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Axial-Weld Land Buckling in Compression-Loaded Orthogrid Cylinders

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Large stiffened cylinders used in launch vehicles, such as the space shuttle external tank, are manufactured by welding curved panels into complete barrels. The effects of the axial-weld lands between the panels on the buckling strength of unpressurized cylinders are studied, along with the interaction between the acreage stiffener arrangement and the weld land geometry. The relatively thick, unstiffened axial-weld lands are shown to significantly reduce the buckling load when the cylinder is loaded in uniform axial compression, and a relationship between the reduction in buckling load and the orthogrid design is shown. Reducing the width of the weld lands is shown to be the most effective means of minimizing the reduction in buckling strength, and thicker weld lands are shown to not always increase their buckling resistance. Detailed models with individual stiffeners modeled as beams are used to show that the weld land buckling phenomenon is very sensitive to the specific location and geometry of stiffeners near the axial-weld lands. It is also shown that the buckling strength can be significantly improved by ensuring that the distance between the weld land and the adjacent longitudinal stiffener is minimized.

Nomenclature

A_{ij} = extensional stiffness matrix, lb/in.
B_{ij} = bending-extension coupling matrix, lb
br = ring spacing, in.
bs = longitudinal stiffener spacing, in.
D_{ij} = bending stiffness matrix, in-lb
E = elastic modulus, psi
H = orthogrid height, in.
h = stiffener height from skin, in.
L = cylinder length, in.
ν = Poisson ratio
P_{cr} = total axial load at buckling, kip
R = cylinder outer mold line radius, in.
t = skin thickness, in.
t_{eff} = effective orthogrid thickness, in.
t_r = ring thickness, in.
t_s = longitudinal stiffener thickness, in.
t_w = weld land thickness, in.
w = total axial-weld land width, in.

I. Introduction

LAUNCH vehicle shell structures generally require lightweight designs with high bending stiffness in order to resist instability due to the compression loads created by acceleration during accent. Integrally stiffened metallic structures are an efficient design choice for this application because their stiffness and strength can easily be tailored to create an optimal design for a given loading condition. Although stiffeners can be arranged in any arbitrary pattern, typically designers use either an isogrid arrangement [1], with the stiffeners forming equilateral triangular bays, or an orthogrid arrangement [2–5], with the stiffeners forming rectangular bays. The orthogrid arrangement is considered in this work, but the response of isogrid stiffener structures is fundamentally similar to the response of orthogrid structures. By using metallic materials such as aluminum alloys, structural components can be welded together to form large structures such as liquid hydrogen tanks. However, in order to manufacture these structures, unstiffened weld lands have to be designed into the panels at the boundaries of the panels so that they can be clamped and welded together. These weld lands also appear in unstiffened launch vehicle structures, where it is necessary to increase the local thickness form welding [6]. Thus, the assembled structure is not a continuously stiffened shell, but rather a segmented shell with discontinuities created by the weld lands. During initial design of the structure the presence of the weld lands in not taken into consideration, but as will be shown herein, weld lands can have a significantly adverse affect on the buckling strength of the cylinder.

Cylindrical shells are ubiquitous in the structural design of most launch vehicles due to their natural structural efficiency and strength. However, in order to create the integrally stiffened cylinders needed to form most liquid fuel tanks, which are often 15 to 30 ft in diameter, multiple curved panels must be welded together along their axial edges to form a single barrel component. The length and arc width of panels used is governed by size of plate stock available for a given thickness, and often multiple barrels must then be welded together to create cylinders with the desired length. In the current state-of-the-art manufacturing process, panels are machined from flat plat stock, in which excess material is removed to form the stiffeners attached to the inner surface of a thin skin before the panels are formed to the correct cylindrical radius. A weld land region is machined around the edges of the panel and the stiffeners are machined to taper down from their full height and blend into the weld lands, as shown in Fig. 1. The weld lands are typically much thicker than the skin thickness used for the panel acreage, but the outer surface of the weld land is often kept flush with the skin. The thickness of the weld land is usually governed by the need to provide sufficient weld strength when subjected to internal pressure loads. The weld land width is necessary in order to provide a sturdy surface to be used for clamping the panels in position during the welding process, while allowing clearance for the weld tool to travel along the weld line. The thickness of the skin between the weld land and the adjacent longitudinal stiffener is often increased to an intermediate thickness between the skin thickness and the thickness of the weld land. This is done to reduced stresses in this region, but has little influence on the buckling strength of the cylinder, so this and other features, such as Dutton grooves [5], are not considered herein.

There is very little discussion of weld lands available in the open literature, and that which is available [5] focuses on local stresses in the vicinity of the weld land vice buckling strength. These weld lands are known to reduce the linear buckling loads of the cylinder relative

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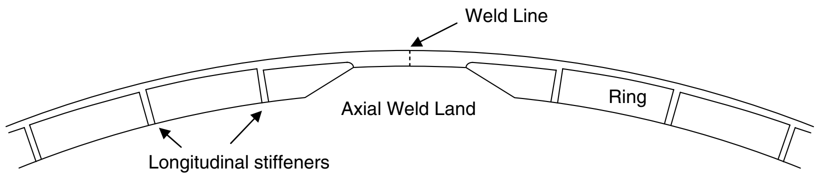

Fig. 1 Typical axial-weld land geometry for a cylindrical barrel.

to ideal cylinders without weld lands, but the mechanism by which this reduction is caused is not fully understood. Part of the reason that the effects of the weld lands are not well understood is that they have traditionally been treated as a manufacturing issue, and are typically added to the design late in the design cycle. Also, traditional closed-form cylinder solutions are not applicable to analysis of cylinders with axial-weld lands, because these cylinders can no longer be treated as shells of revolution. Thus, the adverse effect of the weld lands is often not discovered until a detailed finite element model is constructed and changes to the structural design are more costly.

The objective of this work is to study the influence of the axial-weld lands on the buckling strength of compression-loaded orthogrid cylinders and demonstrate the importance of considering weld land geometry during the design process. The influence of the specific acreage and weld land geometry on the magnitude of the reduction is examined, and the influence of specific modeling details on the predicted buckling load is shown. This information will provide an aid to designers in minimizing the impact of the weld lands on the buckling strength of stiffened cylinder designs, and thereby reduce the structural mass of launch vehicle structures. It should be noted that other influences on the design of launch vehicle barrels, such as material stress limits, pocket buckling, stiffener crippling and the effects of internal pressure are ignored in this work, and separate analysis is needed to study how these phenomena interact with weld land buckling.

