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Structural analysis of hypersonic inflatable aerodynamic decelerator pressure tub testing

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ABSTRACT

Hypersonic Inflatable Aerodynamic Decelerator (HIAD) systems have the potential to deliver the large payloads required for human-scale Mars missions. The structural response of the HIAD is critical as the inflatable members are relatively compliant compared with traditional decelerators. Structural testing and analysis were conducted on a 3.7 m HIAD subjected to uniform pressure. A beam-based finite-element modeling methodology was developed to analyze the inflatable system that incorporates strap pretension and interaction between adjacent members, a significant advance relative to previous analyses of individual inflated HIAD components. The computationally efficient modeling approach accurately captured the load-deformation response of the HIAD system.

1. Introduction

The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) system under development by the National Aeronautics and Space Administration (NASA) has the potential to deliver the size payloads required for a human-scale mission to Mars with a significant mass and volume savings when compared to rigid decelerators [1]. The structure consists of multiple, slender, inflatable, fabric torus members. The tori are stacked to form a cone shape (see Fig. 1). Each torus is strapped to adjacent tori while the innermost torus is strapped to the relatively rigid center-body. Additional radial straps extend from the center-body to outer tori. The outer cone, or fore side of the HIAD, is covered with a flexible thermal protection system (TPS). The TPS protects and insulates the inflatable structure from the extreme heating that is encountered during atmospheric reentry.

The individual torus members consist of a braided fabric shell covering a non-structural gas barrier. Discrete, axial reinforcing cords are braided into the shell and provide the majority of the axial and flexural rigidity of the tori. The inflatable system is deflated and packed within the confines of a launch vehicle. The system is only inflated on the way to the destination planet, or before atmospheric reentry. The inflated cone creates a large surface area to decelerate the payload as it travels through the atmosphere.

In addition to the HIAD system, inflatable structures can be found in many other contexts and applications. The rapidly deployable nature of inflatable structures make them ideal for military applications [2], their low mass and ability to be compactly packed make them well suited for aerospace applications [3–5], and their versatility and shape changing ability lead to unique applications in disaster relief, agriculture and other terrestrial applications [6–8]. Before the HIAD, or any other inflatable system can be utilized, the structural response of the system must be understood. This can be accomplished by means of structural testing at the material [9,10], component [11,12] and structural levels, as well as by developing computational methodologies that are validated with test data and are capable of accurately predicting the response of the inflatable system. HIAD structural modeling efforts to date have utilized a shell-based finite element (FE) approach to model the individual toroidal members with pressure follower forces and both implicit [13,14] and explicit [15,16] solution schemes. Although these approaches can predict the response of the HIAD structure subjected to pressure loading, they are time consuming to develop; difficult to parameterize; and computationally expensive due to the large number of degrees of freedom and contact conditions between adjacent tori. Guo et al. [17] also developed a structural model of the HIAD system to study the influence of deformations on the aerodynamic and aeroheating response of the system, although deformations of the thermal

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Fig. 1. Conceptual rendering of HIAD structure.

protection system that covers the fore side of HIAD structure were of primary interest.

Alternatively, a beam-based FE modeling approach can be utilized to simulate the response of slender, inflatable members, as was accomplished in [18–23]. In the current study, a beam-based FE modeling scheme has been developed to model the inflatable components of the HIAD system. The development of the modeling methodology significantly extends the two-dimensional, beam-based inflatable member modeling methodology that was previously developed [21,22] and applied to the modeling of braided fabric arch members [23]. The current modeling methodology utilizes a three-dimensional, corotational, flexibility-based beam element and incorporates the pressure-volume change work that occurs as the inflatable members undergo certain deformation modes. The element also accounts for axial-bending and in-plane out-of-plane coupling that can occur with the inflatable members. The modeling methodology has been validated using experimental test data of straight-tube and toroidal inflatable members [12,24].

