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Hardware-Based Non-Optimum Factors for Launch Vehicle Structural Design

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Abstract

During aerospace vehicle conceptual and preliminary design, empirical non-optimum factors are typically applied to predicted structural component weights to account for undefined manufacturing and design details. Non-optimum factors are developed here for 32 aluminum-lithium 2195 orthogrid panels comprising the liquid hydrogen tank barrel of the Space Shuttle External Tank using measured panel weights and manufacturing drawings. Minimum values for skin thickness, axial and circumferential blade stiffener thickness and spacing, and overall panel thickness are used to estimate individual panel weights. Panel non-optimum factors computed using a coarse weights model range from 1.21 to 1.77, and a refined weights model (including weld lands and skin and stiffener transition details) yields non-optimum factors of between 1.02 and 1.54. Acreage panels have an average 1.24 non-optimum factor using the coarse model, and 1.03 with the refined version. The observed consistency of these acreage non-optimum factors suggests that relatively simple models can be used to accurately predict large structural component weights for future launch vehicles.

Introduction

During the conceptual and preliminary design of launch vehicles, structural components are often sized using intermediate-fidelity computational and analytical methods (Refs. 1, 2). However, these idealized results do not typically include the additional weight of design details required to manufacture and integrate these structures. Typical design details for large aerospace structures (Ref. 3) may include items such as localized skin and stiffener thickness variations, weld lands, machining fillets, and subsystem attachment fittings.

Empirical non-optimum factors are typically applied to the structural weights predicted during conceptual and preliminary design to account for the additional weight of design details like the ones listed above (Refs. 4 - 6). Since the resulting structural weights are typically used to predict the vehicle mass properties, which are then used in trajectory analyses to determine the vehicle performance, realistic values of these non-optimum factors are necessary to ensure accurate predictions of a design's payload to orbit.

Some distinction should be made to clarify terminology for structural mass prediction and control. Based on the definitions provided in AIAA S-120-2006 (Ref. 7), a component's structural "basic mass" is the current best estimate of mass using whatever estimation, calculation, or weighing procedure is available at the time. This basic mass plus an additional

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amount (termed mass growth allowance, or MGA) is equal to the predicted mass. Predicted mass is the best estimate of what the component's mass will be upon entering service, but made at a specific time in the product development life cycle.

Knowledge of actual flight hardware masses will be incorporated into estimates of structural basic masses that are made in this paper. Such corporate knowledge of mass estimating histories can help a design team determine the values of MGA required for particular components at particular phases of development. This compilation of knowledge is used to provide better MGA allocations than may be obtained by defaulting to suggested values such as those in Ref. 7. Selection of appropriate MGA for application to basic structural masses should be made with a thorough understanding of the bases of estimates provided by the structures engineers. An understanding of the mass estimation process can reduce buildup of multiple conservative factors across design disciplines.