II. General Response of Welded Cylinders

To understand the influence of the axial-weld lands on the response of orthogrid-stiffened cylinders subjected to axial compression, an analytical study has been conducted using the structural analysis of general shells (STAGS) finite element code [7]. All cylinders presented herein have an outer radius, R, of 108 in. and an overall length, L, of 162 in. The nomenclature used to define the orthogrid geometry is shown in Fig. 2. It should be noted that most stiffener heights presented in this work are described in terms of the overall plate height, H, as opposed to the height as measured from the skin, h. The cylinders are all loaded by uniform axial end-shortening, and the cylinders are all assumed to be unpressurized. This is accomplished by enforcing a zero-axial-displacement condition at one end, and constraining all nodes at the other end to have the same axial displacement as a single master node. A point force is then applied to the master node to apply an axial load to the cylinder. The loaded ends were assumed to have a clamped boundary condition, in which all nodal rotations and displacements were constrained at the ends. All cylinders are assumed to be made from an aluminum alloy with an elastic modulus of 11.0E6 psi, a Poisson ratio of 0.33, and a density of 0.098 $\mathrm{lbm/in^3}$.

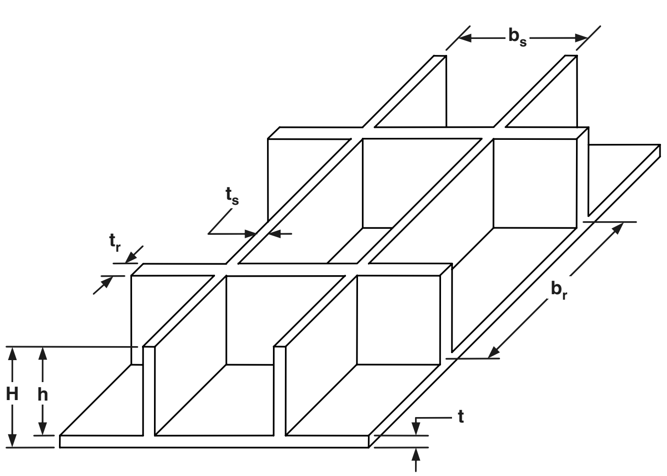

Fig. 2 Nomenclature used to define orthogrid geometry.

Three types of finite element models are used in this work: two that use a smeared-stiffener assumption [3,8] and 1 in.which the stiffeners are approximated as beam elements attached to the skin. The first model based on the smeared-stiffener assumption was a uniform cylinder without any axial or circumferential weld lands. This type of model was used as the baseline reference for the models with weld lands that will be compared with. The stiffnesses for the stiffener skin were not explicitly calculated, but rather the stiffeners were included via the smeared-stiffener shell wall construction capability within STAGS [7]. These models were all meshed with a uniform grid having 90 elements along the longitudinal axis and 360 elements around the circumference. This mesh size ensured that there were at least ten elements per half-wave for all of the linear eigen-mode shapes calculated, thus giving sufficiently converged finite element predictions for the linear buckling loads of the ideal cylinders without welds lands. The second model incorporated the presence of axial-weld lands, but still assumed that the effect of the stiffeners could be modeled by smeared stiffeners within the panel acreage. The mesh around the circumference of the cylinder was broken into segments based on the arc width of the axial-weld lands. Segments corresponding to weld lands were given shell wall properties based on the geometry of the weld lands, while the segments corresponding to the panel acreage were assigned smeared properties based on the orthogrid geometry, just as with the previous model. The purpose of this model was to assess, in a general manner, how acreage design and weld land geometry interact within compression-loaded cylinders. As will be shown later in this paper, the geometric details of the orthogrid stiffeners adjacent to the axial-weld lands have a significant influence on the response of the cylinder and make it difficult to effectively compare different cylinder geometries by using this modeling approach. Specifically, by using smeared-stiffener properties within the acreage, the influence caused by exact location of individual stiffeners can be ignored. This influence is instead captured by the third type of finite element model, which has each discrete stiffener modeled. This model is described in detail in Sec. V.

To understand the response of a typical orthogrid-stiffened cylindrical shell a sample orthogrid design is first considered. The cylinder is first modeled with smeared-stiffener properties, both with and without axial-weld lands. The acreage geometry and dimensions are listed in Table 1 as design 1. The model with axial-weld lands assumes that the cylinder is made from six identical panels, as would be typical for a cylinder of this size. The weld lands extend 2.0 in. to each side of the theoretical weld line, are 0.325-in. thick, and are flush with the outer surface of the skin or outer mold line. When the in-plane and bending stiffnesses of the weld land are compared with the smeared values for the acreage one of the key problems with weld lands is quickly revealed. The weld land has an in-plane stiffness of 4.01E6 lb/in and a bending stiffness about its midsurface of 3.53E4 in.-lb. In contrast, the panel acreage has an effective axial membrane (in-plane) stiffness of 1.67E6 lb/in and a axial bending stiffness about its neutral axis of 1.91E5 in.-lb. This means that the weld land membrane stiffness is over twice that of the acreage, but the bending stiffness is less than a fifth that of the acreage. Thus, when the cylinder is loaded with a uniform axial shortening, the local stress resultant is much greater at the axial-weld lands, while at the same time the weld land has less bending stiffness to resist buckling.

Table 1 **Dimensions (in.) and predicted buckling loads for specific orthogrid designs**

Dimension	Design 1	Design 2	Design 3
t	0.100	0.140	0.060
H	1.30	1.50	0.70
br	7.0	7.0	9.0
t_r	0.100	0.140	0.060
bs	3.0	4.0	3.0
t_s	0.100	0.140	0.060
br	7.0	7.0	9.0
Smeared P_{cr}, kip	3034	4898	698
Smeared with weld land P_{cr}, kip	2693	4326	599
Reduction, %	11.2	11.7	14.2
Detailed model P_{cr}, kip	2487	4146	564
Reduction, %	18.0	15.4	19.2

The predicted buckling load for the cylinder without axial-weld lands is 3034 kips. The predicted linear buckling mode shape for this cylinder, shown in Fig. 3a, is characterized by 4 axial half-waves and 10 full waves around the circumference. Using a model with smeared stiffeners and including axial-weld lands, the predicted linear buckling load was 2693 kips. This is an 11.2% reduction in load carrying capability, in spite of the fact that the weld lands add 3.8% (64 lbs) to the mass of the cylinder. The predicted linear buckling mode shape, shown in Fig. 3b, indicates that the buckling is concentrated along the weld lands. The influence of the weld lands is strong enough to change the displacement pattern into one that shows symmetry based on the six axial-weld lands.

There are other factors that contribute to the reduction in buckling load caused by the axial-weld lands. Figure 4 shows the radial displacement for the cylinder, both with and without axial-weld lands, subjected to a 1000-lb axial load, as calculated by a linear static analysis. In Fig. 4a the radial displacement shows the classic response for a compression-loaded cylinder, with a bending boundary layer at the ends transitioning into a uniform 2.93E-5-in. radial expansion for the majority of the length of the cylinder. The presence of the axial-weld lands, however, changes the linear deformation of the cylinder and creates regions of inward deformation relative to the panel acreage, as shown in Fig. 4b. Relative to the panel acreage, the weld land has a significant coupling between axial compression and circumferential bending which produces large inward bending stresses along the length of the axial-weld lands. From the point of view of resisting buckling during axial compression, this type of deformation is very detrimental to the strength of the cylinder. As discussed above, the axial-weld lands tend to attract stress and reduce bending stiffness, and an inward deformation in this region only further reduces the buckling strength of the cylinder. Because the magnitude of this coupling is influenced by both the acreage geometry and the geometry of axial-weld lands, it would be expected that, by varying the cylinder design parameters, the relative effect of the axial-weld lands on the linear buckling load of the cylinder could be altered.

