EFFECTS OF WELDING-INDUCED INITIAL GEOMETRIC IMPERFECTIONS ON THE NONLINEAR BEHAVIOR OF THE SPACE SHUTTLE SUPERLIGHTWEIGHT LO_2 TANK

Michael P. Nemeth, Richard D. Young, Timothy J. Collins, and James. H. Starnes, Jr.
NASA Langley Research Center
Hampton, Virginia 23681-0001

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Michael P. Nemeth* , Richard D. Young†, Timothy J. Collins‡, and James H. Starnes, Jr.§
NASA Langley Research Center
Hampton, Virginia 23681-0001

Abstract

Results of linear bifurcation and nonlinear analyses of the Space Shuttle superlightweight external liquid-oxygen (LO_2) tank are presented for an important prelaunch loading condition. These results show the effects of actual, measured welding-induced initial geometric imperfections on an important response mode for thin-walled shells that are subjected to combined mechanical and thermal loads. This type of initial geometric imperfection may be encountered in the design of other liquid-fuel launch vehicles. Results are presented that show that the LO_2 tank will buckle in the barrel section at load levels nearly four times the magnitude of the operational load level and will exhibit stable postbuckling behavior. The actual measured imperfections are located in this section of the tank. Results of imperfection sensitivity analyses are presented that show that the largest degradation in the apparent membrane stiffnesses of the LO_2 tank barrel section is caused by an imperfection shape that is in the form of the linear bifurcation buckling mode with a relatively small amplitude. These results also show that the effect of the relatively large-amplitude measured imperfection is benign.

Introduction

Construction of the International Space Station (ISS) has created a requirement for the Space Shuttle to deliver a large number of payloads to a 51.6^{o} high-inclination orbit. Currently, achieving this orbit requires that the payload of the orbiter be reduced by approximately 10,000 lb. To recover most of the lost payload, and to minimize the number of Space Shuttle flights needed to construct the ISS, the National Aeronautics and Space Administration (NASA) is developing a new lightweight external fuel tank for the Space Shuttle. This new fuel tank is made primarily from an aluminum-lithium alloy. This new design, referred to as the superlightweight (SLWT) external tank, is expected to weigh approximately 58,000 lb, which is approximately 8,000 lb lighter than the lightweight aluminum external tank currently in service.

Important considerations in the design of the SLWT tank are the nonlinear behavior of its thin-walled regions that experience compressive and shear stresses, and the sensitivity of the response to initial geometric imperfections. Small initial geometric imperfections are known to cause premature, and sometimes unexpected, buckling of thin shell structures. These effects are very important for the SLWT tank because local or global buckling of the shell wall could cause the thermal protection system (TPS) to separate from the tank, which could cause the vehicle to fail. As part of a plan to ensure that the design does not have a shell-wall instability, accurate predictions of the nonlinear response and imperfection sensitivity of the SLWT tank are needed. Accurate predictions of the nonlinear response of the SLWT tank have been shown to require a large-scale, high-fidelity finite-element model to represent the complex structural details of the SLWT tank, and a robust nonlinear shell analysis capability that can predict local and general instability buckling modes. [1]

One component of the SLWT tank that experiences significant compressive stresses is the liquid-oxygen (LO_2) tank. The weights of the liquid-hydrogen (LH_2) tank, the LO_2 tank, and the fuel are reacted at the solid-rocket-booster attachment points, which causes meridional compressive stresses and shear stresses that extend into to the nose of the SLWT tank. After welding the first SLWT LO_2 tank flight article, relatively large initial geometric imperfections were found and measured, and the effects of these large imperfections became a major concern in the development of the tank.[2]

The present paper presents results of linear bifurcation and nonlinear analyses of the SLWT LO_2 tank that were conducted at the NASA Langley Research Center to determine the effects of these large welding-induced initial geometric imperfections on the response of the shell. These results are for a critical prelaunch loading condition that causes high compressive and shear stresses in the barrel section of the LO_2 tank where the initial imperfections are pronounced. First, an overview of the SLWT structure and the details of the loading condition are presented. Then, details of the finite-element model-

* Senior Research Engineer, Structural Mechanics Branch. Associate Fellow, AIAA.

† Aerospace Engineer, Structural Mechanics Branch. Member, AIAA.

‡ Aerospace Engineer, Structural Mechanics Branch.

§ Head, Structural Mechanics Branch. Fellow, AIAA.

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ing and load simulation are summarized. Next, details of the initial geometric imperfection measurements and analytical results are presented. These results illustrate the differences in the sensitivity of the nonlinear shell response to the measured welding-induced initial geometric imperfections and to imperfections in the form of the linear bifurcation buckling mode. Throughout the paper, generic aspects of the finite-element models, analyses, and results appear that may be applicable to the design of future liquid-fuel launch vehicles.

Overview of the Structure

The Space Shuttle consists of the orbiter, two solid rocket boosters (SRBs), and the external tank (ET), as shown in Fig. 1. The ET consists of a LO_2 tank, a LH_2 tank, and an intermediate structure called the intertank (Fig. 1). The intertank transmits the weight of the fuel, the ET structural weight, and the orbiter weight to the SRBs prior to launch and transmits thrust loads from the SRBs and the orbiter to the ET during ascent. The SLWT LO_2 tank is a thin-walled monocoque shell made primarily of 2195 aluminum-lithium alloy. The LO_2 tank is approximately 49 ft long and has a maximum diameter of approximately 27.5 ft, as indicated in Fig. 2. The LO_2 tank consists of a forward ogive section made from eight gore panels, an aft ogive section made from 12 gore panels, a cylindrical barrel section made from four barrel panels, and an aft elliptical dome section made from 12 gore panels. The coordinate systems used to locate the elements of the LO_2 tank and the intertank also are shown in Figs. 1 and 2. The coordinates (XT, Y, Z) are typically referred to as the global coordinate system of the ET, and axial positions along the tank are indicated by the coordinate value of XT in units of inches. For example, the location of the junction between the forward and aft ogives is indicated by writing XT = 536.74 in. Cylindrical coordinates are also used and are given by (XT, r, θ), where a positive value of θ is measured from the positive Z-axis toward the positive Y-axis, as shown in Fig. 2.