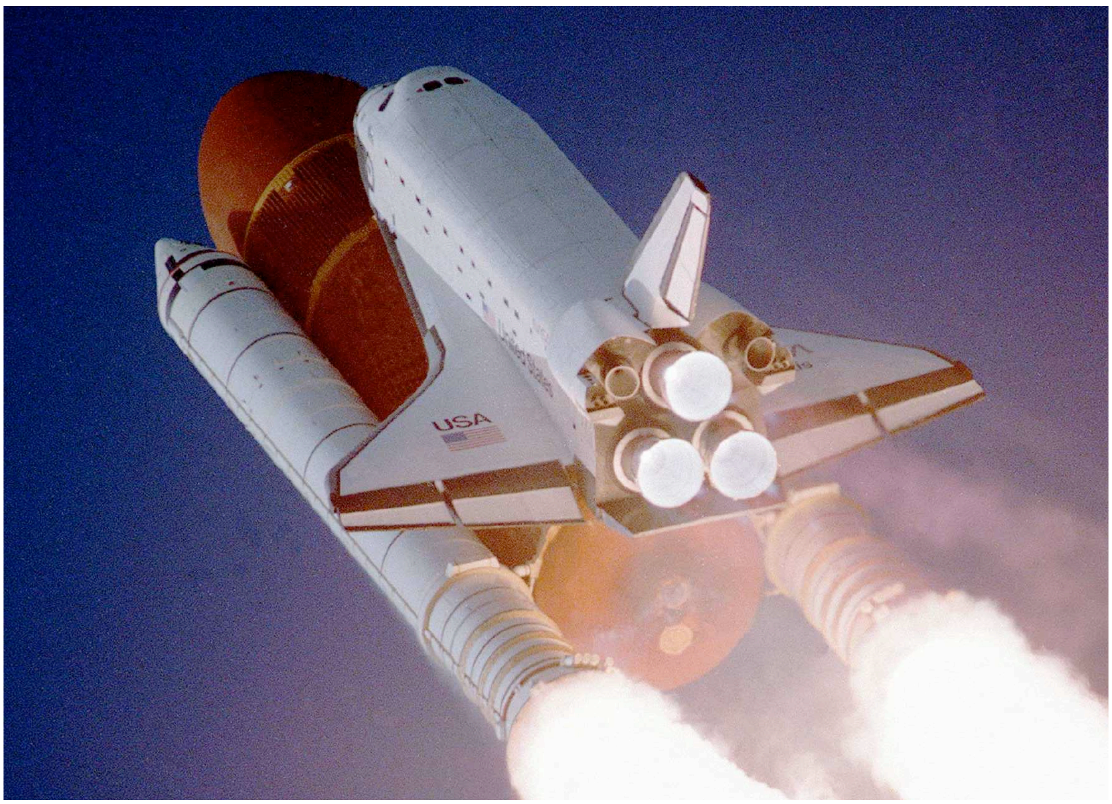

Figure 1. Space Shuttle launch vehicle.

Space Shuttle SLWT LH_2 tank description

The Space Shuttle launch vehicle (Figure 1) is comprised of four major components: the Orbiter, two Solid Rocket Boosters and the External Tank. The current version of the External Tank, designated the Super Lightweight Tank or SLWT (Refs. 3, 8, 9), has been operational since STS-91 in June 1998. The SLWT in Figure 2 contains the 1.62 Mlbs (73.6 kft^3 volume) of liquid hydrogen (LH_2) and liquid oxygen (LO_2) propellants used by the Space Shuttle Main Engines on the Orbiter. Approximate dimensions of the SLWT are 153.8 ft length by 27.6 ft diameter, with an empty weight of 57.8 klbs.

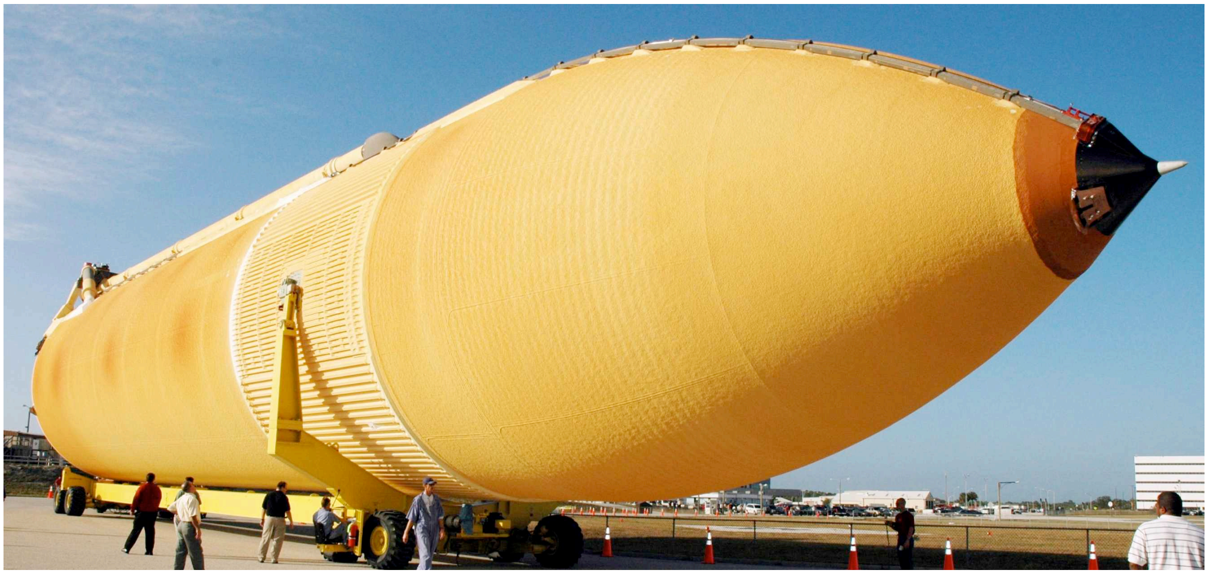

Figure 2a. Super Lightweight Tank (exterior view).

