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ABSTRACT

Composite materials are increasingly being considered and used for launch-vehicle structures. For shell structures, such as interstages, skirts, and shrouds, honeycomb-core sandwich composites are often selected for their structural efficiency. Therefore, it is becoming increasingly important to understand the structural response, including buckling, of sandwich composite shell structures. Additionally, small geometric imperfections can significantly influence the buckling response, including considerably reducing the buckling load, of shell structures. Thus, both the response of the theoretically perfect structure and the buckling imperfection sensitivity must be considered during the design of such structures. To address the latter, empirically derived design factors, called buckling knockdown factors (KDFs), were developed by NASA in the 1960s to account for this buckling imperfection sensitivity during design. However, most of the test-article designs used in the development of these recommendations are not relevant to modern launch-vehicle constructions and material systems, and in particular, no composite test articles were considered. Herein, a two-part study on composite sandwich shells to (1) examine the relationship between the buckling knockdown factor and the areal mass of optimized designs, and (2) to interrogate the imperfection sensitivity of those optimized designs is presented. Four structures from recent NASA launch-vehicle development activities are considered. First, designs optimized for both strength and stability were generated for each of these structures using design optimization software and a range of buckling knockdown factors; it was found that the designed areal masses varied by between 6.1% and 19.6%

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over knockdown factors ranging from 0.6 to 0.9. Next, the buckling imperfection sensitivity of the optimized designs is explored using nonlinear finite-element analysis and the as-measured shape of a large-scale composite cylindrical shell. When compared with the current buckling design recommendations, the results suggest that the current recommendations are overly conservative and that the development of new recommendations could reduce the acreage areal mass of many composite sandwich shell designs by between 4% and 19%, depending on the structure.

NOMENCLATURE

KDF	Buckling knockdown factor
LEO	Low Earth orbit
PAF	Payload Attach Fitting
P_{bif}	Linear bifurcation buckling load
P_{cr}	Nonlinear buckling load
SBKF	Shell Buckling Knockdown Factor Project
SLS	Space Launch System
US	Upper Stage
USA	Universal Stage Adapter

INTRODUCTION

Thin-walled composite shell structures have been used in launch vehicles for many years. For example, there are composite shell structures on the Delta II, Delta IV, Atlas V [1-4], Minotaur V, Vega, Ariane 5, and JAXA H-II. Additionally, NASA is increasingly considering composite structures for use in launch vehicles [5, 6]. For many such launch-vehicle shell structures, sandwich composites, which consist of two laminate facesheets separated by a lightweight core, are chosen for structural efficiency (both strength and stability) and reasonable manufacturing cost. However, it is well known that thin-walled shell structures can be very imperfection sensitive when subjected to destabilizing loads; that is, small geometric or loading imperfections can cause the actual buckling loads of the as-built shells to be significantly lower than the theoretical predictions, which are based on simplified linear bifurcation buckling analyses of geometrically perfect shells (see, for example, ref. [7]). Therefore, it is important to understand the structural response and imperfection sensitivity of sandwich composite shell structures. To account for the imperfection sensitivity during design of a thin-walled shell, the theoretical buckling load is typically multiplied by a design factor called a buckling knockdown factor (KDF) to determine a safe load level. Therefore, the guidelines for determining these knockdown factors can be very important for the design of structurally efficient shells. The most widely used source for knockdown factors for cylindrical shells is the NASA SP-8007 [5], which has recommendations that were developed based on experimental buckling tests from the 1930s-1960s. However, SP-8007 has not been updated since the late 1960s and no composite shells were tested in the development. Therefore, the SP-8007 guidelines may not be applicable to shells constructed from modern materials, improved manufacturing processes, and new structural concepts.

Shell Buckling Knockdown Factor Project (SBKF)

A design technology development project at NASA, the Shell Buckling Knockdown Factor Project (SBKF), is currently working to revise the existing design factors and recommendations for buckling-critical metallic and composite shell structures [8]. A key element of SBKF is to perform trade studies for various concepts (i.e., metallic orthogrid, metallic isogrid, composite sandwich) to determine the relevant design space to be considered and quantify the potential gains to be made by revising the existing design guidelines. To date, most of the SBKF effort has been focused on metallic orthogrid and isogrid cryotank-like structures [8-11]. Currently, the SBKF composite structures effort is being expanded, and the initial composite trade studies are discussed in this paper. Within NASA launch-vehicle development efforts, composites are primarily being considered for dry (i.e., not used in fuel tank applications) launch-vehicle shell structures, and most often, sandwich composites are considered for such dry shell structures. Therefore, sandwich composite structures are the primary composite construction being considered by SBKF.

Sandwich Composite Shells

Sandwich shells in general and composite sandwich shells in particular have been studied for many years and the body of literature is too great to fully describe herein. From the 1940s-1960s, the Forest Products Laboratory and others did extensive work that resulted in the publication of MIL-HDBK 23 and its revisions [12], which primarily considered metallic facesheets, but gave a fairly extensive treatment of structural sandwich design and analysis. Included were treatments of materials, fabrication, repair, durability, flat plates and cylindrical shells under various loadings, local strength and stability phenomena such as facesheet wrinkling and facesheet dimpling, and the global stability phenomena of shear crimping and general global buckling. The 1968 revision of NASA SP-8007 considers the buckling of orthotropic shells and isotropic sandwich shells among others, and a more general treatment of the structural stability of sandwich structures by Sullins, et al. was published in 1969 [13]. Since then, a significant effort has been extended toward understanding sandwich structures, and much of this work is summarized well by Vinson [14], Librescu [15], and Noor [16].

Imperfection Sensitivity in Buckling-Critical Structures

The work of Koiter [17] first identified that small deviations from the idealized geometry of a shell, known as initial geometric imperfections, are the primary source of discrepancy between experimental and predicted buckling loads. Since the work of Koiter, a tremendous number of analytical studies have been conducted towards understanding the effects of initial geometric imperfections on the buckling of isotropic and orthotropic unstiffened and stiffened cylinders, and is now, for the most part, well understood. In contrast, relatively few analytical studies have been conducted on the imperfection sensitivity of sandwich composite cylinders. However, Tennyson and Chan, carried out one of the first analytical studies on the buckling of sandwich composite cylinders with axisymmetric geometric imperfections [18]. In addition, Schultz and Nemeth [19] developed, and compared with finite-element methods, a special-purpose analytical model to examine the imperfection sensitivity of orthotropic cylinders; the considered structures were isotropic and sandwich-composite cylinders.

However, despite the advances in the understanding of imperfection sensitivity and buckling of compression-loaded cylinders in general, current design recommendations include only limited information for composite sandwich cylinders.

Analysis-Based Knockdown Factors

Analysis-based knockdown factors are now becoming a viable replacement for the empirically based knockdown factors currently used. More specifically, improved nonlinear structural analysis tools and improved theories of elastic stability and imperfection sensitivity in shell structures are enabling high-fidelity predictions of the buckling response of thin-walled compression-loaded cylindrical shells [20]. These high-fidelity analysis tools and predictions are the foundation for new analysis-based knockdown factors being developed by SBKF. One of the key attributes of the new analysis-based knockdown factors and their method of development is that specific design features can be isolated and their effects on buckling can be characterized. In addition, it has been suggested by several authors, that a mature manufacturing process will often produce similar imperfection distributions and amplitudes from part to part; that is, there are imperfection signatures for different manufacturing processes [21, 22]. With this information established, high-fidelity analyses that include the imperfection signature data and selective structural testing are being used by SBKF to develop and validate refined, reliable design criteria for shell buckling that are not overly conservative like the present lower-bound approach found in NASA SP-8007 [23].