The LO_2 tank also has a forward ring frame with a "T"-shaped cross section that is referred to herein as the T-ring frame, and an aft ring frame with a "Y"-shaped cross section that is referred to herein as the Y-ring frame. These two ring frames support a baffle assembly that prevents the fuel from sloshing during ascent. The slosh baffle, a lightweight (approximately 455 lb), thin-walled structure, is supported by deep, thin-walled rings at each end that attach to the forward T-ring and the aft Y-ring frames. Other parts of the LO_2 tank include a nonstructural nose cone, a forged forward ogive fitting and cover plate, an aft spherical dome cap that contains the LO_2 suction fitting and a covered manhole, and a vortex baffle attached to the base of the aft dome cap. The LO_2

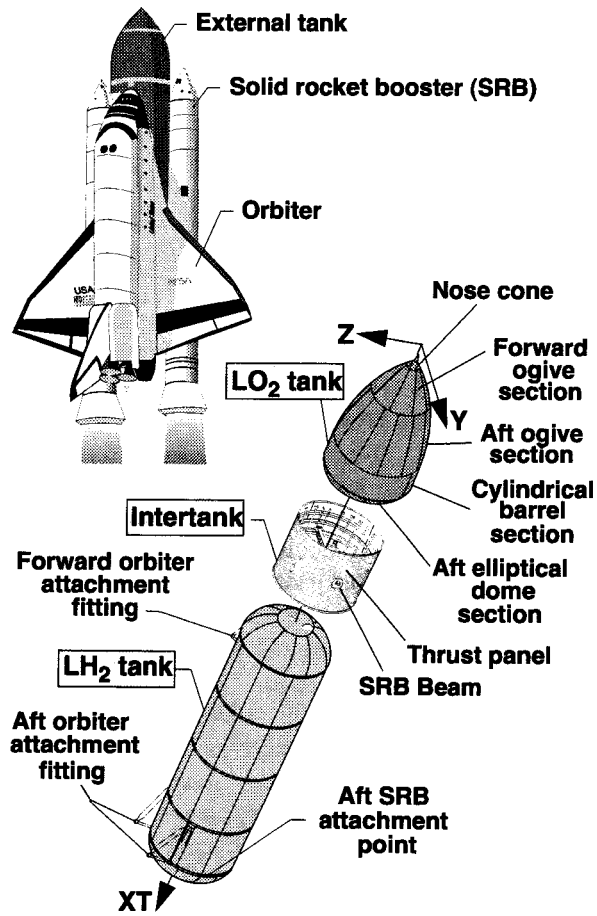


Fig. 1 Space Shuttle External Tank components.

tank gore and barrel panels are stretch formed, chemically milled, and then welded together. The panels are fabricated with substantial thickness tailoring to reduce structural weight. The panels are somewhat thicker at the welds to form a stiffener-like region that is used as a weld land. The primary role of the weld lands is to compensate for any reduction in shell-wall strength that is caused by welding. Tapering the weld lands in thickness and width along their length reduces weight and alleviates stress concentrations in the shell that result from abrupt changes in thickness.

The intertank is a right-circular cylinder that is made from 2090 aluminum-lithium and 7075 aluminum alloys and is shown in Fig. 1. The approximately 22.5-ft-long intertank has a diameter of approximately 27.5 ft and consists of six 45° curved panels that are stiffened longitudinally with external hat stiffeners, and are referred to herein as skin-stringer panels. The intertank also has two massive 45° curved panels, referred to as thrust panels, located perpendicular to the Y-axis of the intertank (see Fig. 1), and these panels are stiffened longitudinally with integrally machined external blade stiffeners. These eight panels are assembled into the intertank with mechanical fasteners and are attached to five large internal ring frames, a forward flange, and an

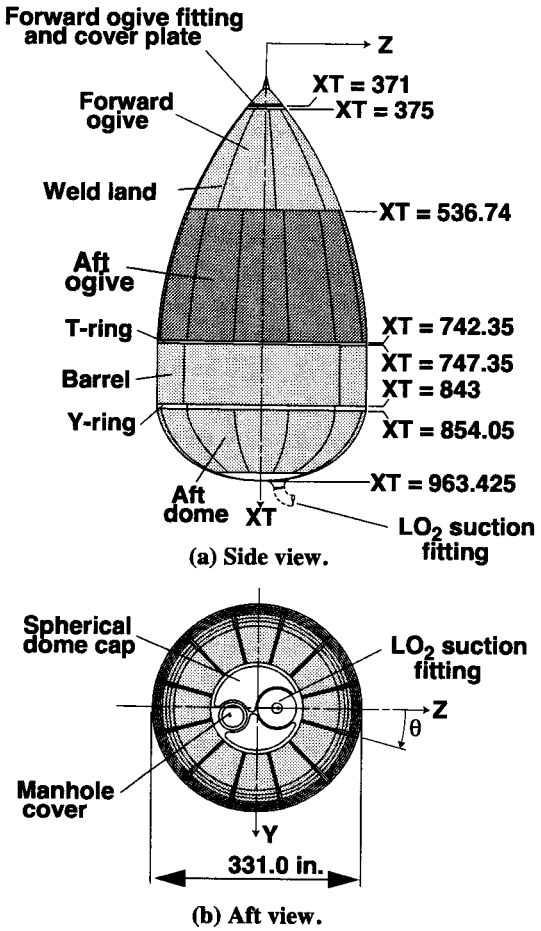


Fig. 2 Space Shuttle External LO_2 Tank components (values of XT given in inches).

aft flange. Longitudinal straps (referred to herein as roll ties) suppress lateral-torsional deflection of the ring frames. The main central ring frame, two thrust panel longerons, and the thrust panels are connected to each end of a tapered beam that is referred to herein as the SRB beam (see Fig. 1). The SRB beam spans the diameter of the intertank along the Y-axis and has a maximum depth (in the XT direction) of approximately 43 in. at its midspan. Forged fittings (referred to herein as SRB thrust fittings) that are incapable of transmitting moments are fastened to the ends of the SRB beam. The primary role of the thrust panels is to diffuse the large axial loads introduced by the SRBs into the intertank and then into the LO_2 tank shell wall. The SRB beam compensates for the eccentricity of the concentrated loads introduced by the SRBs. The SRB beam also supports the loads normal to the intertank (parallel to the SRB beam) at the SRB attachment points. The intertank also has a 46-in.-high by 52-in.-wide frame-reinforced nonstructural access door located along the cylinder generator at approximately $\theta = 146^{o}$.

Critical Loading Condition

The critical SLWT loading condition that was used to assess the importance of the welding-induced initial geometric imperfections was identified by the members of the SWLT team at the NASA Marshall Space Flight Center and the Lockheed-Martin Manned Space Systems Company. This critical loading condition corresponds to prelaunch fueling conditions in which the LH_2 tank is filled with propellant and the LO_2 tank is empty, and it has been described in detail.[1] Details of this loading condition are shown in Fig. 3 and discussed subsequently for convenience.

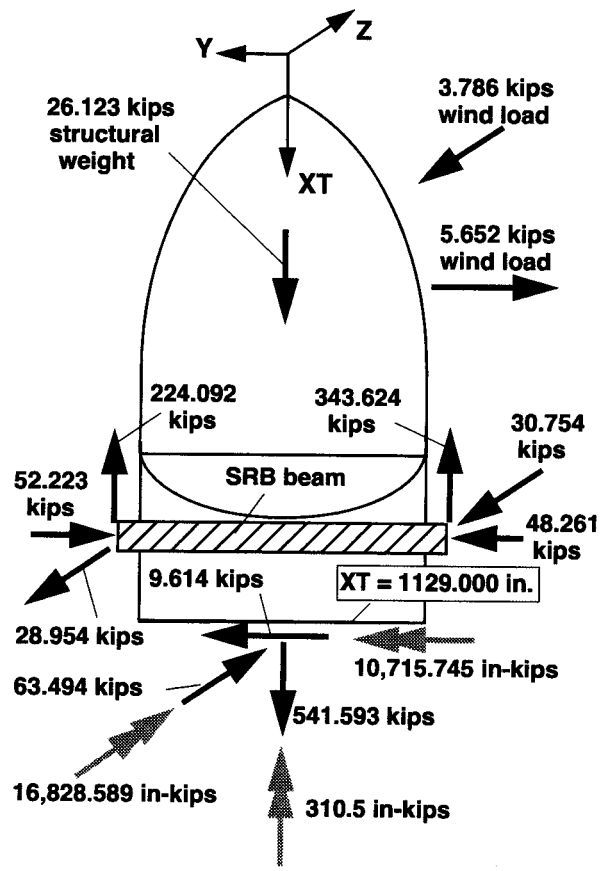


Fig. 3 Prelaunch loads.