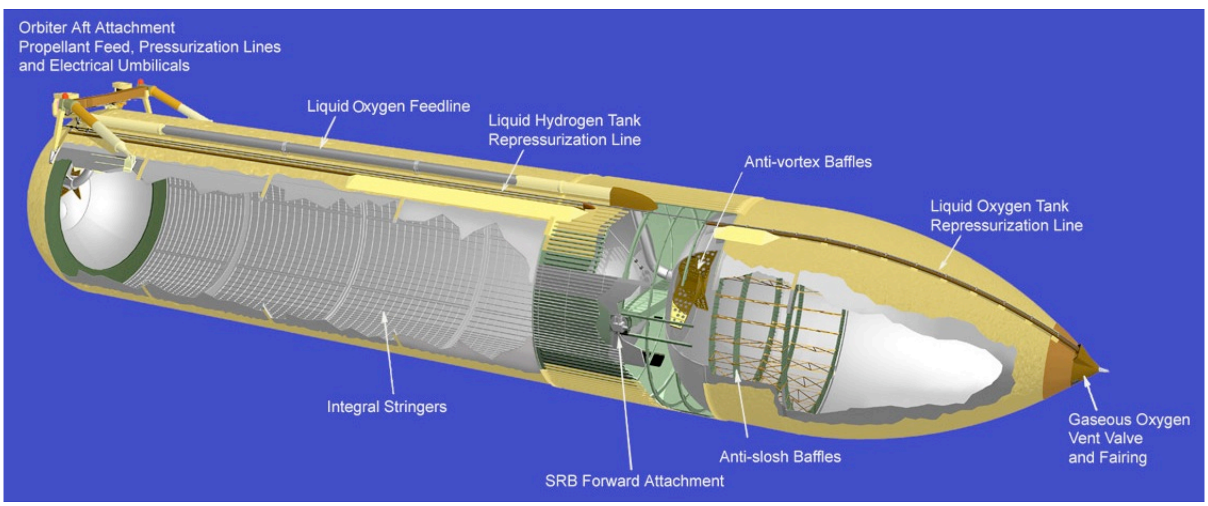

Figure 2b. Super Lightweight Tank (cutaway view).

An exterior planform view of the panels used to assemble the SLWT LH_2 tank barrel is shown in Figure 3 (from Ref. 3). Orthogrid construction with internal blade stiffeners is used almost exclusively throughout the structure. A small number of axial T-stiffeners are used in selected locations, and are included in the non-optimum factors of those panels. Tank axial station numbers in the vehicle coordinate system (given in inches) increase from the forward dome-barrel intersection at Station 1130 to the aft dome-barrel intersection at Station 2058. The LH_2 tank barrel assembly is comprised of four barrels numbered from 1 (aft) to 4 (forward). Panels in barrel 1 are shorter (177.5 in.) than panels in the other three barrels, which are 240.2 (barrel 2) to 240.5 in. long (barrels 3 and 4).