An alternate approach was suggested in 2008, by Hühne [24] who acknowledged that shell buckling typically begins with a single dimple and proposed the use of radial perturbation loads as a way to develop robust buckling design guidelines for composite cylindrical shells before imperfection signatures are known. A number of researchers have since investigated this concept further. Recently, a European Union project, DESICOS (New Robust DESign Guideline for Imperfection Sensitive COmposite Launcher Structures) [25], had the goal of examining the imperfection sensitivity of composite shell structures and included several studies on the radial perturbation concept with sandwich composite shells (e.g., refs. [26], [27], and [28]). Similarly, in 2013, Cha and Schultz [29] used the radial perturbation concept in a numerical study of an 8-ft-diameter sandwich composite test article. However, despite all the work that has been done exploring the radial perturbation concept, it remains unclear to the authors whether this is an appropriate approach for finding practical and robust lower-bound buckling design loads.

In this paper, a two-part study on composite sandwich shells to (1) examine the relationship between the buckling knockdown factor and the areal mass of optimized designs, and (2) to interrogate the imperfection sensitivity of those optimized designs is discussed. In particular, four structural components from recent NASA launch-vehicle development activities, Ares V and Space Launch System (SLS), will be considered and include the Ares V Intertank and Interstage, an SLS Upper Stage Skirt, and the SLS Interstage. Ares V was intended to be a heavy-lift launch vehicle and was being developed under the NASA Constellation Program from 2005 to 2009. Ares V had dimensions similar to the Saturn V vehicle including a 33-foot-diameter first stage and a maximum overall height of 358 feet, and was designed to have a payload capacity of over 180 metric tons to low Earth orbit (LEO). The SLS, currently being designed by NASA, is similar to the Ares V design, but with a 27.5-foot-diameter first stage and a

maximum overall height of 365 feet. In its most powerful configuration, the SLS is planned to have a payload capacity of 130 metric tons to LEO. The Saturn V, Space Shuttle, Ares V, and 130-metric-ton SLS configurations are shown in Figure 1. In the present study, designs optimized for both strength and stability were first generated for each of the chosen structures using optimization software and a range of buckling knockdown factors. Second, geometrically nonlinear finite-element analyses were used to calculate the effects of geometric imperfections of various amplitudes on the buckling performance of some of those optimized designs. Estimates of the potential mass savings that can be achieved for launch-vehicle structures by revising the existing buckling design recommendations can be made from this two-part study.

In the following sections, first, the results of buckling design sensitivity studies are presented, then the imperfection sensitivity studies of the Ares V and SLS structures are described separately. These sections are followed by a presentation and discussion of the results from those studies, and finally by concluding remarks.

BUCKLING DESIGN SENSTIVITY

In this first part of the study, the sensitivity of launch vehicle structural designs to the buckling knockdown factor is explored by optimizing the acreage designs of four launch-vehicle structures using a range of buckling knockdown factors. For all the designs, the structures were considered to be honeycomb-core sandwich composites with aluminum core and unidirectional IM7/8552 facesheets with varying layups and open-hole compression strengths. For the four considered structures, the maximum enveloping axial compression line load for each structure was used as the design load.

Ares V Design Sensitivity

The structural optimization software, PANDA2 [30], has been used for many years to optimize aerospace structures. Among other inputs to this software, the user chooses the structural form, the loads, safety factors, the failure modes to interrogate, and the structural parameters that are used in the optimization. For the current work, two Ares V structures, the Intertank and the Interstage, were selected for optimization. Both these structures were presumed to be 33 ft in diameter; the Ares V Intertank was presumed to be 330-in. long, and the Ares V Interstage was presumed to be 585-in. long. The axial compressive line loads used in this study were 8,000 lb/in. and 4,500 lb/in. for the Ares V Intertank and Interstage, respectively. Both structures were considered to be sandwich composite, with the core being 3.1 pcf Hexcel 5052, 1/8-in. cell size aluminum honeycomb [31]. Additionally, only the acreage designs were considered; that is, details like cutouts, padups, attachment points, etc. were not included in the study. Three different facesheet layups were selected as candidate layups to explore the effects of fiber-angle tailoring on the design sensitivity, and the core thickness and ply thickness (all plies were constrained to have equal thickness) were varied to find optimized constructions for both structures for each chosen knockdown factor. The three chosen layups were *quasi-isotropic* ($[\pm 45/0/90]_{2s}$), *tailored* ($[\pm 45/0/90/0/90/0]_{s}$), and *highly tailored* ($[45/0/-45/0/0/90/0/0/90/0]_{s}$), where the 0° layup direction corresponds to the cylinder axial direction. One common way of representing the tailoring of composite structures is to calculate the percentage of zero-degree plies. Using this metric, the quasi-isotropic layup had 25% zeros, the tailored layup had 43% zeros, and the highly tailored layup had 60% zeros.

PANDA2 is a panel optimization code that uses BOSOR4 [32] to calculate buckling loads and mode shapes. A single optimization analysis was conducted for each combination of structural component and facesheet, with several SUPEROPT executions being conducted to ensure that the minimum-mass design was obtained. SUPEROPT [33] is a process by which PANDA2 automatically generates a series of sequential optimization runs from multiple starting designs to help ensure that the global optimum is achieved. In the current PANDA2 study, skin ply and core thicknesses were the only two design variables, and optimization was carried out for the previously defined line loads. Additionally, clamped boundary conditions were applied to the ends of the cylinders.

SLS Design Sensitivity

The structural optimization software, HyperSizer [34], was used to develop optimized designs for two SLS structures, the Upper Stage Aft Skirt and the Interstage, over a range of design knockdown factors from 0.50 to 0.90. Both structures were presumed to be 27.5-ft.-diameter cylinders. The SLS Upper Stage Skirt was considered to be moderately loaded and 5.83-ft long (to give a very low length/diameter ratio), and the SLS Interstage was more highly loaded and 33.83-ft. long (to give a higher length/diameter ratio more typical of a cylindrical structure). Both structures were considered to be sandwich composite structures, with the core being Hexcel 5052 4.5 pcf 1/8-in. cell size aluminum honeycomb [31]. Unlike PANDA2, HyperSizer can select from a defined set of facesheet layups, and the facesheet layups that were used in the study are shown in TABLE 1. These layups were chosen such that they had a [±45] ply combination on the outer surface, and were balanced and symmetric with no more than four 0-degree plies stacked together and no 90-degree plies stacked together. The HyperFEA feature in HyperSizer was used in the sizing of both SLS structures. HyperFEA is an automatic iteration process in which HyperSizer interfaces with a finite-element analysis and the results therefrom in the sizing process by retrieving the element forces from the finite-element results output file. These forces are then used within HyperSizer to size each structural component via closed-form methods for a wide range of strength and stability failure criteria. After completion of each sizing analysis, HyperSizer updates material properties in the finite-element model for components that have changed. The updated model is reanalyzed with finite-element analysis and a new distribution of element forces is obtained. This procedure is repeated multiple times until a user-defined level of convergence for the structural mass has been achieved. The SLS Upper Stage Aft Skirt was sized using the general-purpose finite-element code Abaqus [35] in the HyperFEA feature, and the SLS Interstage was optimized using the general-purpose finite-element code MSC Nastran [36] in the HyperFEA feature.