Applying the beam-based FE modeling methodology to the analysis of a full HIAD structure is a significant departure from previous HIAD modeling efforts. Further, modeling a full HIAD structure represents a large increase in complexity from the modeling of single, inflatable components. In modeling multiple tori, the interaction between the inflatable members must be accounted for. The straps that connect the tori to each other and to the relatively rigid center-body must also be included. The beam-based FE modeling methodology under development has been partially validated using straight-tube and torus experimentation of braided, inflatable, slender members with axial reinforcing cords located at discrete locations around the cross-section of the member as detailed in [12,24]. The modeling methodology is extended to analyze a full HIAD structure and further validated by comparing the results of load testing on a 3.7 m major diameter HIAD structure.

In the following sections a 3.7 m major diameter HIAD structure is described along with load testing conducted by NASA researchers using a 'pressure tub' configuration. The development of the beam-based FE modeling approach is also described, including the handling of torus, interaction, link and strap elements, along with the boundary, loading and solution schemes. Finally, experimental results of interest are compared to model predictions.

2. Description of HIAD test article

A picture of the 3.7 m major diameter HIAD specimen is shown in Fig. 2 along with the pressure tub test configuration that was used for

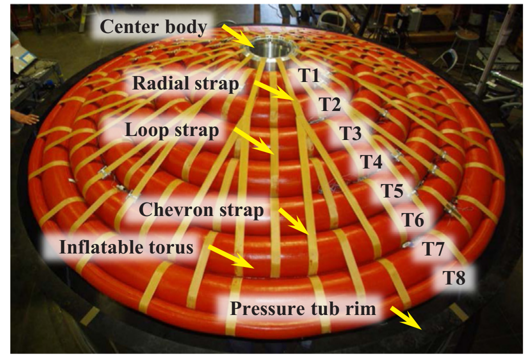

Fig. 2. 3.7 m HIAD specimen and pressure tub.

structural testing and will be described subsequently. The fore side of the HIAD structure is visible in Fig. 2 along with the various strap types that connect the tori to each other and to the center body.

The HIAD structure consisted of eight inflated tori. Tori T1 (the torus closest to the center-body) through T7 (the seventh torus from the center-body) all had minor diameters of 251 mm. Torus T8 (also referred to as the shoulder torus) had a minor diameter of 89 mm. Fig. 3 illustrates a cross-section of the idealized HIAD specimen, along with a plan view of the HIAD with R and θ axes shown. The seven full sized and one shoulder torus are shown, along with the center-body that all tori are securely strapped to, and the distributed load due to the pressure differential between the fore and aft sides of the HIAD (described in the next section). A cylindrical coordinate system will generally be used to describe the HIAD structure. The R axis is aligned perpendicular to the longitudinal axis of the tori. The positive Z axis is perpendicular to the R axis and is out of the page in the plan view portion of Fig. 3 (the positive Z axis is up in the cross-section portion of Fig. 3). The θ axis sweeps about the positive Z axis with counter-clockwise taken as positive.

The tori were configured at a 70° angle from the vertical (Z) axis. The inflation pressure for all tori in the test of interest was 83 kPa. The individual tori consisted of a braided shell with integral axial reinforcing placed at discrete locations around the cross section of the member. The articles were of similar construction to the articles discussed in [9,11,12,24] and are of a similar braided construction as in

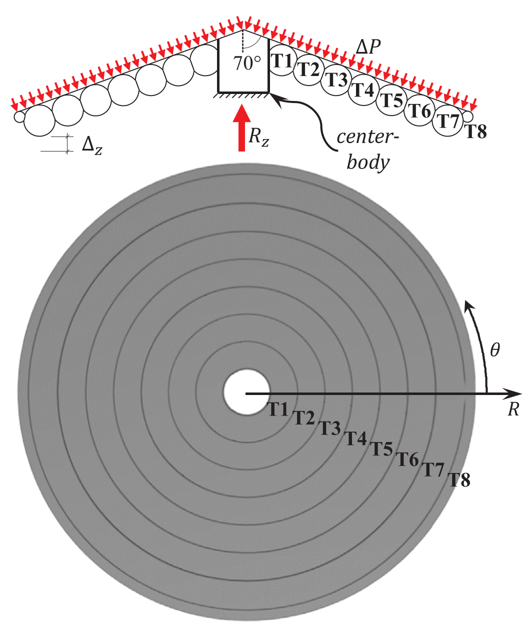

Fig. 3. Cross-section and plan view of idealized HIAD specimen and pressure tub test.