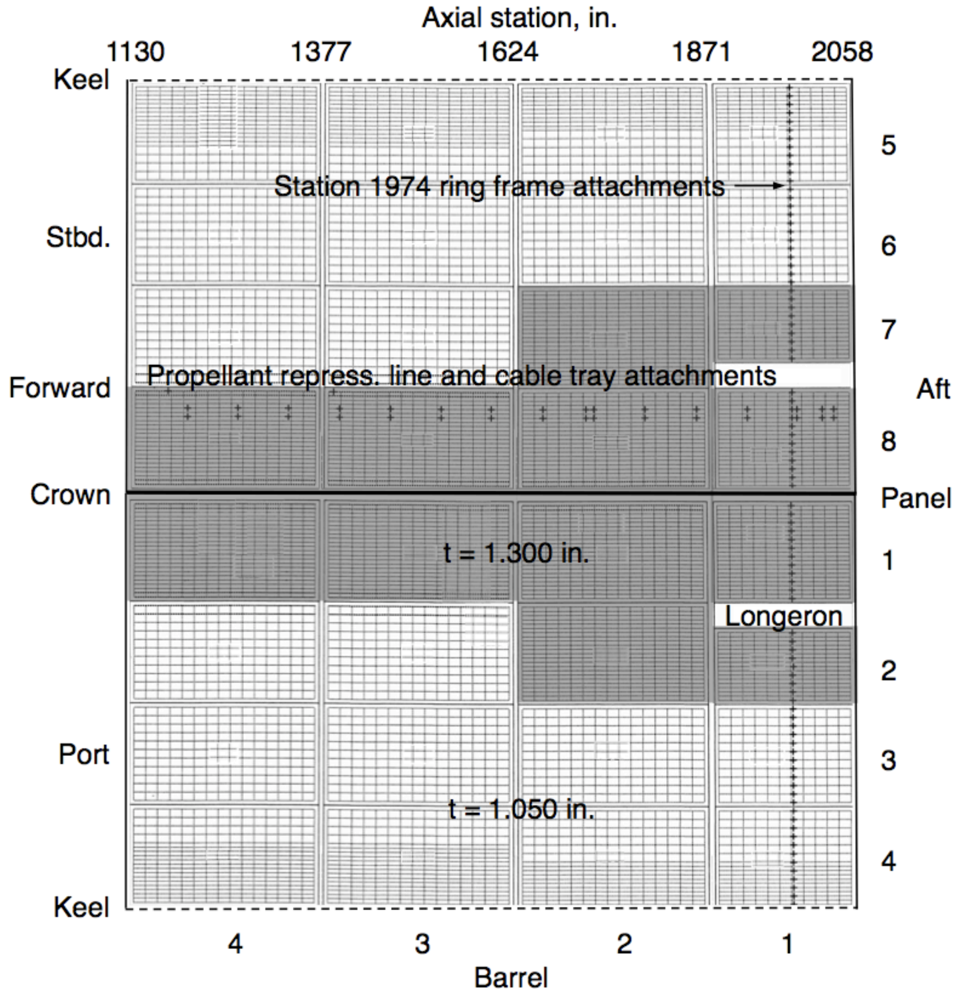

Figure 3. LH_2 tank barrel assembly planform view.

In this study, non-optimum factors for the 32 aluminum-lithium (Al-Li) 2195 orthogrid panels that comprise the 77.3 ft-long LH_2 tank barrel assembly of the SLWT are developed using measured data from flight hardware. Looking aft into the LH_2 tank, Figure 4 shows the complete barrel assembly with installed ring frames, aft LH_2 tank dome and feedline. In this photograph, the forward LH_2 tank dome is not yet attached to the Station 1130 forward ring frame. Other major elements of the SLWT, including the LH_2 tank domes, intertank and LO_2 tank, are not assessed here.

Looking forward, the panels within each barrel are numbered from 1 to 8 moving counter-clockwise from the tank crown directly under the Orbiter (indicated by the thick solid line in Figure 3). Each panel covers 45 degrees of arc and is 129.9 in. wide, except for panels 2 and 7 in barrel 1, which are 97.4 in. wide. The gaps between these two panels and the adjacent panels 1 and 8 are bridged with 32.5 in.-wide, 493-lb monolithic longeron forgings where the Orbiter-to-SLWT aft attachment struts are attached (Ref. 3). The acreage region is defined here as the 16 thinner panels on the tank barrel opposite the tank crown, and excluding the barrel 1 panels where the Orbiter and subsystem attachments are located.

Figure 4. SLWT LH_2 tank barrel assembly (Lockheed Martin photo).

Actual panel weights

A highly detailed, parts-level weights database for ET-121, flown on STS-114 in July 2005, was provided by the Lockheed Martin Space Systems Company - Michoud Operations (Ref. 10). This database contains measured weights for the 32 LH_2 tank barrel panels that are used to calculate the panel non-optimum factors. These actual panel weights are shown in Figure 5 on their corresponding panel locations. When divided by their respective planform areas, the areal weights of these panels range from 1.80 to 2.99 lb/ft^2. With certain exceptions, most notably the crown panels, the panel weights show a high degree of port-starboard symmetry across the tank barrel.