For the SLS Upper Stage Aft Skirt, the Hoffman interaction strength failure theory was used for the composite failure theory, and the SP-8007 and energy solution methods, were used for panel buckling in HyperSizer. The use of six plies in the facesheets was considered to be minimum gage, and the honeycomb core thickness was varied from 0.5 in. to 1.5 in. with 0.125-in. increments in this study. The SLS Upper Stage Aft skirt finite-element model had 17,500 Abaqus S4 four-node composite shell elements. The bottom of the structure was fixed in all translational degrees of freedom in a cylindrical coordinate system and the top of the structure was fixed in the radial and circumferential degrees of freedom. The load was applied at the top of the structure at a

center node which and *wagon wheeled* to the nodes along the circumference. After a HyperFEA-sized solution was obtained, a linear buckling analysis was performed using Abaqus to check the global buckling eigenvalue and the effective buckling knockdown factor of the structure was compared to the design buckling knockdown factor; if need be, the core thickness from the HyperSizer solution was increased to satisfy the global buckling requirement.

The SLS Interstage was assessed using the HyperSizer Hoffman interaction strength failure criteria, the HyperSizer SP-8007 closed-form solution buckling failure criteria, and the Nastran Solution 105 linear buckling. For the study, the core thickness was varied from 0.5 in. to 5.0 in. with 0.125-in. increments. The SLS Interstage finite-element model had 26,520 Nastran CQUAD4 four-node shell elements with PCOMP properties. The boundary conditions and loads were applied in a manner analogous to those used for the SLS Upper Stage Aft Skirt. That is, the Interstage was fixed at center nodes at both the top and bottom, these center nodes were wagon wheeled to the nodes along the circumference, the central top node had a compression load applied.

BUCKLING IMPERFECTION SENSTIVITY

As discussed in the Introduction, there are a number of strategies to analytically explore the imperfection sensitivity of shell structures. The preferred method is to apply characteristic imperfections from an established manufacturing process to analytical or finite-element models and run geometrically nonlinear analyses to predict realistic buckling loads. However, such imperfections from an established manufacturing process were not available for the present study. Therefore, to investigate the imperfection sensitivity of the optimized designs from the previous section, the radial imperfection (deviation from a best-fit cylinder) of a 13-ft-diameter fluted-core sandwich composite barrel was measured (Figure 2). This particular barrel was made from five panels joined with longitudinal scarf joints at the locations shown in the figure; because the joints and padups at the ends add some extra material to the shell wall and only the outer shape was considered, the largest radial imperfections were associated with the joints and padups even though the models in the present study did not consider such joints. The measured imperfection shape was scaled (in both length and circumference) to the geometry of the considered structures, and the amplitude of the measured radial imperfection was varied. This scaled imperfection was then applied to finite-element models based on the previously discussed optimized designs, and geometrically nonlinear finite-element analyses were performed to determine the nonlinear buckling responses and loads. The chosen amplitudes were zero (no imperfection), equal to the as-measured imperfection amplitude, the as-measured imperfection amplitude linearly scaled with diameter from 13-ft diameter to the considered diameter, ten times the as-measured imperfection amplitude, and twenty-five times the as-measured imperfection amplitude. For each considered design, a linear bifurcation buckling analysis of the perfect geometry and geometrically nonlinear analyses for each of the imperfection amplitudes were performed.

Ares V Intertank Imperfection Sensitivity

The general-purpose finite-element code, STAGS [37], was used to explore the imperfection sensitivity of the Ares V Intertank designs for the quasi-isotropic, tailored,

and highly tailored optimized designs for the 0.65 design knockdown factor. The finite-element models had 29,869 STAGS 410 four-node shell elements with layered composite properties and simply supported boundary conditions with tangential and radial displacements and axial and radial rotations fixed. Additionally, the axial displacement was fixed on the bottom of the cylinder. The top edge of the cylinder is constrained to remain planar and perpendicular to the rotational axis by setting all displacements to be equal. Load was applied by applying a point load to a single node on the top edge in a geometrically nonlinear static analysis.

SLS Imperfection Sensitivity

The general-purpose finite-element analysis code, Abaqus, was used to explore the imperfection sensitivity of the SLS Upper Stage Skirt and the SLS Interstage for the optimized designs for all of the considered design knockdown factors. The Upper Stage Skirt finite-element model was as described in the SLS Design Sensitivity section. The Interstage model had 26,520 Abaqus S4 four-node, composite shell elements and used boundary and loading conditions as described in the SLS Design Sensitivity section. The SLS analyses were run in two steps: first, a geometrically nonlinear static step to about 80% of P_{cr}, then a geometrically nonlinear transient step through the buckling event. For the SLS imperfection sensitivity study, the padups were removed and therefore, not included in the imperfection applied to the models.

RESULTS AND DISCUSSION

Buckling Design Sensitivity

The results of the PANDA2 optimization study of the Ares V structures are summarized in TABLE 2 and TABLE 3, and presented graphically in Figure 3 and Figure 4. In particular, the design knockdown factor, optimized facesheet thickness, core thickness, and acreage areal mass (including the facesheets, core, and a total of 0.16 psf for the facesheet-to-core adhesive) are given for all of the considered Ares V Intertank cases in TABLE 2 and the Ares V Interstage cases in TABLE 3. These same results are presented graphically in Figure 3 and Figure 4.

The acreage areal mass is shown as a function of the design buckling knockdown factor in Figure 3 for both Ares V structures and all three facesheet layups. For the Ares V Intertank (Figure 3a), the quasi-isotropic designs have the highest areal masses and the highly tailored designs have the lowest areal masses for all design knockdown factors. For the Ares V Interstage (Figure 3b), the quasi-isotropic designs also have the highest areal masses. For the knockdown factors from 0.6 to 0.8, the Ares V Interstage tailored designs have the lowest areal masses, but for the knockdown factor of 0.9, the highly tailored design has the lowest areal mass. Additionally, for both Ares V structures, the quasi-isotropic designs are the least sensitive to the design knockdown factor and the highly tailored designs are the most sensitive to the design knockdown factor—that is, a change in the knockdown factor used in the design would have a larger effect on areal mass of a structure with more highly tailored facesheets than one with less tailored facesheets. The reductions in areal mass can be calculated from the values given in TABLE 1 and TABLE 3 over the range of knockdown factors from 0.6 to 0.9. For the Ares V Intertank, these reductions are 6.1%, 9.4%, and 13.6%, for the quasi-

isotropic, tailored, and highly tailored layups, respectively. For the Ares V Interstage, these reductions range are 8.0%, 13.0%, and 18.0% for the quasi-isotropic, tailored, and highly tailored layups, respectively. By this measure, the Ares V Interstage designs are more sensitive to the value of the design knockdown factor than the Ares V Intertank designs.

The optimized core and facesheet thicknesses for the Ares V Intertank and the Ares V Interstage are presented graphically as a function of the buckling knockdown factor in Figure 4. For all of the cases, there is little variation of the facesheet thickness with knockdown factor; in fact, the only case that shows any variation of the facesheet with knockdown factor is the highly tailored Ares V Interstage case. Therefore, in this study it is observed that the facesheets are sized to carry the in-plane (membrane) loads and the core is sized to meet the buckling requirements, and that the changes in areal mass for each case shown in Figure 3 are due almost entirely to changes in the core thickness. It should also be noted that for all design buckling knockdown factors for both the Ares V Intertank and the Interstage, the quasi-isotropic design had the thickest facesheets and the thinnest core, and the highly tailored design had the thinnest facesheets and the thickest core. The core thicknesses were also quite large for the highly tailored shells with the low design buckling knockdown factors, so some of these designs may not be good choices in practice.