III. Effect of Acreage Design

A parametric study was conducted on cylinders with axial-weld lands in order to determine how acreage geometry influences the reduction in buckling load caused by the weld lands. The goal was to determine what parameters are most influential, and whether there are any trends that would provide designers with the ability to take into account the effects of the weld lands early in the design process. The linear buckling loads of cylinders modeled with axial-weld lands and smeared-stiffener properties for the panel acreage were compared with the buckling loads for models without weld lands. The use of the smeared models enable an assessment of how acreage design, as described by a small set of parameters, affects the buckling load without having to consider the effect of individual stiffener locations.

The study was performed on a 108-in.-radius cylinder with an overall length, L, of 162 in. The cylinder was assumed to have six

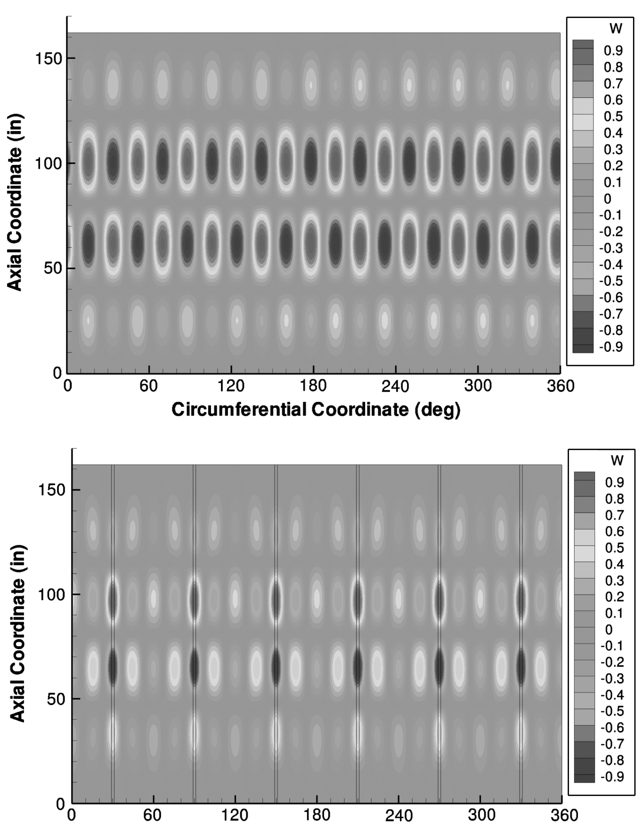

Fig. 3 Predicted buckling mode shape for cylinder design 1 using smeared stiffeners: a) without weld lands and b) with axial-weld lands.

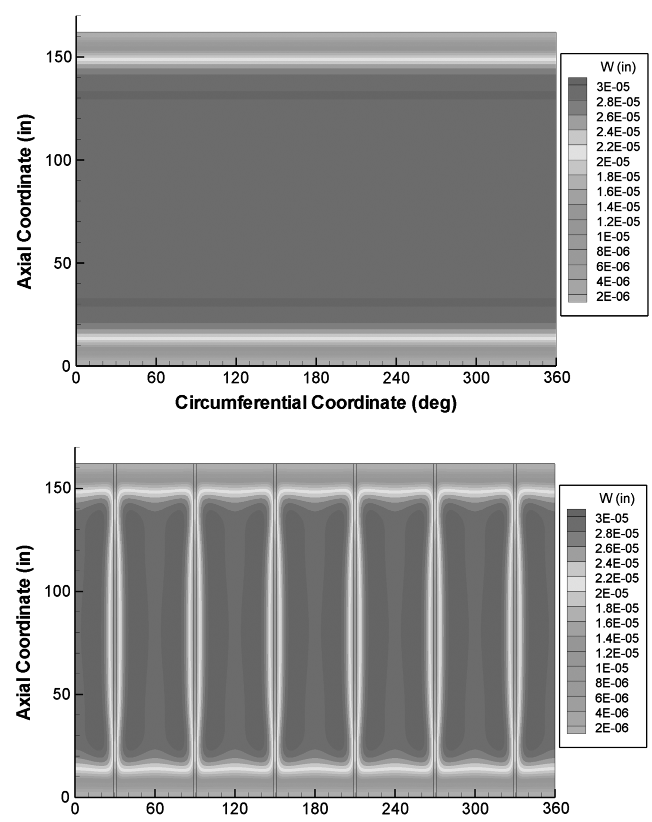

Fig. 4 Predicted radial deformation caused by a 1-kip axial load for cylinder design 1 using smeared stiffeners: a) without weld lands and b) with axial-weld lands.

panels, with 0.325-in. thick weld lands that extend 2.0 in. to each side of the theoretical weld line and are flush with the outer surface of the skin. The four design parameters used were skin thickness (t), orthogrid height (H), longitudinal stiffener spacing (bs), and ring spacing (br). The ring thickness (t_r) and longitudinal stiffener thickness (t_s) were assumed in this study to be equal to the skin thickness, since there was no attempt made to take pocket buckling or stiffener crippling into consideration. This assumption ignores the influence changes in stiffener torsional stiffness have on the buckling load, but it was determined to be necessary in order to limit the number of variables used in this study. The skin thicknesses used were 0.06, 0.08, 0.10, 0.14, and 0.18 in. The orthogrid heights used were 0.70, 0.90, 1.10, 1.30, 1.50, and 1.70 in. The longitudinal stiffener spacings considered were 3.0, 4.0, 5.0, 6.0, and 7.0 in. The ring spacings used were 5.0, 7.0, 9.0, 11.0, and 13.0 in. This yields 750 combinations that span most of the practical design space for large orthogrid cylinders typical for launch vehicle designs. While some of the design parameters, such as the smaller values of H, might not seem appropriate for 108-in.-radius cylinders, they could be considered typical for larger (27–30 ft-diam) designs scaled down to 18-ft diameter, since the thickness of some aluminum alloy plate stock is limited by manufacturing constraints.