Direct examination of these actual weights can provide useful information on subsystem attachment non-optimum factors. Attachments for two subsystems are denoted in Figure 3 by the small black crosses. The barrel 1 panels have numerous local reinforcements for internal attachment of the Station 1974 intermediate ring frame, as well as stabilizers for the Station 1871 and 2058 major ring frames (not marked in the figure). Panel 8 in each barrel also has a smaller number of local reinforcements for the 5-in. gaseous oxygen and gaseous hydrogen repressurization lines and cable tray external attachment fittings.

The panel weights listed in Figure 5 can be used to estimate the ring frame attachment weight impact on the barrel 1 panels. The adjacent barrel 2 panel weights (which do not have the ring frame attachments) are first multiplied by the ratio of the barrel 1 and 2 lengths (177.5 in./240.2 in., or 73.9 percent), to determine an equal-area reference panel weight. The weights for panels 2 and 7 in barrel 2 are then scaled by an additional 75 percent (97.4 in./129.9 in.) to account for the reduced width of the adjacent barrel 1 panels 2 and 7, for a cumulative reduction of 55.4 percent in these two panels.

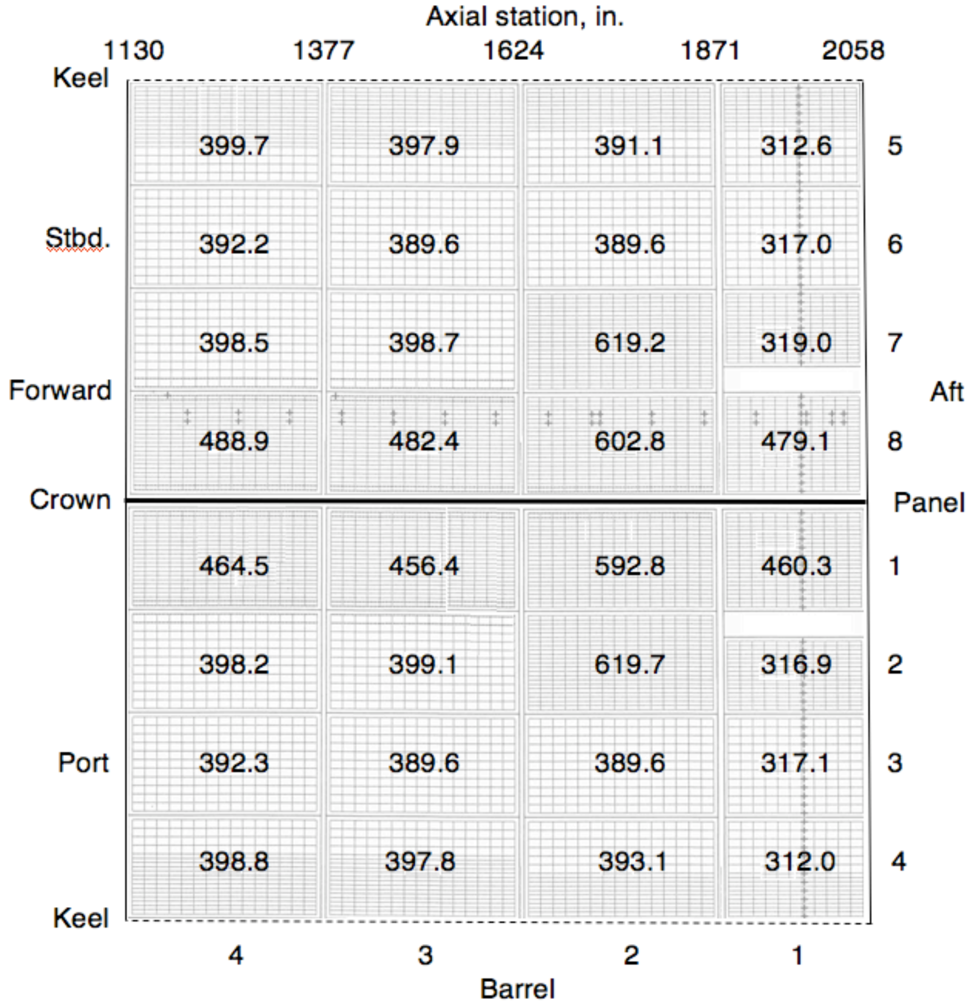

Figure 5. Actual panel weights, lbs.