The loads consist of a wind load, the structural weight, the SRB interface forces, and the LH_2 tank interface force and moment. In addition, there is no ullage pressure and no temperature change in the LO_2 tank. However, the lower 45 in. of the intertank are subjected to an axisymmetric, uniform through-the-thickness temperature field that varies linearly from -423 ^{o}F, where the intertank is attached to the LH_2 tank (XT = 1129 in.), to 50 ^{o}F at the top of the LH_2 tank forward dome (XT = 1084 in.). The nominal ambient temperature of the LO_2 tank and the intertank prior to fueling is 50 ^{o}F. The SRB interface forces are given by $\mathbf{R_1} = -224.092\mathbf{i} - 52.223\mathbf{j} +$

-28.954**k** kips and $\mathbf{R_2} = -343.624\mathbf{i} + 48.261\mathbf{j} - 30.754\mathbf{k}$ kips where the vectors $\mathbf{R_1}$ and $\mathbf{R_2}$ correspond to the +Y and -Y sides of the SRB beam that is shown in Fig. 3. The vectors **i**, **j**, and **k** are standard orthonormal base vectors associated with the XT, Y, and Z axes, respectively. Similarly, the interface force and moment between the intertank and the LH_2 tank at XT = 1129 in. are given by $\mathbf{F} = 541.593\mathbf{i} + 9.614\mathbf{j} + 63.494\mathbf{k}$ kips and $\mathbf{M} = -310.500\mathbf{i} + 10{,}715.745\mathbf{j} + 16{,}828.589\mathbf{k}$ in.-kips. The wind pressure that acts on the LO_2 tank and the intertank has a resultant force given by -5.652**j** - 3.786**k** kips.

Analysis Code and Finite-Element Modeling

The results of the linear bifurcation buckling and nonlinear analyses were obtained with the STructural Analysis of General Shells (STAGS) nonlinear structural analysis code for general shells.[3] The finite-element models of the SLWT tank used in the present study are very complex and include many structural details including the skin thickness variations or tailoring used to reduce structural weight. A detailed description of these models is presented in Ref. 1. STAGS was chosen for analyzing the SLWT tank because of its robust state-of-the-art nonlinear-equation solution algorithms and its general user-input capability that is convenient for modeling branched shells that are typically used for launch vehicles. In particular, STAGS uses both the full and modified Newton methods to obtain an accurate nonlinear solution, and large rotations in the shell are represented by a co-rotational algorithm at the element level. The Riks arc-length projection method is used to continue a solution past limit points. STAGS permits complex geometries, loading conditions, and initial geometric imperfections to be modeled in a direct manner by the use of user-written subroutines that are essentially independent of the mesh discretization. For example, these user-written subroutines allow the user to define reference surface geometries; tapered shell walls and stiffener cross-sections; complex nodal force, temperature, pressure distribution functions; and initial geometric imperfections in a direct manner, using the FORTRAN computer language. This feature greatly simplified the definition of the finite-element models and the mesh convergence studies conducted in the present study. A description of how the features of STAGS were used in the present study to model the SLWT LO_2 tank and intertank, and details of how various applied loads were simulated are presented in Ref. 1.

The basic approach used in the present study to simulate the actual prelaunch loading process is to apply all of the loads illustrated in Fig. 3 to the model, except for the SRB interface loads. This approach is described in detail in Ref. 1. The nodes on the ends of the SRB beam, where the SRB forces act (see Fig. 3), were restrained so that the SRB interface forces become reactions and rigid body motion is eliminated. Next, the applied loads were separated into two groups. The first group of loads contains the LH_2 tank interface force and moment which are treated as the primary source of destabilizing compressive stresses in the LO_2 tank. These stresses may occur at load levels greater than the corresponding operational load level. The second group of loads consists of the wind load, the structural weight, and the weight of the slosh baffle that is located inside the barrel section of the LO_2 tank. The loads in the second group are constant in value, are part of the operational loads, and are considered to be passive loads when determining the stability margin of safety of the LO_2 tank. In performing linear bifurcation buckling and nonlinear analyses with STAGS, two load factors, p_a and p_b, were assigned to the first (active) and second (passive) load groups, respectively.

In modeling the SLWT LO_2 tank and the intertank, several assumptions were made to simplify the finite-element models. Limited parametric studies were conducted to determine the adequacy of the assumptions and simplifications. For each case in these studies, the modeling assumptions used to simplify the finite-element models were found to be acceptable for analyzing the nonlinear behavior of the SLWT LO_2 tank. In addition, the finite-element modeling approach that was used for the SLWT LO_2 tank was also applied for the analysis of two full-scale structural tests that were conducted at the NASA George C. Marshall Spaceflight Center on the original standard weight ET during the development program of the original Space Shuttle ET. The analytical results for these two test articles, which buckled unexpectedly during the tests, suggest that the finite-element modeling approach is adequate for representing the nonlinear behavior of the SLWT LO_2 tank.[1]

Imperfection Measurement and Shape

During construction of the first SLWT tank flight article, relatively large initial geometric imperfections were found in the LO_2 tank barrel section, next to the meridional weld lands, after the barrel section was welded together into a cylinder. Because of the uncertainty of their importance on the stability of the shell, initial geometric-imperfection measurements were made on the barrel by staff members of the Lockheed Martin Manned Space Systems Division. The measurements were made by placing one end of the barrel on several evenly spaced pedestals and then surveying the barrel with a laser tracking system. The entire barrel was not measured. Only four sections of the barrel that surround each of the four weld lands were measured. These sections span an axial length of 95.651 in. and the circumferential locations are

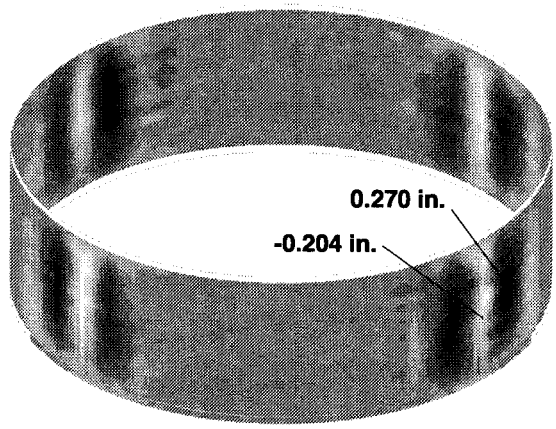
given by $21.462^\circ \le \theta \le 73.385^\circ$, $107.308^\circ \le \theta \le 158.538^\circ$, $202.154^\circ \le \theta \le 253.384^\circ$, and $287.308^\circ \le \theta \le 339.232^\circ$. For each section of the barrel, a laser target was moved over a rectangular grid that had 49 points along the barrel length, 75 or 76 points along the barrel circumference, and a 2 in. by 2 in. mesh spacing. After measuring one section of the barrel, the laser set-up was moved to another convenient location to measure the next section. After completion of the barrel measurements, mid-surface inital imperfection data were calculated to account for the highly variable thickness distribution of the barrel.