To compare the results for the different orthogrid geometries, an effective cylinder wall thickness is used:

$$t_{\text{eff}} = \sqrt[4]{\frac{144 D_{11} D_{22}}{A_{11} A_{22}}} \tag{1}$$

This thickness is essentially the ratio of bending stiffness to axial stiffness and can be thought of as representing the efficiency of the orthogrid design from a buckling standpoint. For reference, the axial buckling load for the cylinders without weld lands as a function of t_{eff} is shown in Fig. 5. For a given skin thickness, the buckling load is approximately linearly proportional to t_{eff}. Designs on the left end of the graph would be typical in lightly loaded cylinders or very large cylinders with manufacturing limits. Designs on the right end are much more structurally efficient and heavily loaded. Many of these designs would not be practical in launch vehicles, because they would suffer from pocket buckling or stiffener crippling before general instability. For comparison purposes, the classical buckling prediction for an unstiffened shell wall is also shown.

The addition of the axial-weld lands resulted in a reduction of the linear buckling load in all 750 cases, ranging in magnitude from 1.0 to 27.6%. The reduction in axial buckling load as a function of t_{eff} is shown in Fig. 6. Although it was hoped that some overt trend would emerge, it is clear that no single parameter governs the effect of the axial-weld lands on the axial buckling load. However, a careful examination of all of the results does reveal a number of trends. With all other parameters being equal, the reduction in buckling load increases with decreasing skin thickness. Similarly, the reduction in buckling load increases with increasing H, increasing bs, and decreasing br. Thus, the cylinder with $t = 0.18$ in., $H = 0.70$ in., $bs = 3.0$ in., and $br = 13.0$ in. had the smallest reduction in buckling load (1.0%), although this is one of the least efficient and least practical designs. These trends do not bode well for designers, since optimal acreage designs generally involve thin skins, large stiffener heights, and smaller stiffener spacings. Designs with thicker skins probably have a smaller reduction in buckling load, because the difference between the skin thickness and the weld land thickness of the skin is the primary source of the coupling between axial compression and circumferential bending that helps drive the weld land inward during axial compression. Designs with large stiffener heights logically suffer larger reductions in buckling load because the weld lands have even less bending stiffness relative to the acreage. The most useful of these trends is that axially stiff designs ($bs < br$) in general seem to be less affected by the presence of the axial-weld lands than hoop stiff designs ($br < bs$) for a given nominal buckling load. However, as will be shown later, even this trend has limits. It should be noted that although the longitudinal stiffener and ring thicknesses were set equal to the skin thickness in this study, these can also be changed to control the ratio of the hoop stiffness to the axial stiffness and alter the reduction caused by the weld lands.

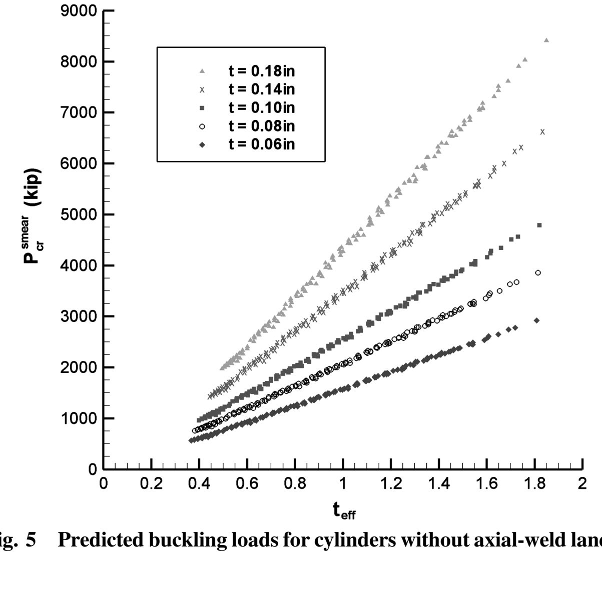

Fig. 5 Predicted buckling loads for cylinders without axial-weld lands.

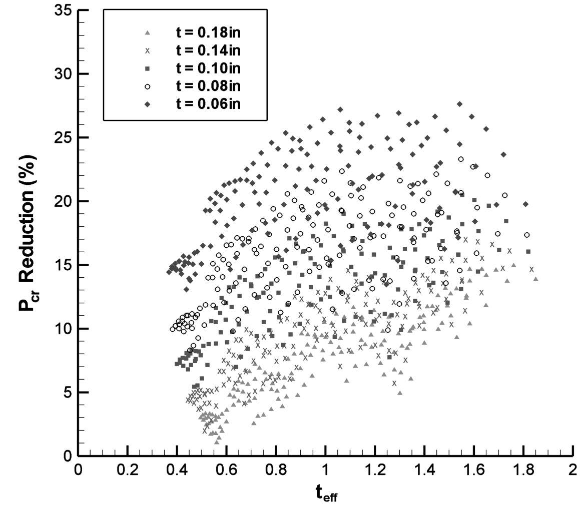

Fig. 6 Predicted buckling loads for cylinders with axial-weld lands.

Since the weld lands, in general, have greater axial stiffness than the panel acreage, the total axial load at buckling may not be the ideal quantity for assessing the reduction of the buckling strength caused by the axial-weld lands. If the weld lands increases the axial stiffness of the cylinder it implies that for a given axial load the axial stress in the acreage is less than in a similar cylinder without the axial-weld lands. Thus, comparison of the average axial strain at buckling may be a better measure of the influence of the weld lands on the buckling performance of a cylinder. The reduction in the average axial strain at buckling as a function of t_{eff} is shown in Fig. 7. The average axial strain is calculated as the ratio of the end shortening displacement at buckling to L. As shown in Fig. 7, the reductions in buckling strength calculated by using the average strain are 2 to 7% larger than the reductions in total axial load, but there is still no clear pattern with respect to t_{eff}. A similar trend can be seen for changes in H, t, br, and bs as was observed in the reduction in buckling load, but there is still no clear method available for estimating the reduction in buckling strength for a given acreage design with explicitly analyzing a model with weld lands present in it.

IV. Effect of Weld Land Design

Next, three designs were chosen to study the effects of varying the weld land geometry. The details of the three designs are listed in Table 1 along with the predicted buckling loads with and without

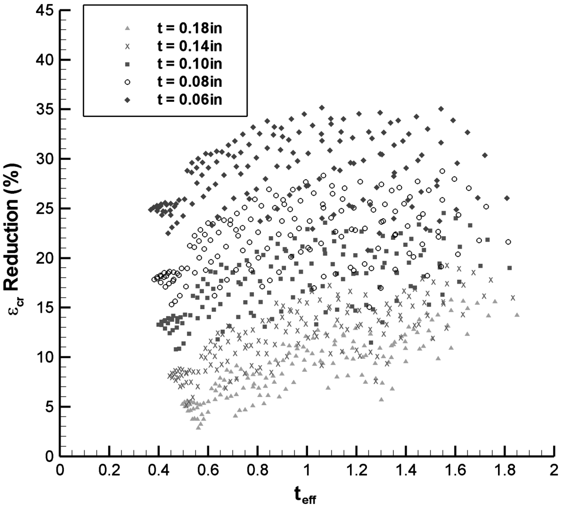

Fig. 7 Reduction in buckling strength caused by axial-weld lands.

axial-weld lands. Although none of these designs could be considered optimal, they are all relatively efficient and can be considered representative of the types of orthogrid designs used in modern launch vehicles. The first design is the design discussed above, and represents a relatively efficient design with moderate load carrying capability. The second design is representative of a very heavily loaded cylinder. The third design is representative of a lightly loaded structure or a scaled version of a very large-diameter cylinder. In all three cases the design was chosen such that general instability would occur before local pocket buckling of the skin or crippling of the longitudinal stiffeners.