Consider next the SLS structures. The optimized layup, honeycomb core thickness, and areal mass (including a total of 0.16 psf for the facesheet-to-core adhesive) are shown in TABLE 4 and TABLE 5 as a function of the design knockdown factor for the SLS Upper Stage Aft Skirt design study and the Interstage, respectively. All core thicknesses were optimized to between 0.750 in. and 1.625 in., and were within the limits used for this study.

The HyperSizer-optimized acreage areal mass is shown as a function of the design knockdown factor in Figure 5 for both SLS structures. The areal mass for both SLS structures is monotonically decreasing with increasing design knockdown factor, and the more highly loaded SLS Interstage has higher areal mass than the SLS Upper Stage Skirt. Over the range of knockdown factors from 0.5 to 0.9, the areal mass was reduced by 23.1% for the SLS Upper Stage Skirt, and by 17.4% for the SLS Interstage. The optimized core and facesheet thicknesses for both SLS structures are shown as a function of the design knockdown factor in Figure 6. As with the general trend of the PANDA2 results for the Ares V structures discussed above, the core thickness of the SLS Interstage monotonically decreased with increasing design knockdown factor, and the facesheet thickness remained constant. In contrast, the core thickness of the SLS Upper Stage Aft Skirt did not monotonically decrease with increasing design knockdown factor, and the facesheets did not remain constant. This was seen in part because the facesheet layup was changing as well as the core and facesheet thicknesses. As discussed earlier, HyperSizer has this flexibility to select from the predefined family of layups, whereas PANDA2 does not.

The knockdown factors recommended by SP-8007 are calculated based on the geometry and shell stiffnesses, and can therefore be calculated for the optimized designs generated by this study. If the calculated SP-8007 knockdown factor is lower (more conservative) than the design knockdown factor for that optimized design, then that particular design would not meet the SP-8007 recommendations. Such Ares V and SLS designs that do not meet the SP-8007 guidelines are circled in red in Figure 3 and Figure 5, respectively. It is seen that the thinner, lower-mass designs generated with the higher

design knockdown factors do not meet these guidelines. If these current guidelines are overly conservative, then much of the potentially important design space is eliminated by following these guidelines and there is potential for mass savings through knockdown factor improvement.

Buckling Imperfection Sensitivity

Results from the Ares V Intertank imperfection sensitivity study are presented in Figure 7. In this figure, the normalized buckling loads are plotted for the three different facesheet layups. These normalized buckling loads are the knockdown factors calculated from SP-8007 for orthotropic shells and the nonlinear buckling analyses as P_{cr}/P_{bif}, where P_{cr} is the nonlinear buckling load of the imperfect shell and P_{bif} is the linear bifurcation buckling load of the corresponding idealized geometrically perfect shell. Nonlinear analyses were performed with imperfection amplitudes between zero and 3.75 in.

Results from the SLS Upper Stage Skirt and SLS Interstage are presented in Figure 8a and Figure 8b, respectively. In these figures, the normalized buckling loads calculated from SP-8007 for orthotropic shells and from the nonlinear buckling analyses are presented for each of the optimized designs for both structures. Nonlinear analyses were performed on these structures with imperfection amplitudes between zero and 3.47 in. (Note: the maximum amplitude used for the SLS structures is smaller than that used for the Ares V Intertank because, as discussed above, the padups were not considered in the imperfection shape applied to the SLS structures.)

In Figure 7 and Figure 8, it is seen that the nonlinear-perfect normalized buckling loads for most of the considered cases is quite close to unity; that is, the nonlinear buckling loads are quite similar to the linear bifurcation buckling loads for these cases. However, the nonlinear-perfect normalized buckling load for several of the designs is near 0.9 or lower for the nonlinear perfect analysis; this result indicates that there is a significant nonlinear response that cannot be captured with the linear bifurcation buckling analysis. More study is needed to fully understand why some of the designs show this nonlinear effect and others do not. Despite this, for each of the considered cases, there is little sensitivity to small imperfections when comparing the nonlinear perfect analysis to those with small imperfections (≤0.37 in.)—in fact, only the SLS Interstage 0.9-design-buckling-knockdown-factor case has more than 2.5% difference between the nonlinear perfect and the two smallest nonzero imperfections. Additionally, the SP-8007 knockdown factor recommendation is the lowest normalized buckling load for each case except for the Ares V quasi-isotropic case where the normalized buckling load for the largest imperfection is just slightly lower than the SP-8007 recommendation. That is, for the given imperfection shape even imperfections with amplitudes approaching or greater than 3.5 in. do not produce knockdown factors lower than the SP-8007. This imperfection amplitude is very large and it is unlikely geometry deviations this large would be seen in any real launch vehicle.

More work needs to be completed before actual recommendations can be made, but Figure 7 and Figure 8, coupled with Figure 3 and Figure 5 can be used to estimate the reductions in acreage areal mass that can be achieved by revising the SP-8007 design recommendations. For example, if the observation that for imperfection amplitudes less than or equal to 1.5 in. the normalized buckling loads are greater than 0.8 for all cases is used to justify using a design knockdown factor of 0.8, the approximate reductions in

acreage areal mass can then be estimated using the data in Figure 3 and Figure 5. Using this approach, and considering only the example cases presented in the figures, it is estimated that the reductions in acreage areal mass could be between 4% for the Ares V quasi-isotropic Intertank and 19% for the SLS Upper Stage Aft Skirt.

CONCLUDING REMARKS

Thin-walled composite sandwich shell structures have been used in launch vehicles for many years. However, the buckling design guidelines from NASA SP-8007 that are currently used for launch vehicles were not developed with data from tests of composite cylinders and are thought to be overly conservative for most modern launch-vehicle configurations. The NASA Shell Buckling Knockdown Factor Project (SBKF) was established to address these shortcomings and to revise the buckling design guidelines for metallic and composites launch-vehicle structures. The two-part study described in this paper was used to examine the relationship between the design buckling knockdown factor and the acreage areal mass of optimized designs, and the buckling imperfection sensitivity of those optimized designs to better understand how much the acreage areal mass of composite launch-vehicle structures can be reduced by updating the buckling design recommendations. It was found that varying the design buckling knockdown factor from 0.6 to 0.9 reduced the acreage areal mass between 6.1% and 19.6%, and that most of the considered structures showed little buckling sensitivity to all but very large imperfections. Overall, it is estimated that revising the buckling design recommendations has the potential to reduce the acreage areal mass between 4% and 19%, depending on the structure.

