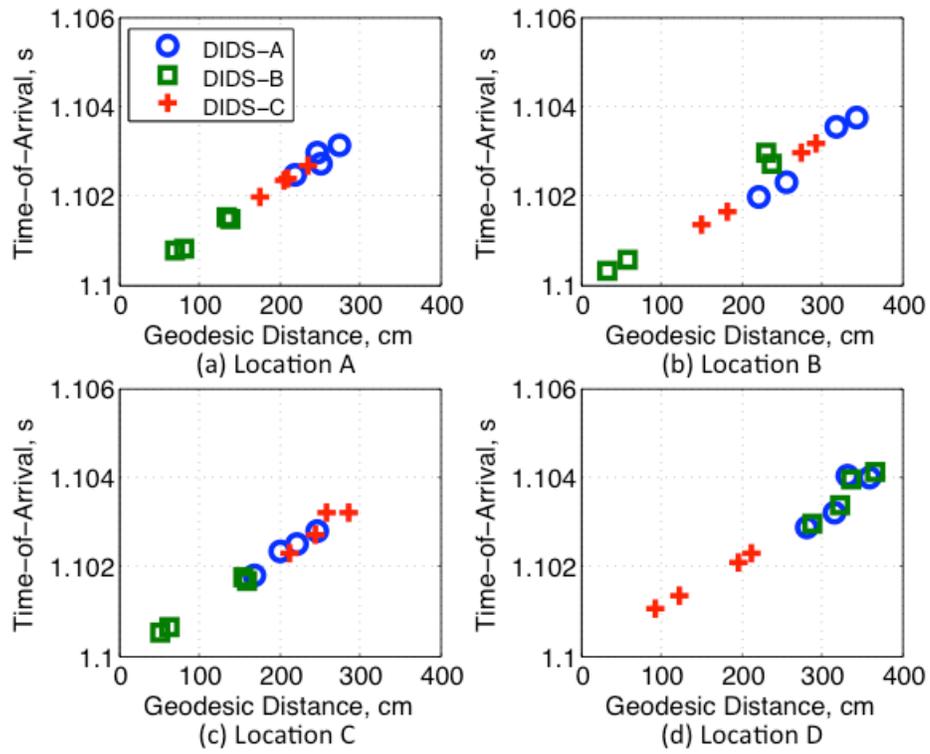
Figure 11. Correlation of impulse Time-of-Arrival with geodesic distance for Soft-Goods excitations and responses.
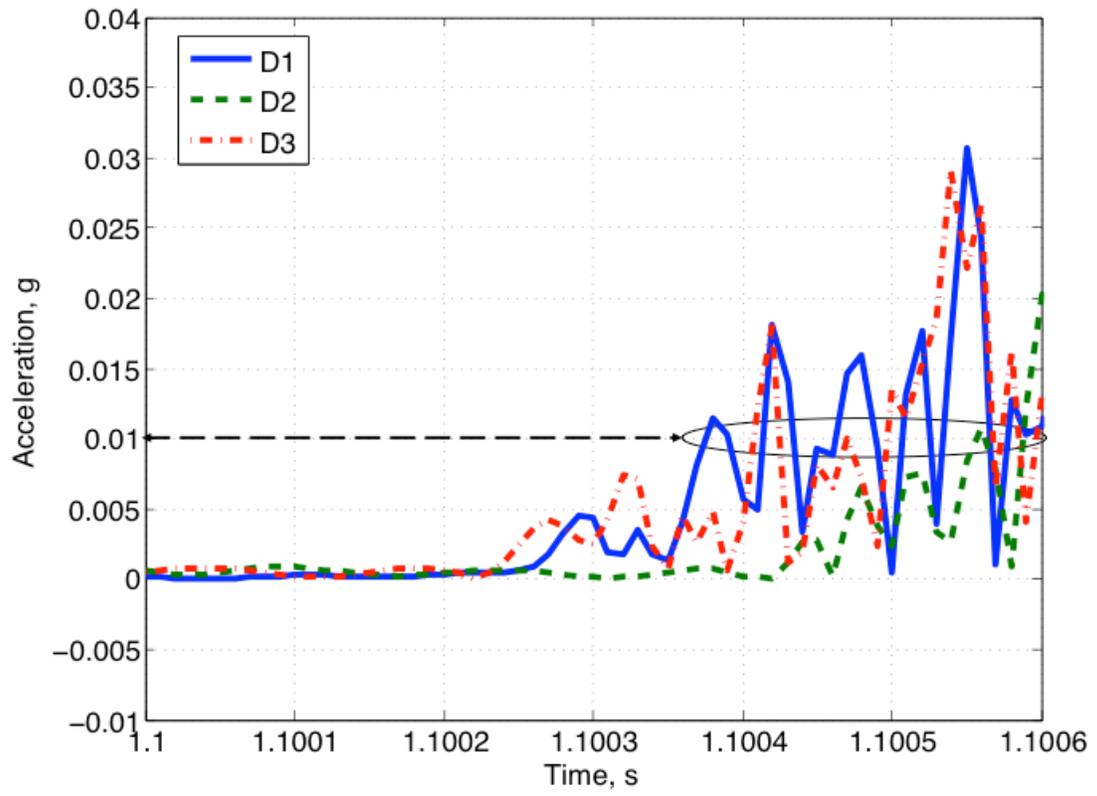
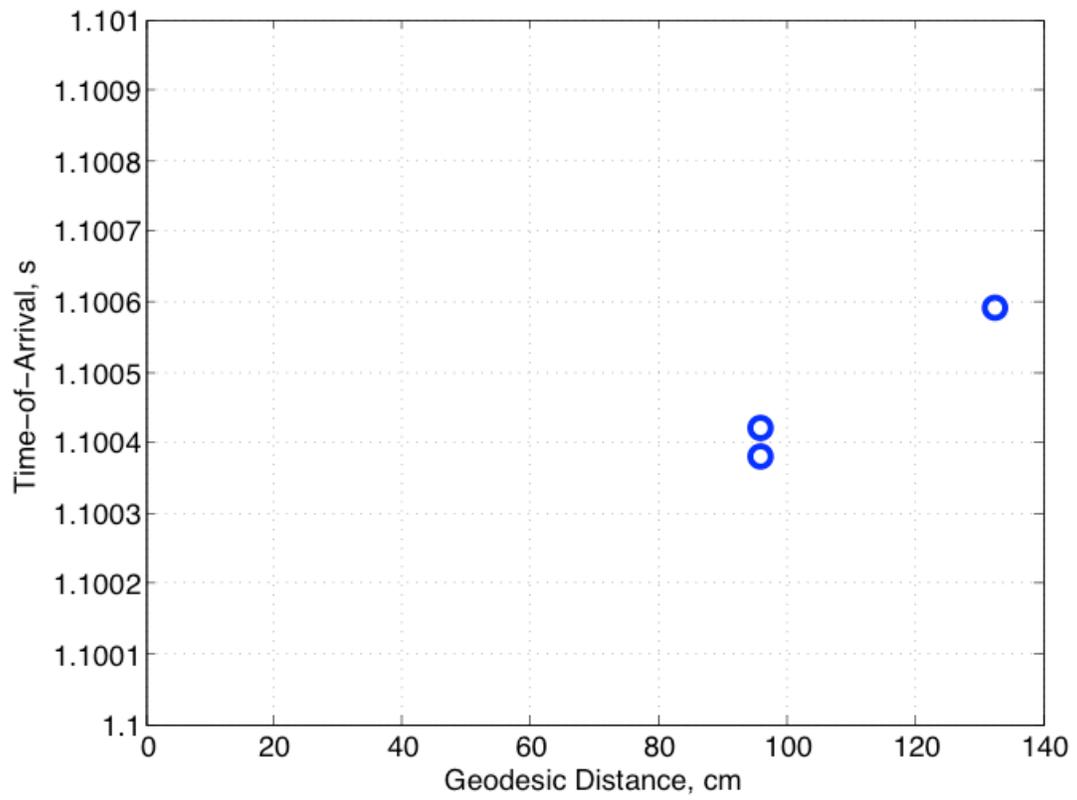Figure 12. Sample time histories for bulkhead impulse at the DIDS bulkhead sensor locations.