When these scaled barrel 2 panel weights are then compared with the corresponding panel weights from barrel 1, the ring frame attachments are found to increase the barrel 1 panel weights by an average of 8 percent. The exceptions are panels 2 and 7, which are actually 7 percent lighter than their scaled neighbors from barrel 2. This may result from the substantial structural stiffness provided by the longeron forgings.

The panel weights data from Figure 5 are also used to estimate the impact of the propellant repressurization lines and cable tray attachment fittings on panel 8 from each barrel. The differences in weights between each panel 8 and the adjacent panel 1 on the port side of the crown with the same structural configuration are therefore directly attributable to the weight of these attachment fittings. Division of the difference by the adjacent panel 1 weight and averaging the results shows that these attachment fittings increase the panel 8 weights by 4 percent. This percentage is lower than the result computed for the ring frame attachments, which makes sense since there are not as many of these fittings in their respective panels.

Panel thickness variations

Manufacturing drawings for the 32 panels on the LH_2 tank barrel assembly were obtained (Ref. 11) from Lockheed Martin and the panel manufacturer, AMRO Fabricating Corporation. These drawings are examined to determine minimum nominal values for the skin thickness, axial and circumferential blade stiffener thicknesses, and the overall thickness for each panel. Port-starboard symmetry of the tank skin and panel stiffener dimensions is assumed where specific drawings were not available. Ref. 4 indicates that three different thicknesses (1.050, 1.250 and 1.300 in.) are used on the LH_2 tank panels. However, the drawings show only two unique panel thicknesses (1.050 and 1.300 in.), with the thicker panels located around the tank crown and Orbiter attachments shaded in Figure 3.

Although only minimum values for the skin thickness are extracted from the drawings, there are substantial variations in skin thicknesses both within and between individual panels where more localized loads must be carried. To illustrate this, qualitative skin thickness contour plots are generated for several panels from the manufacturing drawings. Skin thicknesses in these plots are represented using the same gray-scale scheme, where darker colors correspond to thicker gages and lighter shades to lower thicknesses. The dark gray edges around the borders of the panel orthogrid patterns represent the typical 0.325 in.-thick weld lands used to integrate the panels into larger subcomponents. Thicker weld lands up to a maximum 0.670 in. near the longeron forgings are treated here as part of the panel non-optimum factor. The longeron forgings themselves are not assessed in this study.

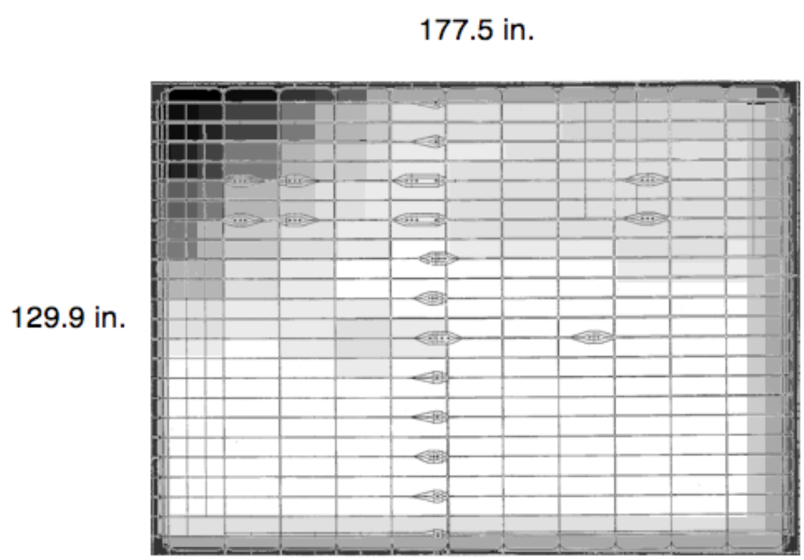

Figure 6. Barrel 1 - panel 8 skin thicknesses.