Synthesis of the measured initial geometric imperfection data was done to obtain an imperfection shape for use in a nonlinear stability analysis of the LO_2 tank. The synthesis was done by staff members of the Lockheed Martin Engineering Sciences and Services Co.[4] by using the measured initial geometric imperfection data reduction capability of the Delft Interactive Shell Design Code (DISDECO).[5,6] This data reduction capability of DISDECO is a modern version of the procedure described in detail in Ref. 7. To make use of this code, which is for right circular cylinders with a uniform data grid that covers the entire surface of the cylinder, zero-valued imperfection data were input for the regions of the LO_2 barrel that were not measured. This step was performed by using a rectangular grid that had 49 points along the barrel length, 521 points along the entire barrel circumference, and a 2 in. by 2 in. mesh spacing. Next, a "best-fit" right circular cylindrical surface was obtained that corresponds to a least squares fit of the data. This analysis yielded a "best-fit" cylinder with a radius $r = 165.385$ in. Then, points of the imperfect-shell surface were defined relative to the "best-fit" surface. Following this step, the coefficients of a two-dimensional Fourier series representation of the imperfect-shell surface were obtained. The series is given by

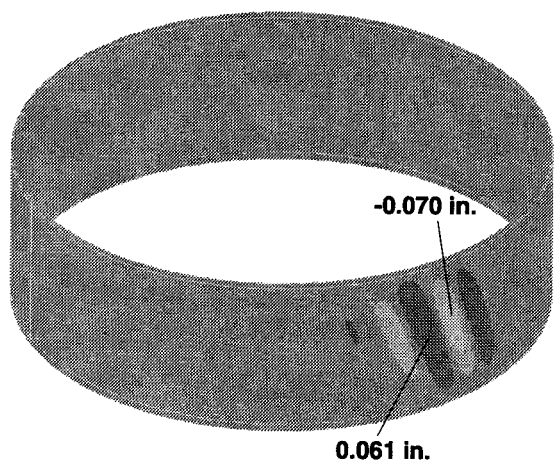
$$\bar{w}(x,\theta) = \sum_{k=0}^{23} \sum_{l=0}^{260} \left\{ \left[A_{kl} \cos l\theta + B_{kl} \sin l\theta\right] \cos\left(\frac{2k\pi x}{L}\right) + \left[C_{kl} \cos l\theta + D_{kl} \sin l\theta\right] \sin\left(\frac{2k\pi x}{L}\right) \right\}$$

where $L = 95.651$ in. and $\bar{w}(x,\theta)$ is the deviation of the imperfect-shell surface that is measured perpendicular to the "best-fit" surface. A comparison of the surface coordinates of the imperfect-shell surface that were calculated from the Fourier series with the corresponding coordinates of the measured data (referred to the "best-fit" cylinder) yielded a difference of less than 1.2 percent.

The initial imperfection shape was implemented into the STAGS analyses by using the user-written subrountine called DIMP. In particular, the Fourier series that was given previously was input directly into DIMP with a series of FORTRAN statements. The resulting shape of the measured imperfection that was generated by STAGS is shown in Fig. 4. This figure indicates that the maximum outward and inward amplitudes are 0.270 in. and -0.204 in., respectively. These amplitudes correspond to approximately twice the minimum thickness in the region of the barrel where they are located.



(a) Measured imperfection (A = -0.204 to 0.270 in.)



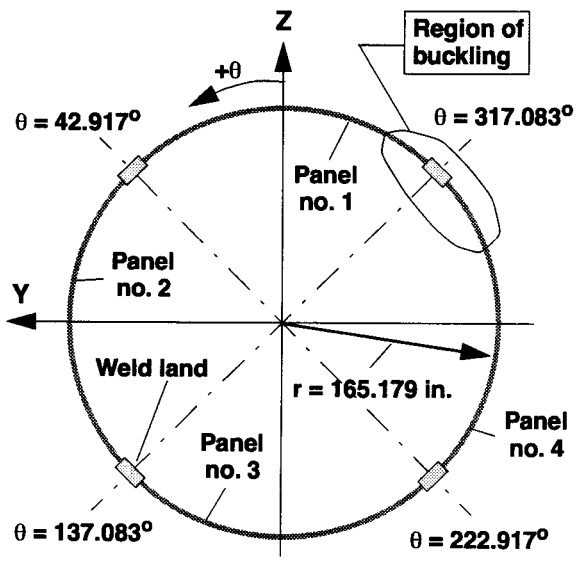
(b) Linear bifurcation mode imperfection (A/t = 0.5; A = -0.070 to 0.061 in.).

Fig. 4 Measured imperfection and linear bifurcation buckling mode imperfection shapes (LO_2 barrel section).

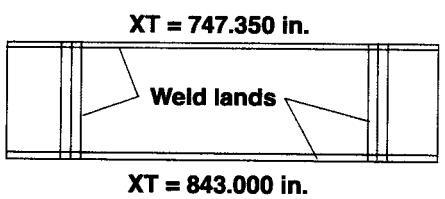
Results and Discussion

The results that are presented herein are closely related to the results that are presented in Ref. 1 for the prelaunch loading condition with a full LH_2 tank and an empty LO_2 tank. In Ref. 1, it was shown that the LO_2 tank buckles locally in the barrel section between approximately $\theta = 280^\circ$ and $\theta = 330^\circ$, as indicated in Figs. 5 and 6. Moreover, results of nonlinear analyses were presented that show a benign effect of initial geo-

metric imperfections in the form of the linear bifurcation buckling mode with imperfection-amplitude-to-wall-thickness ratios $A/t \leq 1$. More specifically, the imperfection sensitivity study showed that the barrel section exhibits stable postbuckling load-carrying capability that is commonly associated with stable-symmetric bifurcations and weak unstable-asymmetric bifurcations that are associated with shallow singly curved panels loaded by edge compression and shear loads.



(a) Top view.



(b) Side view.

Fig. 5 LO_2 barrel panel layout.

The concern over the welding-induced initial geometric imperfections came later in the development of the SLWT LO_2 tank than the stability issues that are presented in Ref. 1. At this later stage in the development of the SLWT LO_2 tank, the thickness distribution of the barrel section had matured. This matured thickness distribution differs somewhat from the thickness distribution that was used to generate the results presented in Ref. 1. Essentially, the matured thickness distribution is thicker in the region surrounding the buckle mentioned previously (The matured thicknesses in this region are shown in Fig. 6.). This matured thickness distribution was used in the analysis models that were used to obtain all of the results that are presented subsequently.