Figure 13. Correlation of Time-of-Arrival with geodesic distance for bulkhead excitation and response.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)* 01-11-2015	2. REPORT TYPE Technical Memorandum	3. DATES COVERED *(From - To)*	
4. TITLE AND SUBTITLE Modeling of Global BEAM Structure for Evaluation of MMOD Impacts to Support Development of a Health Monitoring System		**5a. CONTRACT NUMBER**	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Lyle, Karen H.; Vassilakos, Gregory J.		**5d. PROJECT NUMBER**	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER 149030.01.99.99.99.99.23	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199		**8. PERFORMING ORGANIZATION REPORT NUMBER** L-20612	
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-2015-218984	

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 18
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report summarizes the initial modeling of the global response of the Bigelow Expandable Activity Module (BEAM) to micrometeorite and orbital debris (MMOD) impacts using a structural, nonlinear, transient dynamic, finite element code. These models complement the on-orbit deployment of the Distributed Impact Detection System (DIDS) to support structural health monitoring studies. Two global models were developed. The first focused exclusively on impacts on the soft-goods (fabric-envelop) portion of BEAM. The second incorporates the bulkhead to support understanding of bulkhead impacts. These models were exercised for random impact locations and responses monitored at the on-orbit sensor locations. The report concludes with areas for future study.

15. SUBJECT TERMS

Inflatable habitat; MMOD impacts; Numerical analysis

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	22	(757) 864-9658

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