For each of the three designs the weld land thickness and width was varied and the linear buckling load was calculated by using the weld land model with smeared-stiffener properties in the acreage. The weld land thickness was varied between 0.15 and 0.40 in., while the total width of the weld land was varied between 1.0 and 6.0 in. The resulting buckling loads for the three acreage designs are shown in Figs. 8–10. Designs 1 and 2 show similar trends; reducing the weld land width consistently increases the buckling strength of the cylinder, but the effect of the weld land thickness is dependent on the weld land width. For relatively narrow weld lands, increasing the

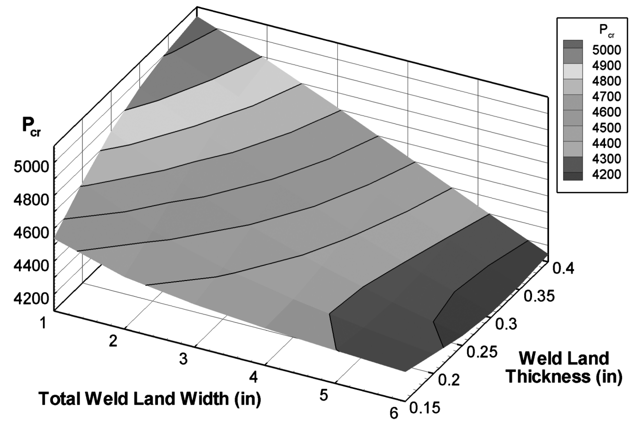

Fig. 9 Predicted buckling loads for cylinder design 2 with varying weld land geometry.

thickness increases the buckling load of the cylinder, but for sufficiently wide weld lands there exists a thickness for which the buckling load is a minimum and below which decreasing the thickness results in an increased buckling load. For the third acreage design the principle of reducing weld land width to increase cylinder buckling load still holds, but the effect of weld land thickness is different. For this design there is an optimal weld land thickness of approximately 0.20 in. for weld land widths less than 3.5 in. For widths greater than this, increasing the weld land thickness increases the buckling strength of the cylinder.

For the designer the consequences of this are clear; the width of the weld lands should be minimized to the limits permitted by manufacturing in order to maximize the buckling strength of the cylinder. Also, the designer should not assume that a thicker weld land adds strength to the cylinder. Nor should a weld land thickness be blindly selected without some analysis or historical design information to determine how thickness influences the buckling load for a particular acreage and weld land width combination.

As discussed above the coupling between axial compression and circumferential bending in the weld land differs significantly from the orthogrid acreage. This difference can be changed by varying the location of the weld land midsurface relative to the skin. Although this may not be practical from a manufacturing standpoint, it is

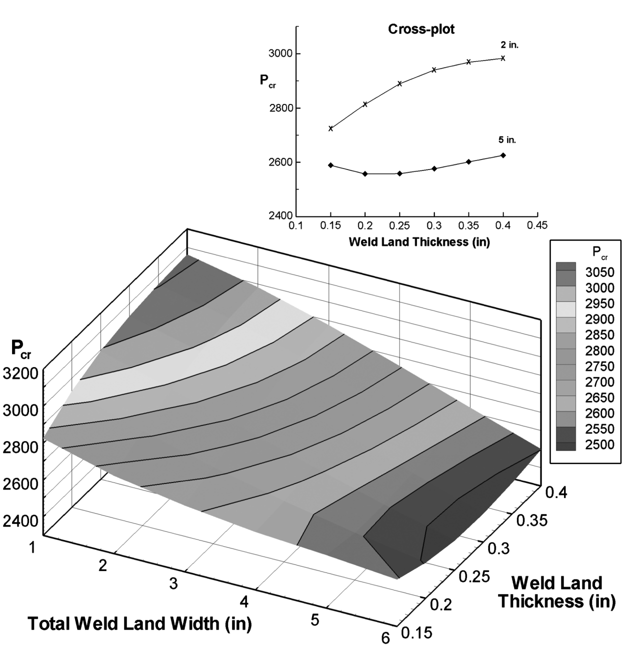

Fig. 8 Predicted buckling loads for cylinder design 1 with varying weld land geometry, including cross-plot for total weld land widths of 2 and 5 in.

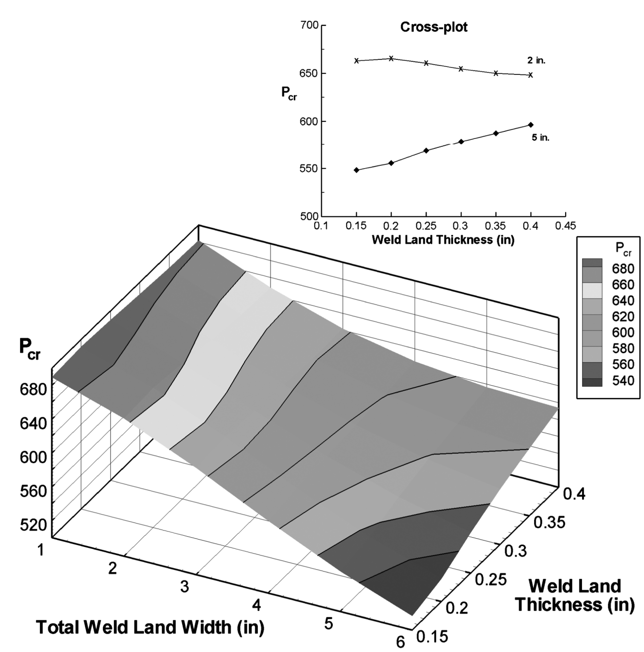

Fig. 10 Predicted buckling loads for cylinder design 3 with varying weld land geometry, including cross-plot for total weld land widths of 2 and 5 in.

valuable to understand the influence the weld land eccentricity has of the buckling response of compression-loaded cylinders. The three designs were analyzed with a varying combination of weld land thicknesses and eccentricities by using the weld land model with smeared-stiffener properties in the acreage. The total weld land width was held constant at 4.0 in., but the weld land thickness was varied between 0.15 and 0.40 in. The eccentricity of the weld land was varied between values of 0.0 and 1.0, with 0.0 corresponding to the traditional arrangement of the outer surface of the weld land being flush with the outer surface of the skin and 1.0 corresponding to an arrangement where the weld land has been shifted radially outward so that the inner surface of the weld land is flush with the inner surface of the skin.