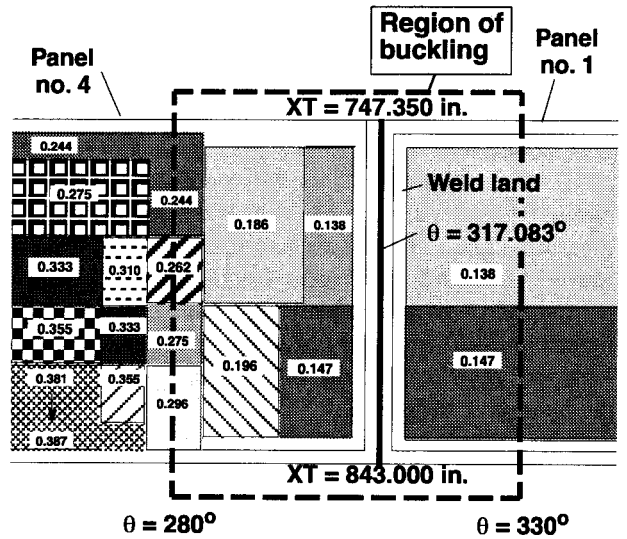


Fig. 6 Thickness distribution of LO_2 barrel in and around the buckle (thicknesses are given in in.).

Three different finite-element models were used in the present study for analysis of the LO_2 tank that is subjected to the prelaunch loading condition. To identify an adequate model with as few degrees of freedom as possible, linear bifurcation buckling analyses were conducted first. The passive loads associated with load factor p_b were applied to the STAGS models as a linear prebuckling stress state ($p_b = 1$), and the active (destabilizing) loads associated with load factor p_a were used to obtain the minimum eigenvalue. The models that were investigated had 86,700, 104,600, and 146,700 degrees of freedom. The model that was identified as adequate for predicting the linear bifurcation buckling behavior is shown in Fig. 7 and corresponds to 146,700 degrees of freedom.

The first linear bifurcation mode (referred to herein as the linear bifurcation buckling mode) for the geometrically perfect shell is shown in Fig. 7 for the STAGS model with 146,700 degrees of freedom. The eigenvalue for this model corresponds to active loads that are approximately 4.08 times the magnitude of the corresponding active operational loads shown in Fig. 3. This buckling mode shape is practically identical to the corresponding mode shape shown in Ref. 1; that is, it is isolated in a portion of the barrel section that envelops the entire length of the barrel and extends from approximately $\theta = 280°$ to $330°$ (the quadrant that contains the negative Y-axis and positive Z-axis side of the tank shown in Fig. 5). The large amplitude region for this section is centered approximately on $\theta = 310°$. The second through fourth linear bifurcation modes are also localized, short-wavelength modes, similar to the mode shown in Fig. 7, with eigenvalues equal to 4.21, 4.66, and 4.81, respectively. These eigenvalues are all more than 3% higher than the lowest eigenvalue. The second linear bifurca-

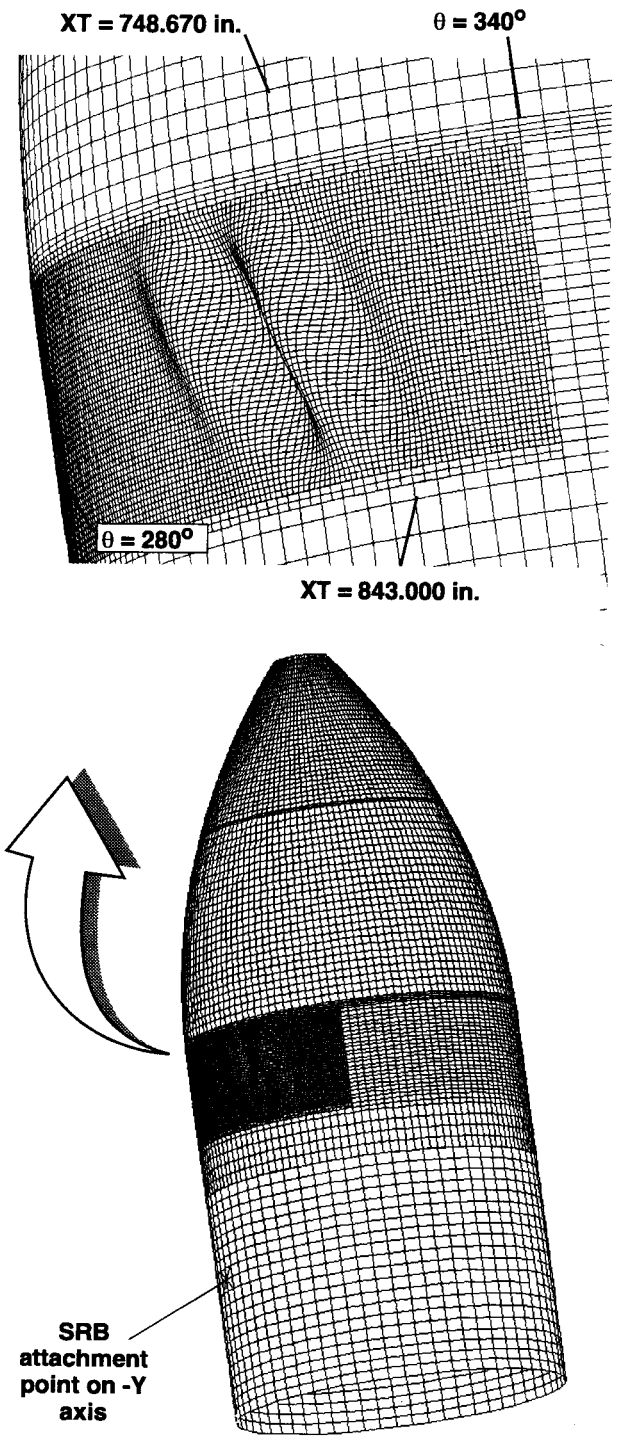


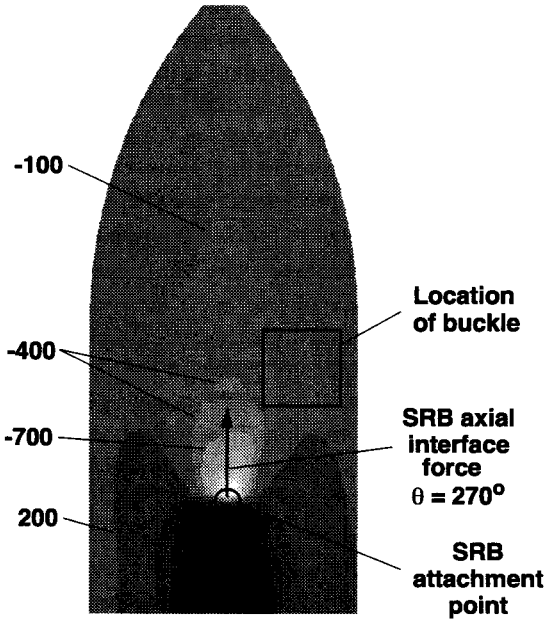
Fig. 7 Linear bifurcation buckling mode for prelaunch loading condition with full LH_2 tank and empty LO_2 tank (146,700 degrees of freedom; $p_a = 4.08$ and $p_b = 1.0$).

tion mode is similar to the first mode and is at nearly the same location. The third and fourth modes also have a buckle pattern that is similar in shape to the buckle pattern of the first mode, but the buckled region extends from approximately $\theta = 210^o$ to 260° (the quadrant that contains the negative Y-axis and negative Z-axis side of the tank shown in Fig. 5).