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TABLE 1. SLS STRUCTURE PLY LAYUPS EXAMINED

Number of Plies	Layup Tailoring (%0, %45, %90)	Layup
7	(15, 57, 29)	$[\pm45/90/\overline{0}]_s$
7	(29, 57, 14)	$[\pm45/0/\overline{90}]_s$
8	(25, 50, 25)	$[\pm45/90/0]_s$
9	(22, 44, 33)	$[\pm45/90/0/\overline{90}]_s$
9	(33, 44, 22)	$[\pm45/0/90/\overline{0}]_s$
9	(33, 44, 22)	$[\pm45/90/0/\overline{0}]_s$
9	(44, 44, 11)	$[\pm45/0/0/\overline{90}]_s$
10	(40,40, 20)	$[\pm45/90/0/0]_s$
11	(36, 36, 27)	$[\pm45/90/0/0/\overline{90}]_s$
11	(36, 36, 27)	$[\pm45/90/0/0/\overline{90}]_s$
12	(33, 33, 33)	$[\pm45/90/0/90/0]_s$
13	(38, 31, 31)	$[\pm45/90/0/90/0/\overline{0}]_s$

TABLE 2. ARES V INTERTANK OPTIMIZED FACESHEET THICKNESS, CORE THICKNESS, AND ACREAGE AREAL MASS

Facesheet layup	Design KDF	Facesheet thickness (in.)	Core thickness (in.)	Acreage areal mass (lb/ft^2)
	0.6	0.153	1.74	3.12
	0.65	0.153	1.60	3.08
Quasi-isotropic	0.7	0.153	1.46	3.04
	0.8	0.153	1.23	2.99
	0.9	0.153	1.03	2.93
	0.6	0.109	2.78	2.66
	0.65	0.109	2.58	2.61
Tailored	0.7	0.109	2.39	2.56
	0.8	0.108	2.06	2.47
	0.9	0.109	1.80	2.41
	0.6	0.082	4.10	2.57
	0.65	0.082	3.82	2.50
Highly Tailored	0.7	0.083	3.57	2.44
	0.8	0.082	3.11	2.31
	0.9	0.083	2.72	2.22

TABLE 3. ARES V INTERSTAGE OPTIMIZED FACESHEET THICKNESS, CORE THICKNESS, AND ACREAGE AREAL MASS

Facesheet layup	Design KDF	Facesheet thickness (in.)	Core thickness (in.)	Acreage areal mass (lb/ft^2)
Quasi-isotropic	0.6	0.0859	1.72	2.01
	0.65	0.0859	1.59	1.98
	0.7	0.0859	1.47	1.95
	0.8	0.0859	1.26	1.89
	0.9	0.0859	1.08	1.85
Tailored	0.6	0.0612	2.66	1.85
	0.65	0.0612	2.47	1.80
	0.7	0.0612	2.29	1.76
	0.8	0.0612	1.96	1.67
	0.9	0.0612	1.74	1.61
Highly Tailored	0.6	0.0464	3.94	1.94
	0.65	0.0524	3.28	1.87
	0.7	0.0484	3.28	1.80
	0.8	0.0502	2.72	1.69
	0.9	0.0464	2.61	1.59

TABLE 4. SLS UPPER STAGE AFT SKIRT OPTIMIZED FACESHEET LAYUP, CORE THICKNESS, AND AREAL MASS

Design KDF	Number of acreage plies	Acreage layup	Facesheet thickness (in.)	Core thickness (in.)	Acreage areal mass (lb/ft^2)
0.5	9	$[\pm45/90/0/\overline{90}]_s$	0.0468	1.125	1.43
0.6	8	$[\pm45/90/0]_s$	0.0416	1.000	1.29
0.7†	7	$[\pm45/90/\overline{0}]_s$	0.0364	1.125	1.24
0.8	7	$[\pm45/0/\overline{90}]_s$	0.0364	0.875	1.15
0.9	7	$[\pm45/0/\overline{90}]_s$	0.0364	0.750	1.10

†Core thickness had to be increased to satisfy global buckling requirement

TABLE 5. SLS INTERSTAGE OPTIMIZED FACESHEET LAYUP, CORE THICKNESS, AND AREAL MASS

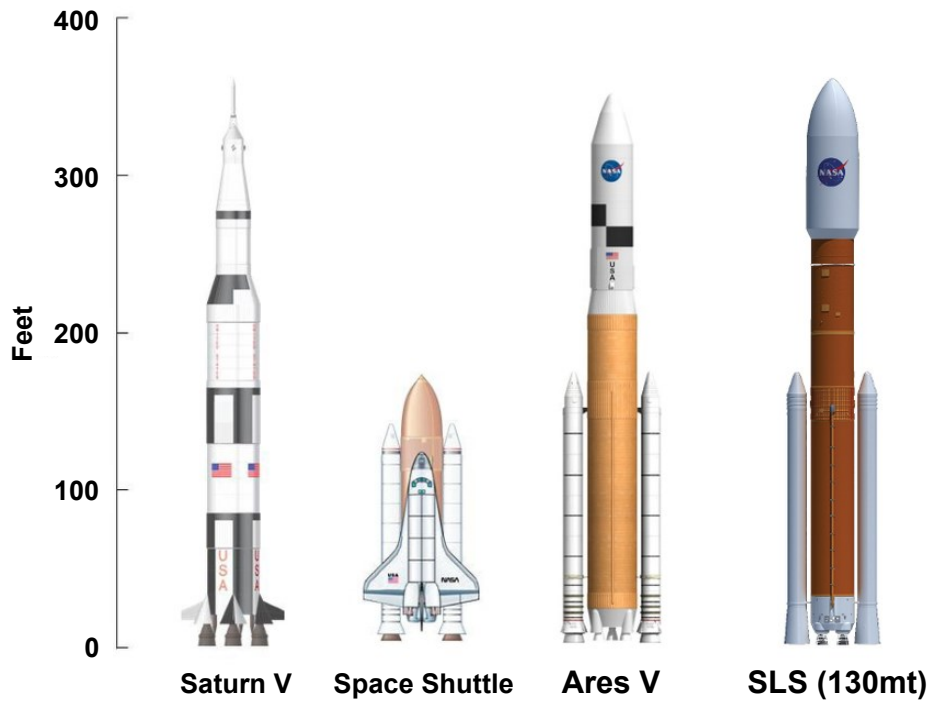| Design KDF	Number of acreage plies	Acreage layup	Facesheet thickness (in.)	Core thickness (in.)	Acreage areal mass (lb/ft^2)
0.5	9	$[\pm45/90/0/\overline{0}]_s$	0.0468	1.625	1.61
0.6	9	$[\pm45/90/0/\overline{0}]_s$	0.0468	1.375	1.52
0.7	9	$[\pm45/90/0/\overline{0}]_s$	0.0468	1.250	1.42
0.8	9	$[\pm45/90/0/\overline{0}]_s$	0.0468	1.000	1.38
0.9	9	$[\pm45/90/0/\overline{0}]_s$	0.0468	0.875	1.33