The panel (barrel 1 - panel 8) presented in Figure 6 has fifteen different skin thicknesses ranging from 0.089 to 0.550 in., which are plotted as shades of gray ranging from white to black, respectively. Located inboard of the starboard longeron connecting the Orbiter and SLWT, high ascent loads are transferred from the Orbiter through the thrust strut into barrels 1 and 2 and diffused into the LH_2 tank near the longeron's forward end, accounting for the increased skin thicknesses in that corner of the panel. Loads from the vertical strut to the back of the longeron enter the tank in the plane of the Station 2058 ring frame, and do not appear to require similar large increases in skin thickness. This particular panel is unique among all the panels, because it has reinforcements for both the Station 1974 intermediate ring frame attachments and the propellant repressurization lines and cable tray attachment fittings.

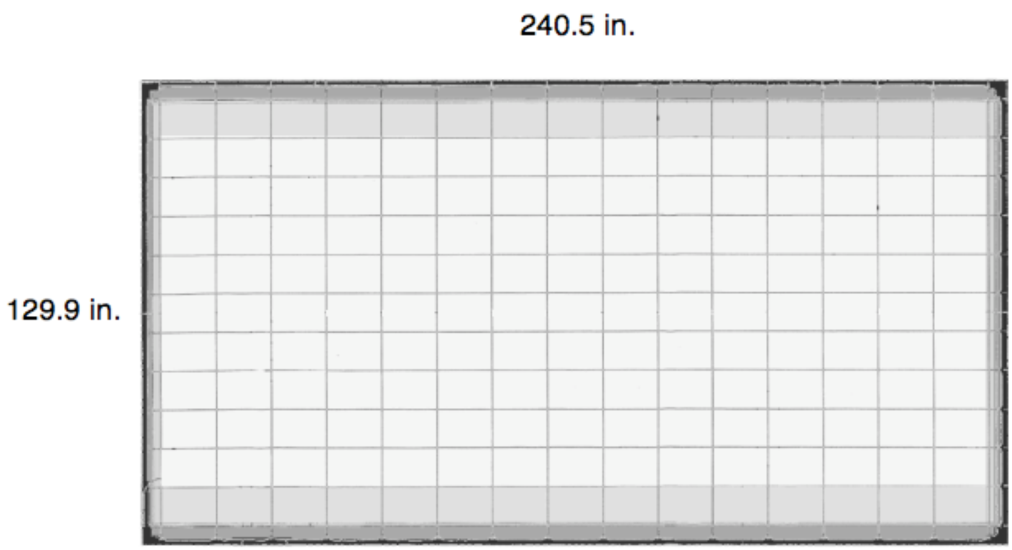

Figure 7. Barrel 3 - panel 3 skin thicknesses.

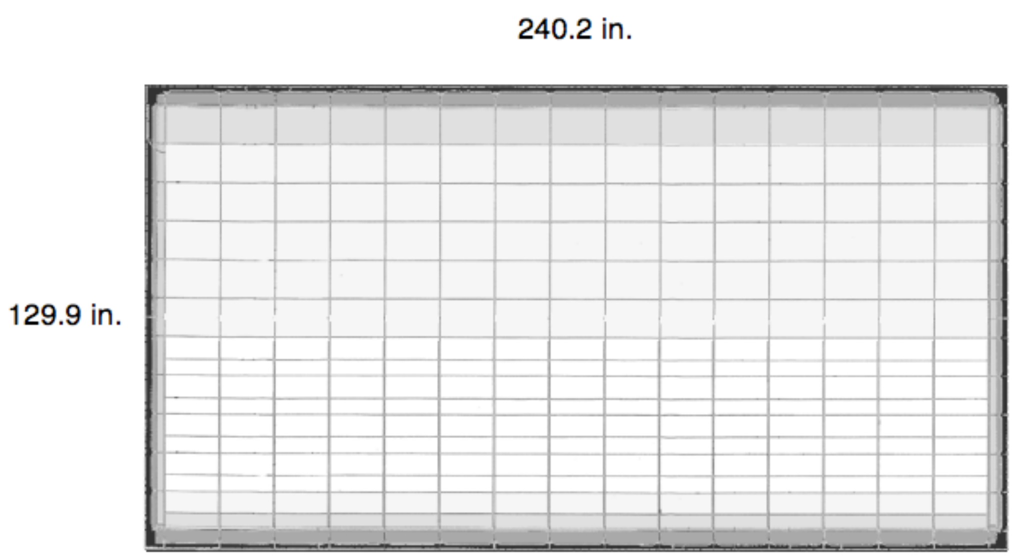

Figure 8. Barrel 2 - panel 4 skin thicknesses.