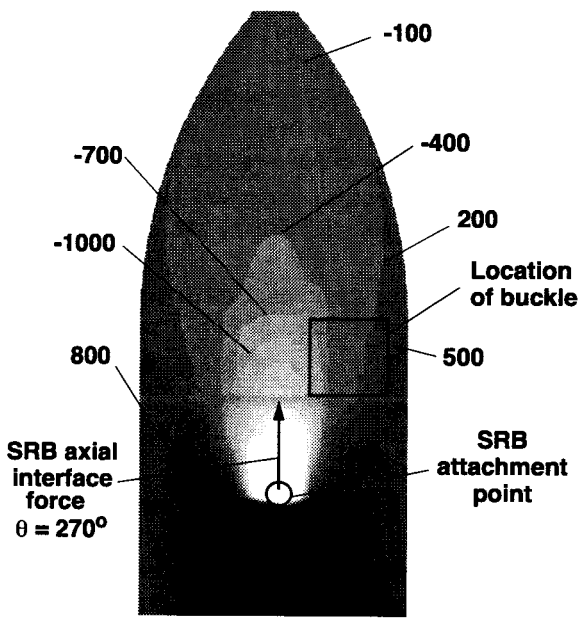
The isolated nature of the first four linear bifurcation modes led to the dense mesh refinement of the barrel that is shown in Fig. 7. The mesh refinement was done by increasing the mesh fineness in the local region containing the buckle shown in Fig. 7, and then by eliminating unneeded mesh refinement elsewhere, with care not to introduce spurious solutions. This step was facilitated by the use of the five-node and seven-node rectangular transition elements available in STAGS.[8] The 104,600- and 146,700-degree-of-freedom models have the same general mesh arrangement shown in Fig. 7, but the level of local refinement of the mesh shown in Fig. 7 for the 146,700-degree-of-freedom model is essentially twice that of the 104,600-degree-of-freedom model. The lowest eigenvalues for the 104,600- and 146,700-degree-of-freedom models are given by $p_a = 4.17$ and $p_a = 4.08$, respectively. The smoothness of the buckling mode shown in Fig. 7 and the approximately two-percent difference in the eigenvalues, indicate that the 146,700-degree-of-freedom model is adequate for representing the linear bifurcation behavior of the LO_2 tank for this loading condition. The 104,600- and 146,700-degree-of-freedom models were also used to obtain nonlinear solutions for geometrically perfect and imperfect shells. These solutions, which are in good agreement, indicate that the 146,700-degree-of-freedom model adequately represents the nonlinear behavior of the LO_2 tank for this loading condition. Thus, all subsequent results presented in this section were obtained with the 146,700-degree-of-freedom model.

Contours of the meridional membrane and shear stress resultants (given in units of lb/in.) on the negative Y-axis side ($\theta = 270^o$) of the tank that were obtained from nonlinear analyses are shown in Figs. 8 and 9, respectively, for values of $p_a = p_b = 1$ and for $p_a = 3.91$ and $p_b = 1$. These figures indicate that high meridional compression stress resultants exist above the thrust panel and that buckling occurs in a region of the barrel where there are significant shear stress resultants. The shear stress resultants are responsible for the slightly skewed appearance of the linear bifurcation buckling mode shown in Fig. 7.

Results are presented in Figs. 10 through 12 that show the nonlinear deformations that were obtained from STAGS analyses of a geometrically perfect shell, a geometrically imperfect shell with an imperfection in the form of the linear bifurcation buckling mode and an imperfection-amplitude-to-wall-thickness ratio A/t = 0.5, and a geometrically imperfect shell with the measured imperfection, respectively. The thickness t in the ratio A/t, and referred to in the figures, is the minimum wall thickness in the buckled region that is shown in Fig. 6 (t = 0.138 in.). For the results shown in Fig. 11, the negative of the linear bifurcation buckling mode was used as

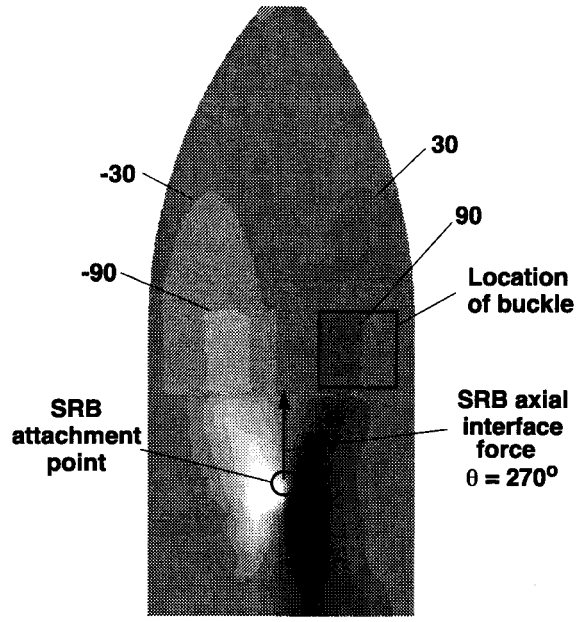


(a) $p_a = p_b = 1.0$.

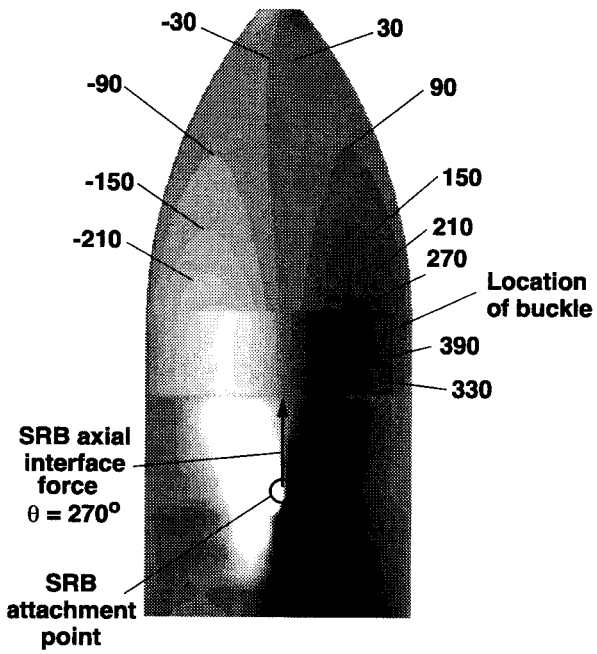


(b) $p_a = 3.91$ and $p_b = 1.0$.

Fig. 8 Meridional membrane stress resultants (lb/in.).



(a) $p_a = p_b = 1.0$.



(b) $p_a = 3.91$ and $p_b = 1.0$.

Fig. 9 Shear stress resultants (lb/in.).

the imperfection shape because it was found to provide a stronger nonlinear interaction with the compressive stresses in the shell wall than the positive-valued imperfection shape. The results shown in these three figures are for nonlinear solutions that were obtained by increasing the load factors p_a and p_b simultaneously to a value of one, and then holding p_b constant while increasing the magnitude of the load factor p_a. The nondimensional normal displacements w/t along the circumference of the barrel shell wall at XT = 789.94 in. and from θ = 200° to 340° are represented by the solid lines in the figures for values of the load factor p_a approximately equal to 1.0, 3.77 to 3.91, and 4.43 to 4.69. The linear bifurcation buckling mode, the corresponding imperfection shape, and the measured imperfection shape along XT = 789.94 in. are given by the dashed lines shown in Figs.