The resulting buckling loads for designs 1, 2, and 3 are shown in Figs. 11–13, respectively. These results indicate that regardless of the weld land thickness, shifting the weld land outward increased the buckling load for all three designs. For designs 1 and 2, this increase was approximately 10% for a 0.325-in.-thick weld land, and for design 3 the increase was approximately 20%. There was only a slight change in the linear out-of-plane deformation created by the uniform axial compression, but the resulting mode shapes showed much less localization along the axial-weld lands. This effect would be very beneficial to take advantage of from a buckling design point of view, but the manufacturing of such a panel would require almost the entire outer surface of the panel to be machined, which increases cost and may complicate the forming of the curvature into the panels.

V. Effect of Local Details

All analysis described up to this point has used models with the effect of the stiffeners incorporated by use of smeared acreage

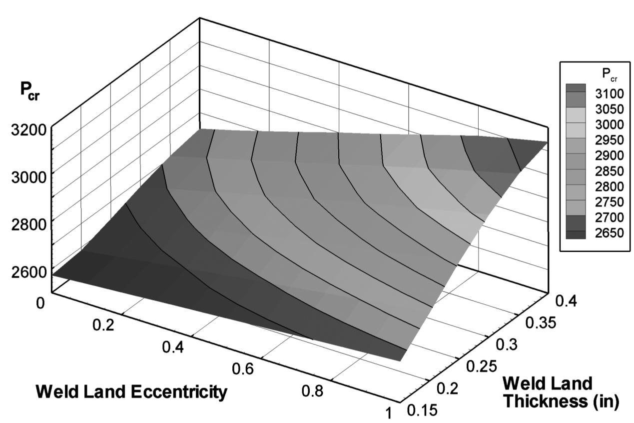

Fig. 11 Predicted buckling loads for cylinder design 1 with varying weld land eccentricity.

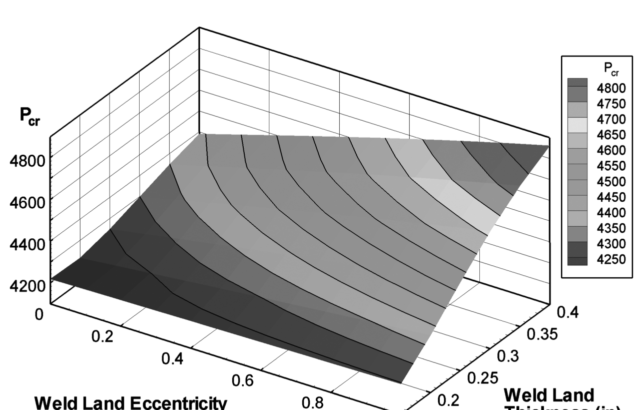

Fig. 12 Predicted buckling loads for cylinder design 2 with varying weld land eccentricity.

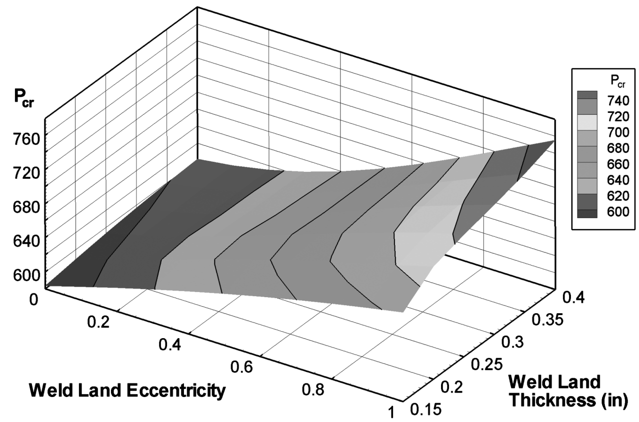

Fig. 13 Predicted buckling loads for cylinder design 3 with varying weld land eccentricity.

properties. While this permits an inspection of the interaction between the orthogrid design and the influence of the axial-weld lands, it omits local effects caused by the exact locations of the individual stiffeners adjacent to the weld lands. As will be shown, these effects can be significant, but local tailoring of the stiffener configuration can be used to improve the buckling load of the cylinder.

The model used to study these effects is a shell model of the cylinder skin which includes both the longitudinal stiffeners and rings by means of STAGS's discrete stiffener feature [7]. In STAGS the stiffeners are modeled as beam elements and coupled to the nodes that comprise the cylinder skin mesh. In addition to the axial-weld lands a 2.0-in.-wide circumferential weld land was added at each end of the cylinder to simulate the typical means used to join cylinder barrels together. The overall length remained 162 in., and these weld lands simply reduced the axial length of the panel acreage. The weld lands were included by changing the shell wall properties for the elements that represented the weld lands. A mesh size of approximately 0.5° was used around the circumference and approximately 1.2 in. was used axially. The exact mesh spacing varied as necessary to align nodes with stiffener locations and the edges of the weld lands.

The predicted buckling loads for the detailed models of designs 1, 2, and 3 are 2487, 4146, and 564 kip, respectively, (kip = 1000 lbf). This corresponds to a reduction from the nominal buckling load without weld lands of 18.0, 15.4, and 19.2%, respectively. All three designs show a larger reduction in buckling load than the models with smeared acreage properties, so clearly the refined modeling details can have a significant influence on the response of the cylinder with weld lands. When the buckling mode shapes are examined, the mode shapes predicted by the detailed model typically show more localization along the axial-weld lands. An example of this can be seen in Fig. 14, which shows the buckling mode shape predicted by the detailed model of design 1. The buckling mode shape for the detailed model shows much less deformation in the acreage away from the weld land than the model with smeared stiffeners and axial-weld lands (Fig. 3b). This design case also shows another change that was often observed in the detailed models, which is an increase in the number of axial half-waves in the mode shape compared with the models with smeared acreage properties.

A. Influence of Adjacent Stiffeners

When going from a smeared acreage design to a detailed design that accounts for each individual stiffener, one of the primary issues the designer is faced with is where to place the first stiffener adjacent to the weld lands. Longitudinal stiffeners and rings typically have transitions where they taper down from their full height to the blend into the weld lands, so the designer is limited in how close the weld land can be to the adjacent parallel stiffener and not interfere with the transitions. Typically, the pocket formed between the adjacent

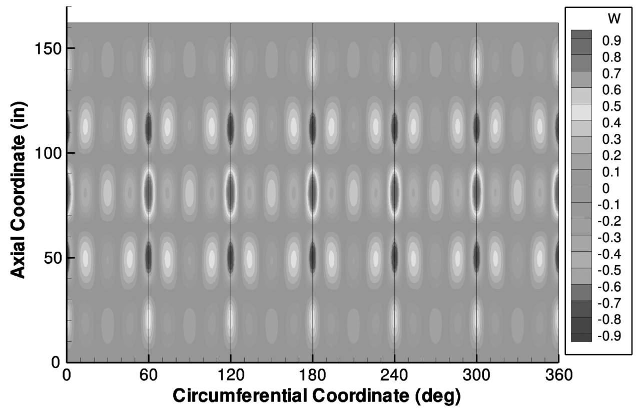

Fig. 14 Predicted buckling mode shape for the detailed model of cylinder design 1.

stiffener and the weld land is roughly the spacing used between individual stiffeners. However, since axial-weld land buckling is dominated by local deformation along the weld land it is expected that the exact location of the adjacent longitudinal stiffeners will influence the buckling load of the cylinder.