Figure 1. Comparison of the heights and configurations of the Saturn V, Space Shuttle, Ares V, and SLS vehicles.
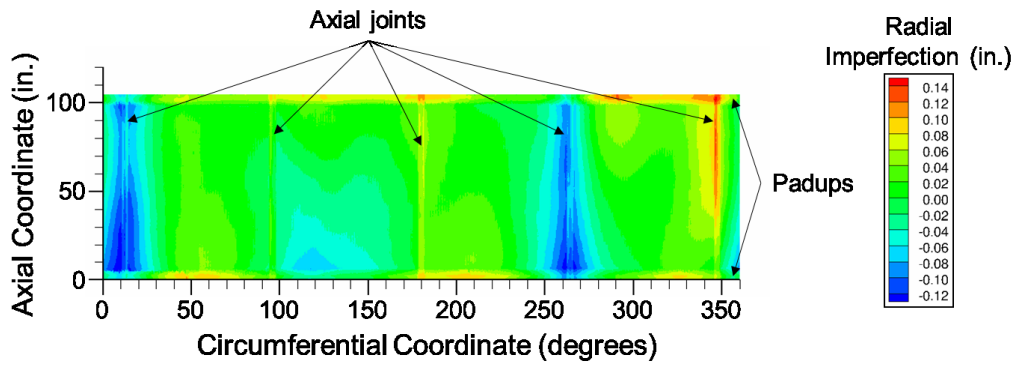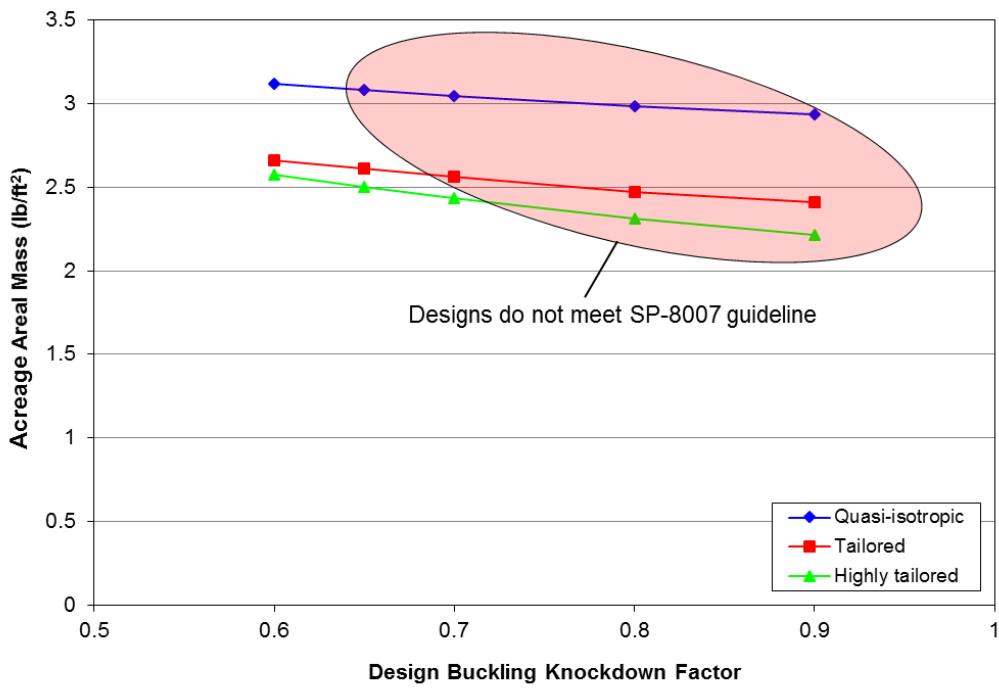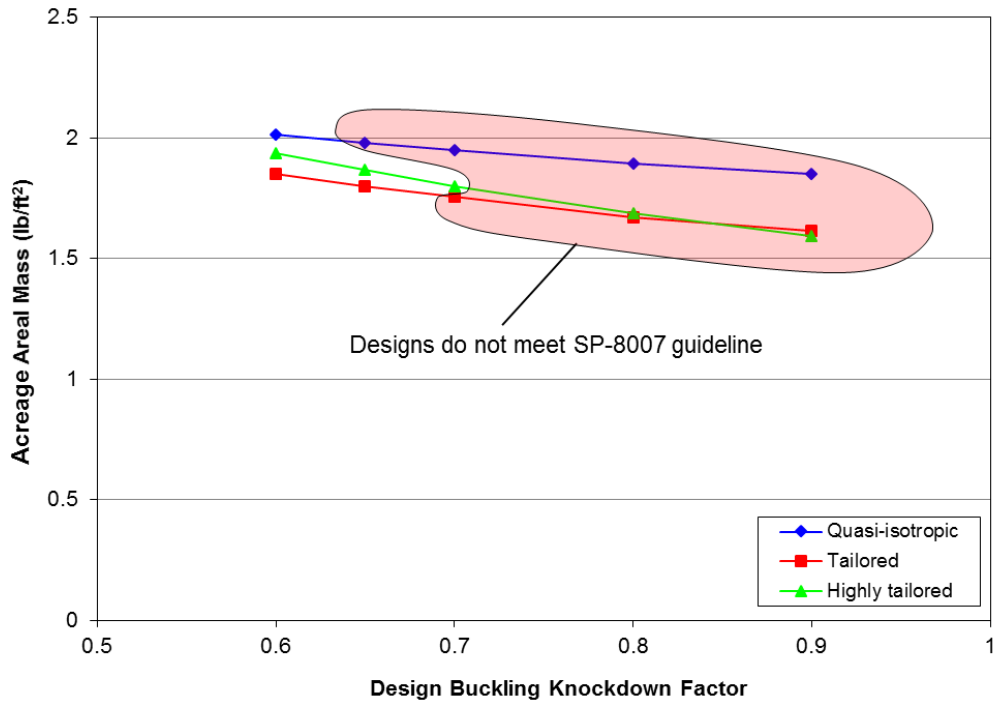

Figure 2. As-measured outer radial imperfection of 13-ft-diameter composite barrel.