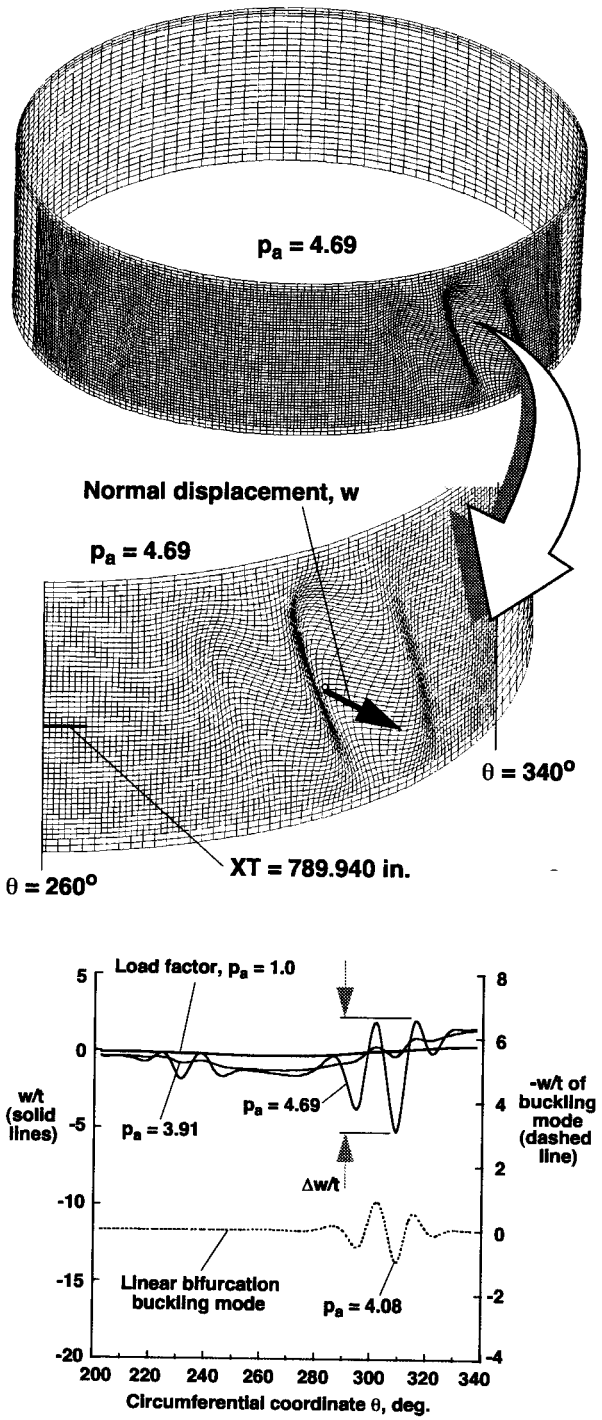


Fig. 10 Nondimensional normal displacement w/t of geometrically perfect aft dome (t = 0.138 in.; XT = 789.94 in.).

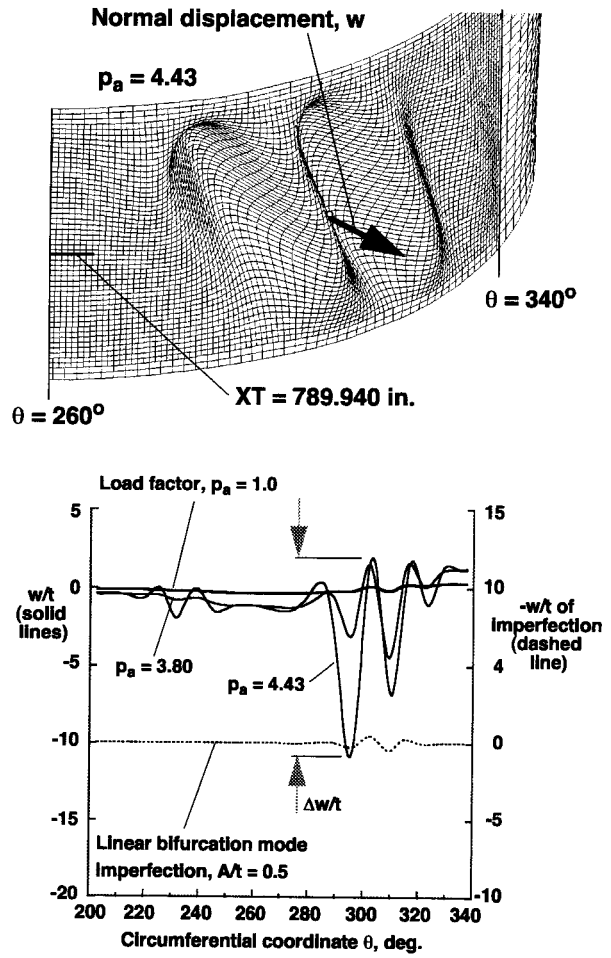


Fig. 11 Nondimensional normal displacement w/t of geometrically imperfect shell with linear bifurcation mode imperfection (t = 0.138 in.; XT = 789.94 in.).

10 through 12, respectively, with their normalized amplitudes given by the right-hand ordinate of the figures. The linear bifurcation buckling mode imperfection (A/t = 0.5), which is considered to be relatively large for thin shells, is also shown in Fig. 4 and has a much smaller amplitude than the measured imperfection. For this imperfection, the maximum outward and inward amplitudes are 0.061 in. and -0.070 in., respectively. In addition, the linear bifurcation buckling mode imperfection is similar in shape to the negative of the measured imperfection. These shapes along XT = 789.94 in. are included in Figs. 11 and 12 to give an indication of how the imperfection shape influences the nonlinear solution.

The barrel section that is shown in the top part of Fig. 10 for the geometrically perfect shell indicates a nonlinear deformation pattern that encompasses most of panels number 1 and number 4 and part of panel number 2 (see Fig. 5). The deformation is the most pronounced in the region that extends from approximately θ = 280° to 330° and has a pattern that is similar to the linear bifurcation buckling mode shown in Fig. 7. The solid lines in Fig. 10 indicate that bending deformations begin to grow in the region that encloses the linear bifurcation buckling mode at approximately p_a = 3.91, which is slightly lower in value than the linear bifurcation buckling load level of p_a = 4.08. As the load level is increased to p_a = 4.69, the bending deformations in this region become severe and additional bending deformations start to grow in the region that extends from approximately θ =