To study this effect, the detailed models of the three cylinder designs were modified by increasing the longitudinal stiffener spacing to move the location of the adjacent stiffeners closer to the axial-weld lands. Although it is somewhat counter-intuitive, the objective of this is to see if you can actually increase the buckling load of the cylinder by increasing the stiffener spacing. Since no stiffeners were added the mass of the cylinder remained constant. The results of this study are shown in Fig. 15 with the predicted buckling load normalized by the buckling load of the cylinder with weld lands and smeared acreage properties. The points on the far right edge represent the results for the initial detailed models described above. The values at the far left edge represent the case with the first longitudinal stiffener placed at the edge of the weld land. The resulting longitudinal stiffener spacing within the acreage for this case is 3.12 in. for designs 1 and 3, and 4.20 in. for design 2. These results show that the designer can increase the buckling load by moving the stiffeners closer to the axial-weld lands, even though this means increasing the spacing between the longitudinal stiffeners in the acreage. Interestingly, the effect seems to taper off within a certain distance from the weld land. Practically speaking, this should not be an issue, since the designer must allow a minimum distance between the weld land and the adjacent stiffener for the rings to taper down and blend into the weld land.

B. Ring Spacing

Another effect that was observed when creating detailed models using discrete stiffeners was that there is a limit to which the ring spacing can be increased without adversely affecting the buckling load of the cylinder. As noted above, orthogrid designs with wider ring spacings tended to suffer slightly less reduction in buckling load due to the addition of the axial-weld lands than designs with closely spaced rings. This assessment was based on models using smeared-stiffener properties, but when this concept was tested with detailed models it proved to only be true up until a limiting value for the ring spacing. Above this limit the buckling loads were observed to drop rapidly. The detailed model of design 2 was used as a reference, and a study was performed in which only the ring spacing was changed. To eliminate any possible effects due to movement of the rings adjacent to the two ends of cylinder, the location of these two rings was held constant and the ring spacing was altered by varying the number of rings distributed between these two. Figure 16 shows the buckling load for the detailed models in this study along with the predicted buckling loads for the weld land models with smeared-stiffener properties. For values of *br* less than or equal to 7 in. the detailed models show the same behavior as the smeared-stiffener models, and the buckling mode shape, shown in Fig. 16, shows the same large buckling deformations along the weld land. Above 7 in., the predicted buckling load drops sharply and the buckling mode shape has shifted into a pattern in which the weld land is now buckling between the individual rings. Based on how sharply the buckling load drops, it is clear that an optimal cylinder design will need to maintain a ring spacing above this limiting value. Analysis of the other designs showed that this phenomenon is highly dependent on the acreage and weld land designs, and that it primarily manifests itself in heavily loaded cylinder designs. For the designer, a simple check of the buckling mode shape for a detailed model with discrete stiffeners is likely sufficient to ensure that this interring weld land buckling is not occurring.

VI. Minimizing the Impact

Based on the results above it is clear that the buckling load for compression-loaded cylinders with axial-weld lands is very sensitive to local acreage stiffness adjacent to the weld land. A number of options to improve local bending stiffness are available to the designer. As discusses above, the first adjacent stiffener can be placed as close as practical to the weld land. Also, the longitudinal stiffeners close to the weld land can be reinforced to improve bending stiffness. Similarly, the longitudinal stiffener spacing can be tailored so that the stiffeners are more closely spaced near the weld land than they are towards the center of the panel. Local circumferential bending stiffness is also important and can be modified by reinforcing

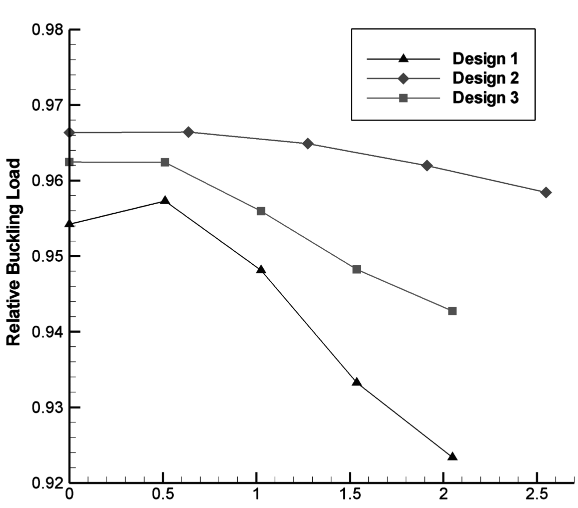

Fig. 15 Influence of the distance between the axial-weld land and the nearest axial stiffener.

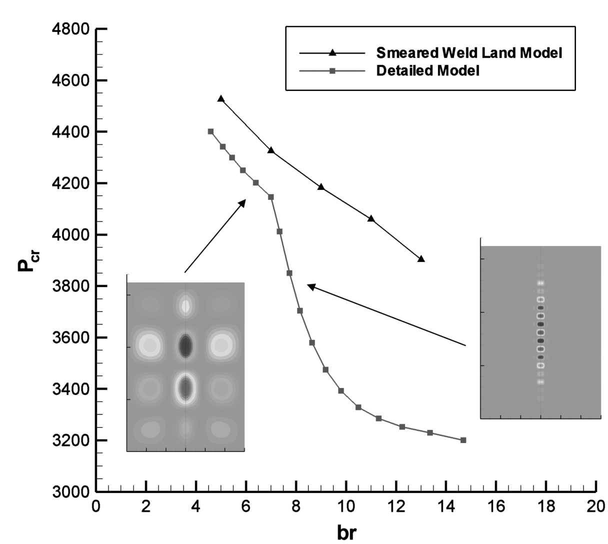

Fig. 16 Effect of ring spacing on the buckling response along the axial-weld land.

portions of the rings adjacent to the axial-weld lands, e.g., make them thicker or add a flange to the top of the ring. Finally, a more radical option is to use an externally stiffened configuration which not only increases overall structural efficiency for the acreage, but also reduces the effect of the axial-weld land on the buckling load.