(a) Ares V Intertank

(b) Ares V Interstage

Figure 3. Optimized areal mass as a function of buckling knockdown factor for (a) the Ares V Intertank and (b) the Ares V Interstage.
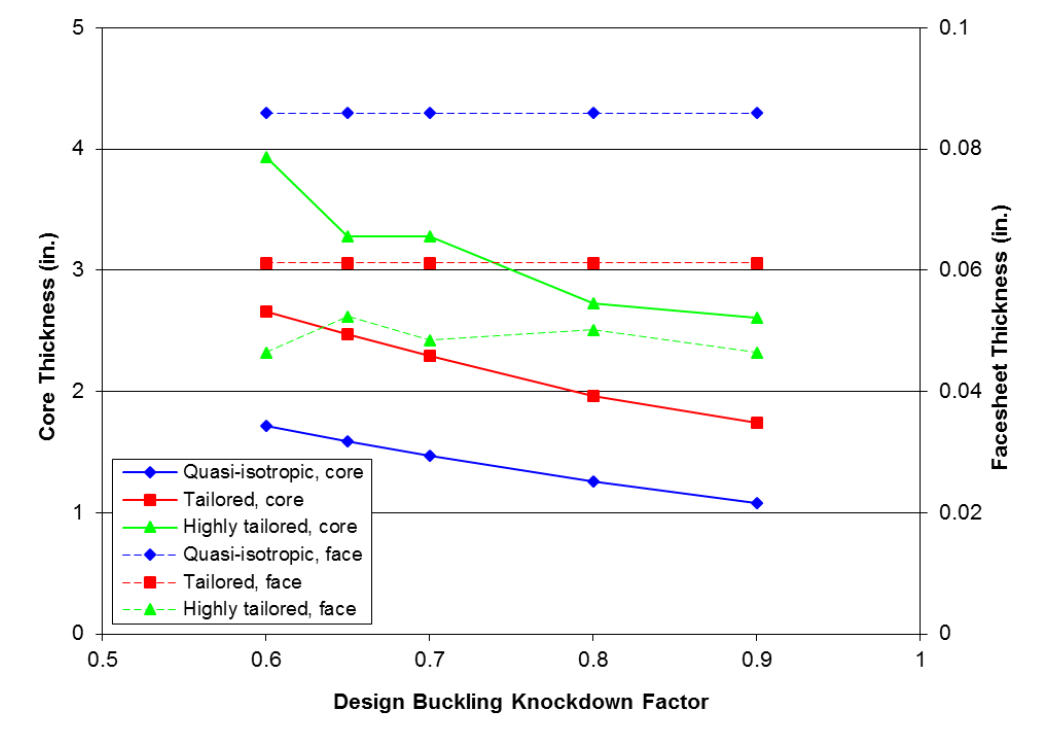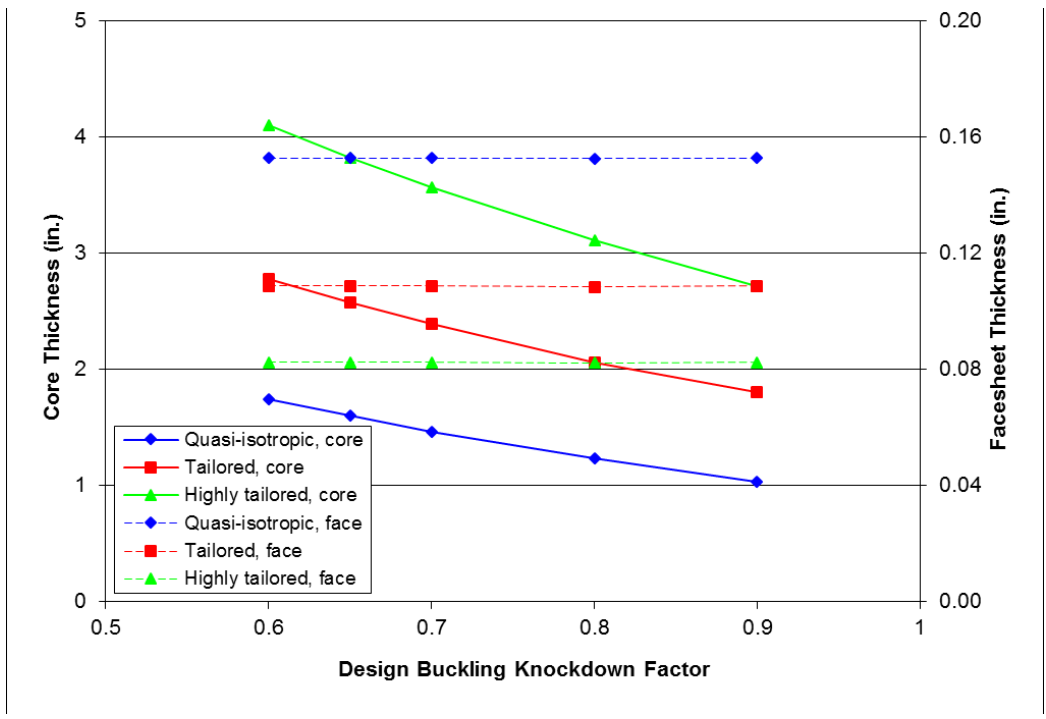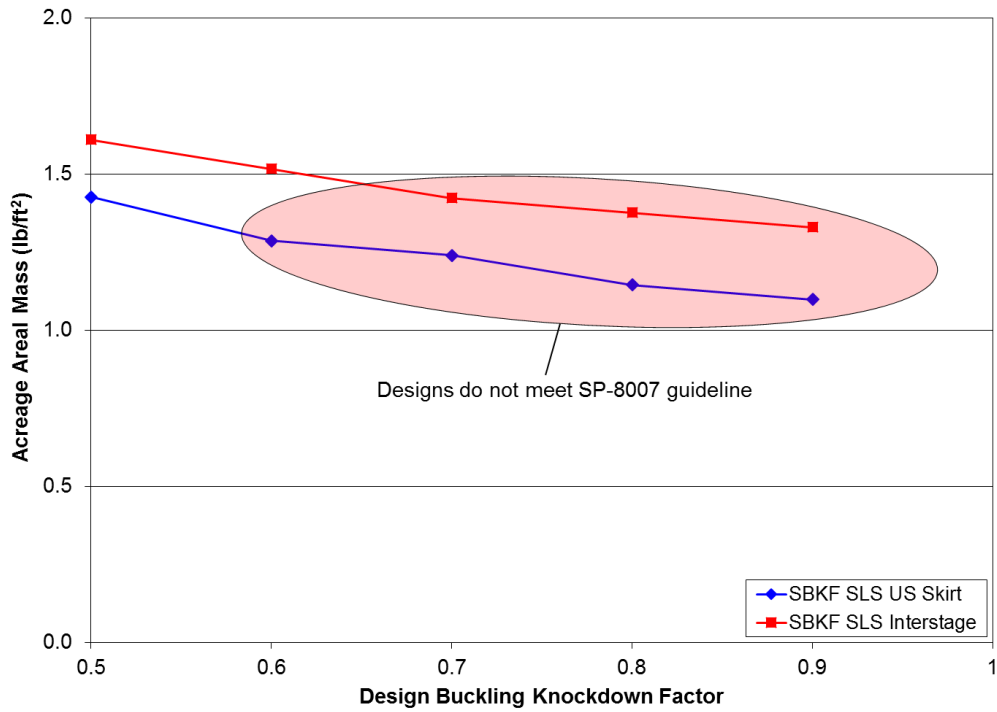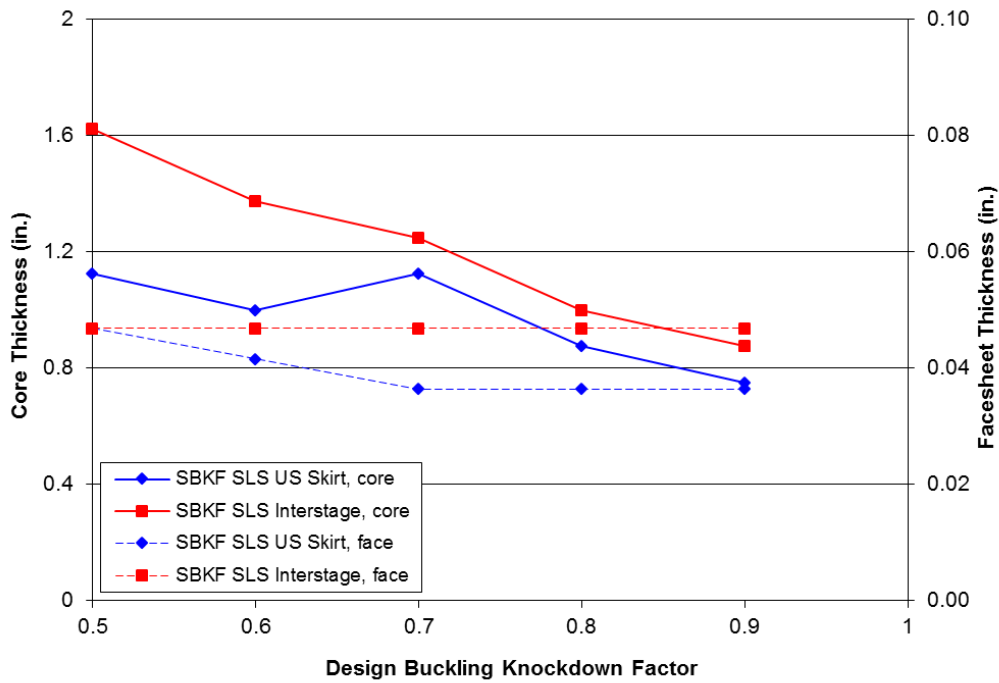
(a) Ares V Intertank

(b) Ares V Interstage

Figure 4. Optimized core and facesheet thicknesses as a function of buckling knockdown factor for (a) the Ares V Intertank and (b) the Ares V Interstage.

Figure 5. Optimized areal mass as a function of buckling knockdown factor for the SLS Skirt and SLS Interstage.