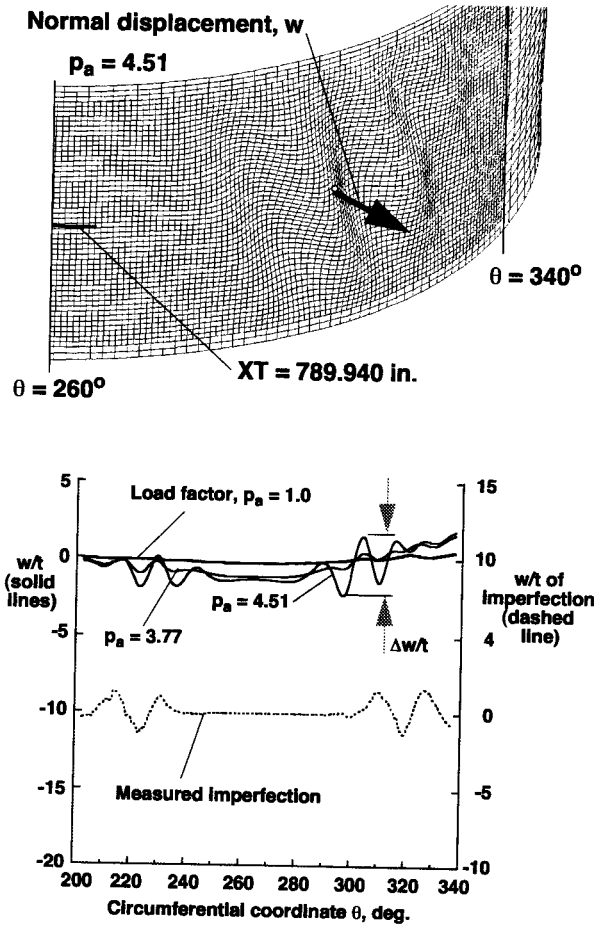


Fig. 12 Nondimensional normal displacement w/t of geometrically imperfect shell with measured imperfection (t = 0.138 in.; XT = 789.94 in.).

220° to 250°. This growth in the amplitude of the bending deformations corresponds to a reduction in the apparent membrane extensional and shear stiffnesses.

Results that were obtained for the imperfect shells also indicate nonlinear deformation patterns that are similar to the barrel section that is shown in the top part of Fig. 10. These deformation patterns encompass most of panels number 1 and number 4 and part of panel number 2 (see Fig. 5). Likewise, the deformations are the most pronounced in the region that surrounds the linear bifurcation buckling mode (θ = 280° to 330°), and these deformations have patterns that are similar to the pattern of the linear bifurcation buckling mode. Comparison of the solid lines in Figs. 10 through 12 indicate that bending deformations in the region from θ = 280° to 330° are significantly more pronounced for the linear bifurcation buckling mode imperfection, and significantly less pronounced for the measured imperfection, than for the corresponding bending deformations of the perfect shell. This dramatically different behavior of the imperfect shells appears to be a result of the substantial difference in the shape of the two imperfections in the region from θ = 290° to 340°.

The results presented in Figs. 10 through 12 also indicate stable nonlinear responses at load levels greater than the load level predicted by the linear bifurcation buckling analysis (p_a = 4.08). At the operational load level given by p_a = 1, the results indicate practically no significant nonlinear deformations. As the load is increased, substantial bending deformations (indicated by the waviness of the curves) develop and grow in the shell wall, and these deformations reduce the apparent membrane extensional and shear stiffnesses of the barrel section. The reduction in the apparent stiffnesses of the barrel is shown more explicitly in Fig. 13 for the geometrically perfect and imperfect shells. In this figure, the intensities of the most severe bending deformations along XT = 789.940 in., that are shown in Figs. 10 through 12, are given as a function of the load factor p_a. The intensi-

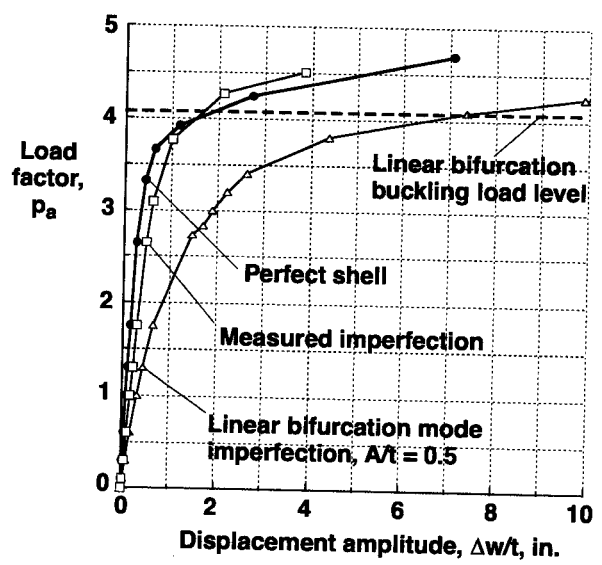


Fig. 13 Local nondimensional normal displacement amplitudes Δw/t of geometrically perfect and imperfect barrels at XT = 789.94 in. (t = 0.138 in.).

ty of these severe bending deformations is given by the nondimensional quantity Δw/t, which is the normalized distance from the maximum value of the local shell-wall displacement to the adjacent minimum value, as shown in Figs. 10 through 12. The locations of Δw/t that are shown in Figs. 10 through 12 correspond to approximately θ = 312°, 299°, and 300°, respectively. The filled circles shown in Fig. 13 correspond to results for a geometrically perfect shell, and the unfilled tiangles and squares correspond to results for the geometrically imperfect shells. In particular, the unfilled triangles and squares correspond to shells with a linear bifurcation buckling mode imperfection (A/t = 0.5) and with the measured imperfection, respectively. The horizontal dashed line shown in Fig. 13 represents the linear bifurcation buckling load level (p_a = 4.08).

The results shown in Fig. 13 indicate that the perfect and imperfect barrel sections of the LO_2 tank exhibit stable postbuckling load-carrying capacity; that is, the geometric imperfections do not cause a premature buckling response. Moreover, the results indicate that the much smaller-amplitude linear bifurcation buckling mode imperfection has a more detrimental effect on the nonlinear response than the larger-amplitude measured imperfection. For the geometrically perfect shell and the shell with the measured imperfection, the linear bifurcation buckling solution gives a reasonable engineering estimate of the onset of a nonlinear shell response that is associated with a large reduction in stiffness for a small increase in load level.

Concluding Remarks

Linear bifurcation and nonlinear analyses of the Space Shuttle superlightweight (SLWT) liquid-oxygen (LO_2) tank have been presented. The loading details for an important prelaunch loading condition have been described and the analytical method used to simulate the loading condition has been discussed. Results have been presented herein that were obtained from complex, large-scale finite-element models of a portion of the Space Shuttle. These results show the effects of actual, measured welding-induced initial geometric imperfections on the linear bifurcation buckling and nonlinear behavior of the SLWT LO_2 tank for a critical prelaunch loading condition. These results are important because they highlight a commonly encountered type of initial geometric imperfection that was measured for a large-scale launch vehicle. The effect of this type of initial geometric imperfection on the buckling behavior of the SLWT LO_2 tank was previously unknown. Moreover, this type of initial geometric imperfection may be encountered in the fabrication of other liquid-fuel launch vehicles. In addition, the results indicate that large-scale, high-fidelity finite-element models are generally required to predict accurately the linear bifurcation and nonlinear responses of these structures.

For the prelaunch loading condition, the analyses predict that the LO_2 tank will buckle in the barrel section, where the actual measured imperfections are located, and will exhibit stable postbuckling behavior at load levels nearly four times the magnitude of the operational load level. The largest degradation in the membrane stiffnesses of the LO_2 tank barrel section is caused by an imperfection shape that is in the form of the linear bifurcation buckling mode with a relatively small amplitude. The effect of the relatively large-amplitude measured imperfection is benign.

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