To demonstrate the effectiveness of reinforcing longitudinal stiffeners near the weld lands, designs 1, 2, and 3 were modified by adding a flange on the top of some of the longitudinal stiffeners adjacent to the axial-weld lands and analyzed with the detailed modeling method. The original stiffener locations were used and the stiffener spacing was not altered to move the stiffeners closer to the weld lands. The flange added to the longitudinal stiffeners was flush with the inner edge of the stiffener so the stiffener height did not change. For each case the flange width was set equal to the orthogrid height, and the flange thickness was set equal to the stiffener thickness. Models were first analyzed with the flange added to only the nearest longitudinal stiffener on each side of the axial-weld lands. Then models were analyzed with the flanges added to the nearest two and nearest three longitudinal stiffeners.

The resulting buckling loads and improvement over the model without flanged stiffeners are shown in Table 2. The improvement in the buckling load varied between the three designs with design 2 showing approximately half of the improvement shown for designs 1 and 3. This is largely a result of the fact that design 2 has a wider stiffener spacing than designs 1 and 3 (4 vs 3 in.) and that in design 2 the distance between the weld land and adjacent longitudinal stiffener is greater (2.55 vs 2.05 in.). For all three designs, there were diminishing returns for the addition of flanges to more than the nearest stiffener, since the bending stiffness further away from the weld land has less influence on the weld land buckling phenomenon. Flanged stiffeners are the most effective method for adding bending stiffness while minimizing the mass and axial stiffness added to the structure. Similar results can be obtained by increasing the thickness of the unflanged longitudinal stiffeners close to the weld lands, but this method adds less bending stiffness relative to the additional mass, so the improvements seen will be less.

The results above indicate that the buckling response is heavily influenced by the stiffener geometry very close to the axial-weld lands. Thus, the designer is severely constrained in how much the buckling load can be influenced if the stiffener spacing and thickness is held constant for the entire panel acreage. As was shown above, the benefits of moving the adjacent stiffener closer to the axial-weld lands outweighed the impact of wider stiffener spacing in the panel acreage. By creating a nonuniform longitudinal stiffener pattern with more closely spaced stiffeners near the axial-weld lands and slightly increasing the spacing away from the weld lands improvements can be made to the buckling load with little impact on the mass of the cylinder. Similarly, the thickness of the rings can be modified so that they are thicker near the axial-weld lands while having the nominal thickness for the bulk of the panel acreage away from the weld lands. A tradeoff study would need to be performed to assess the most effective use additional structural mass near the weld lands for a particular cylinder design.

Although it is conventional to have an internally stiffened geometry in launch vehicle structures, consideration should be given to using an externally stiffened arrangement. If the structure is to be covered with a sufficiently thick layer of insulating foam, there should be little aerodynamic effect caused by external stiffeners. The bending compression coupling that occurs in externally stiffened structures results in a more stable response when the cylinder is loaded in compression and significantly increases the buckling load. Table 3 lists the predicted buckling loads for externally stiffened versions of designs 1, 2, and 3 based on the smeared model, smeared acreage and weld land model, and detailed model. For all three cases the outer radius of the skin was held constant and the stiffeners and weld lands were reflected to the external surface. These results show that the external stiffeners offer a 30–40% improvement in buckling strength over comparable internally stiffened designs. It can also be seen that the model with smeared acreage properties and axial-weld lands predicts a smaller reduction in buckling load than the conventional internally stiffened models. This is because in the external configuration the bending stresses produced by axial compression are in the opposite direction resulting in an outward deformation along the axial-weld lands. This prebuckling deformation pattern is inherently more stable than the inward deformation seen in the internally stiffened cylinders and helps minimize the impact the weld land has on the buckling load. The large drop in buckling load seen for the detailed models is a result of the fact that since the acreage is so much more efficient the lack of bending stiffness adjacent to the weld lands becomes much more significant. The buckling mode shapes for the detailed models show a very narrow deformation pattern along the axial-weld lands, so it is even more important in this arrangement to ensure longitudinal stiffeners are located a close as practical to the weld lands. However, even without any modification or reinforcement of the stiffeners near the axial-weld lands, all three of the detail models for the externally stiffened cylinders predict greater buckling loads than the predicted buckling loads for the internally stiffened cylinder without weld lands. It should also be noted that the externally stiffened configuration is so much more efficient that these design would like exhibit local pocket buckling or stiffener crippling before global instability, so the cylinder would have to be redesigned to take full advantage of the external stiffener configuration.

Table 3 Predicted buckling loads for externally stiffened orthogrid designs

	Smeared	*Smeared with weld land*		*Detailed model*	
Design	P_{cr}, kip	P_{cr}, kip	Reduction, %	P_{cr}, kip	Reduction, %
1	4429	4077	8.0	3329	24.9
2	7079	6532	7.7	5432	23.3
3	932	888	4.7	821	11.8

VII. Conclusions

The results presented in this work show that the presence of axial-weld lands in orthogrid cylinders, in general, causes a significant reduction in the buckling strength when the cylinder is loaded in axial compression. Although acreage design clearly influences the reduction in buckling load there are no clear trends that a designer can take advantage of to minimize the impact of adding weld lands. Results show that minimizing the width of the weld lands is the most effective means to reduce the performance penalty associated with the axial-weld lands. Modeling results have shown that the specific location of stiffeners near the weld lands has a direct impact on the weld land buckling phenomenon. Effort should be made to minimize the distance between the weld land and the adjacent longitudinal stiffeners, and adding flanges to these stiffeners has been shown to be highly effective in improving buckling load.

Experience has shown that the amount of buckling load that can be recovered is highly dependent on the width of the axial-weld lands. Since the manufacturing constraint on the width of the weld lands is usually independent of the cylinder radius weld land buckling is a

Table 2 Predicted buckling loads for orthogrid designs with flanged reinforced stiffeners near the axial-weld lands

	Initial	*1 Flanged stiffener*		*2 Flanged stiffeners*		*3 Flanged stiffeners*	
Design	P_{cr}, kip	P_{cr}, kip	Improvement, %	P_{cr}, kip	Improvement, %	P_{cr}, kip	Improvement, %
1	2487	2742	10.2	2793	12.3	2819	13.3
2	4146	4305	3.8	4357	5.1	4406	6.3
3	564	611	8.4	623	10.5	629	11.5

more significant issue in smaller-diameter launch vehicle structures than it is in large-diameter ones. A 27-ft-diam cylinder with a 4-in. total weld land width might be able to be reinforced with flanged stiffeners to remove almost all of the penalty in buckling load associated with the weld lands, while no practical amount of reinforcement might be able to improve the buckling load to better than 90–95% of the nominal buckling load for a 18-ft-diam cylinder with 4-in.-wide weld lands. It should be noted that the discussion in this work has focused on structural failure associated with global buckling caused by the axial compression. In practice, material stress limits and the stresses created by internal pressure also place constraints on the orthogrid design. The goal for improving the buckling load is to minimize weld land width and arrange stiffeners to increase bending stiffness as close as possible to the weld lands, and local stresses may prevent the designer from achieving an optimal design from a buckling standpoint.

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