Figure 6. Optimized core and facesheet thicknesses as a function of buckling knockdown factor for the SLS Skirt and SLS Interstage.
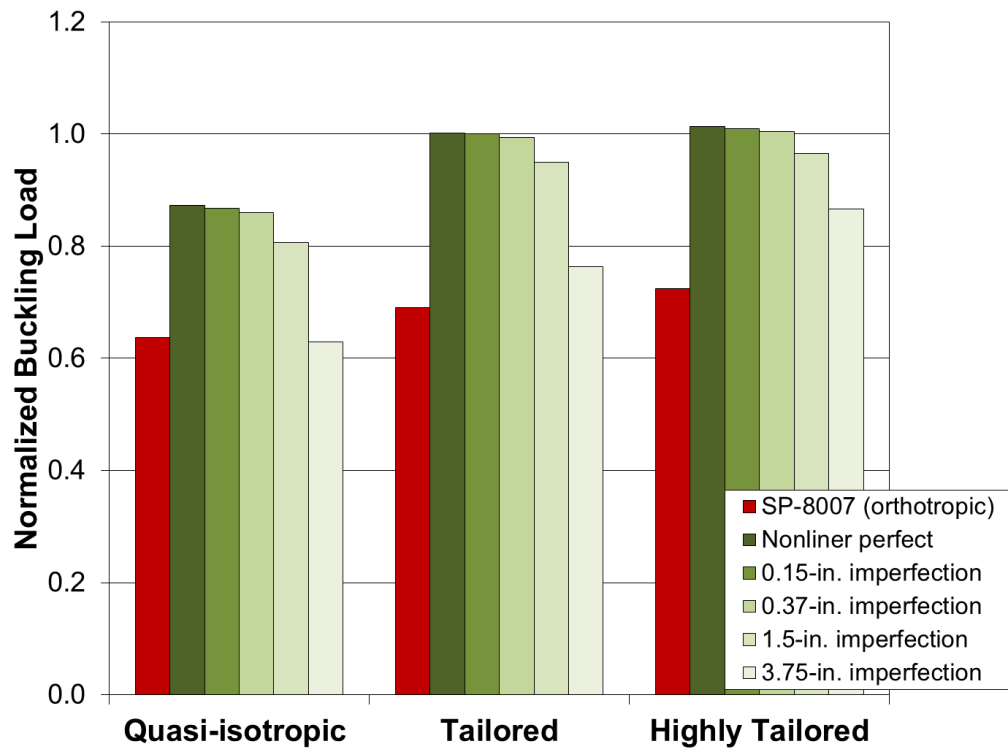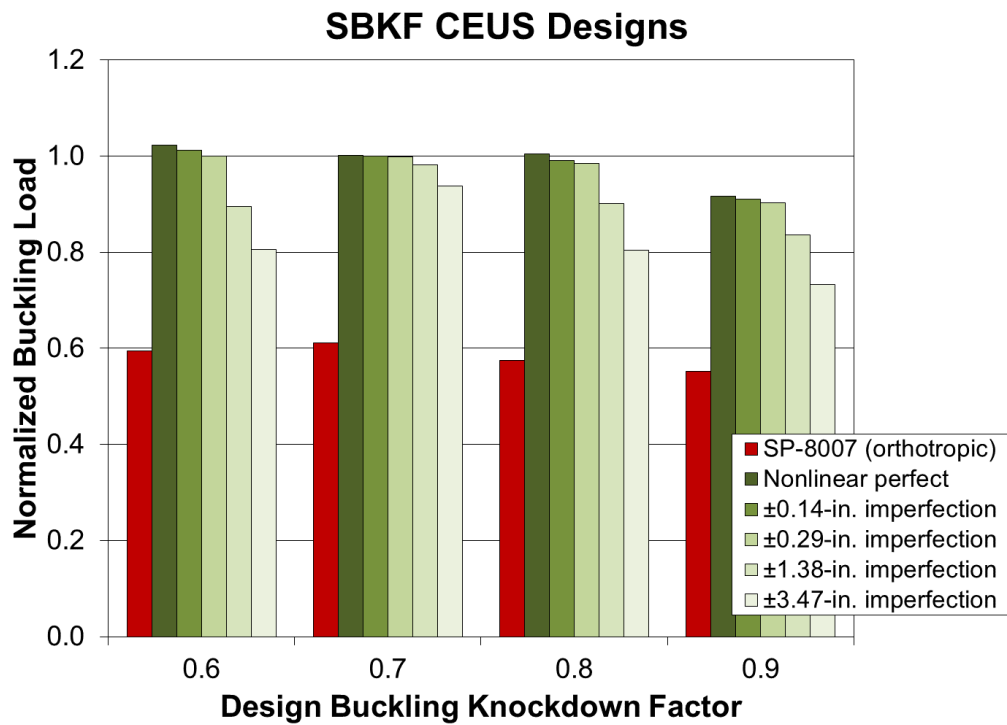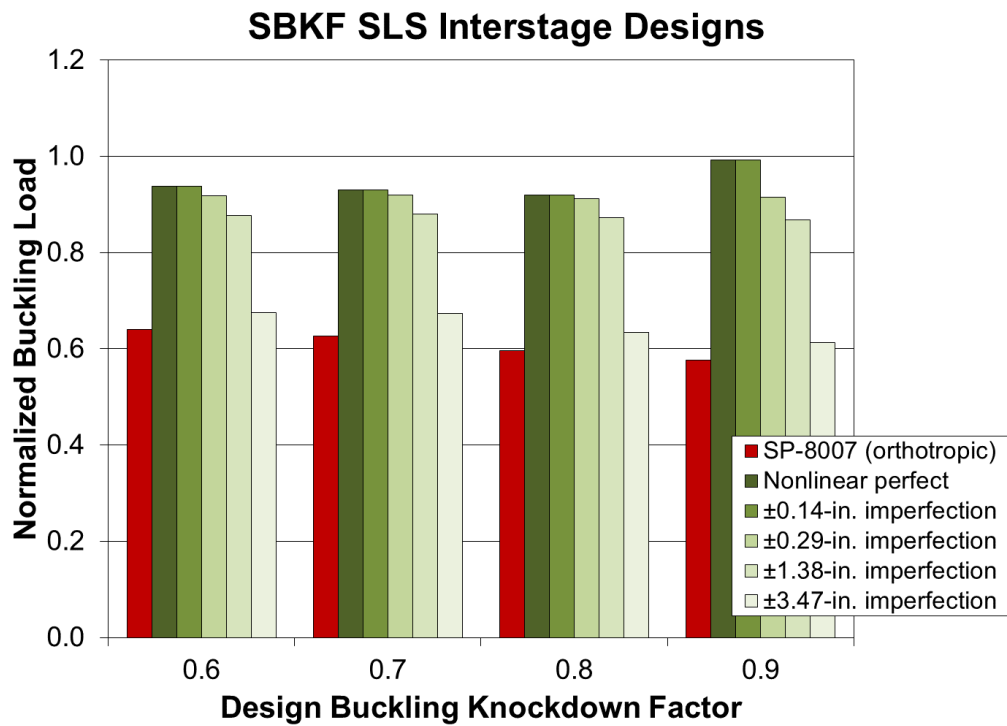
Figure 7. Imperfection sensitivity of the optimized Ares V Intertank designs for knockdown factor of 0.65.

(a) SLS Skirt

(b) SLS Interstage

Figure 8. Imperfection sensitivity of the optimized (a) SLS Skirt and (b) SLS Interstage designs.