On the other extreme, the second panel (barrel 3 - panel 3) examined has only four unique skin thicknesses between 0.093 and 0.160 in., as shown in Figure 7. This panel has minimal variation in skin thickness, as opposed to the panel in Figure 6. Figure 8 shows a different panel (barrel 2 - panel 4), which has orthogrid cells with two different circumferential spacings. The minimum skin thickness of 0.090 in. for this panel is in the region with closely spaced stiffeners (adjacent to the tank keel indicated by the dashed line in Figures 3 and 5), with 0.093 in.-thick skins in most of the remaining cells. These latter two panels, along with similar panels in barrels 2, 3 and 4, comprise the tank acreage region.

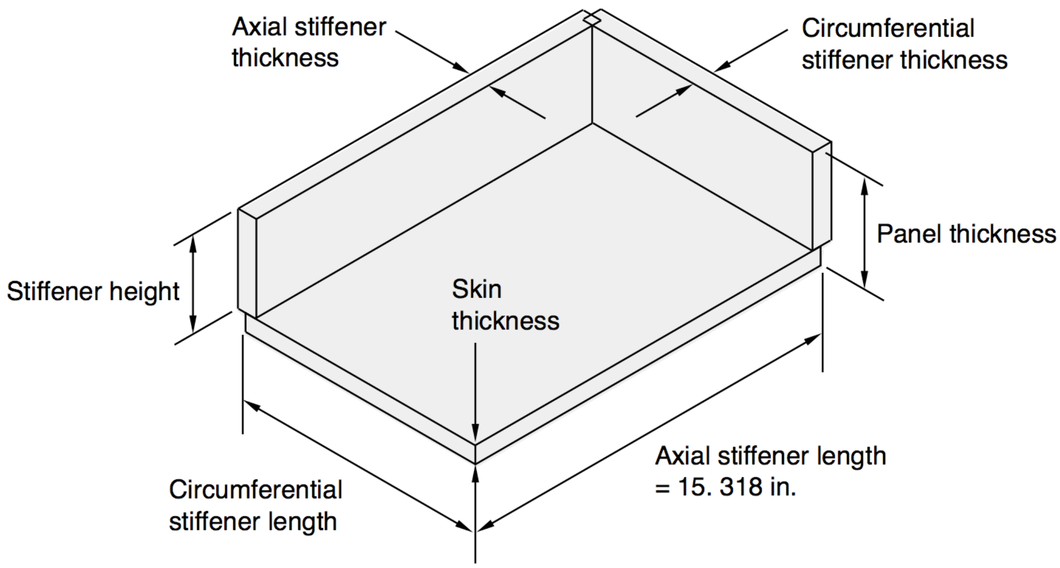

Figure 9. Orthogrid unit cell model.

Unit cell type	Panel thickness	Skin thickness	Stiffener height	Axial stiff. thickness	Circ. stiff. thickness	Circ. stiff. length
1	1.300	0.089	1.211	0.095	0.125	5.416
2	1.300	0.089	1.211	0.100	0.125	5.416
3	1.050	0.090	0.960	0.080	0.100	5.416
4	1.050	0.093	0.957	0.086	0.100	10.832

Table 1. SLWT orthogrid unit cell dimensions, in.

Estimated panel weights

A generic orthogrid unit cell is shown in Figure 9, with minimum dimensions specific to the four different unit cell configurations used in the LH_2 tank barrel panels listed in Table 1. The skin thicknesses range from 0.089 (sized by proof test internal pressure) to 0.093 in. (sized to resist skin buckling in the wider unit cells). Axial and circumferential blade stiffener thicknesses vary from 0.086 to 0.125 in., as shown in the table. The axial and circumferential stiffener heights are identical within each unit cell type, and are equal to the overall panel thickness minus the minimum skin thickness. The axial stiffener length is a uniform 15.318 in. for all panels, with a circumferential stiffener length of either 5.416 or 10.832 in. in the tank hoop direction.

Unit cell type	Unit cell weight, lbs	Areal weight, lb/ft^2
1	0.977	1.70
2	0.986	1.71
3	0.890	1.55
4	1.672	1.45

Table 2. Orthogrid unit cell and areal weights.

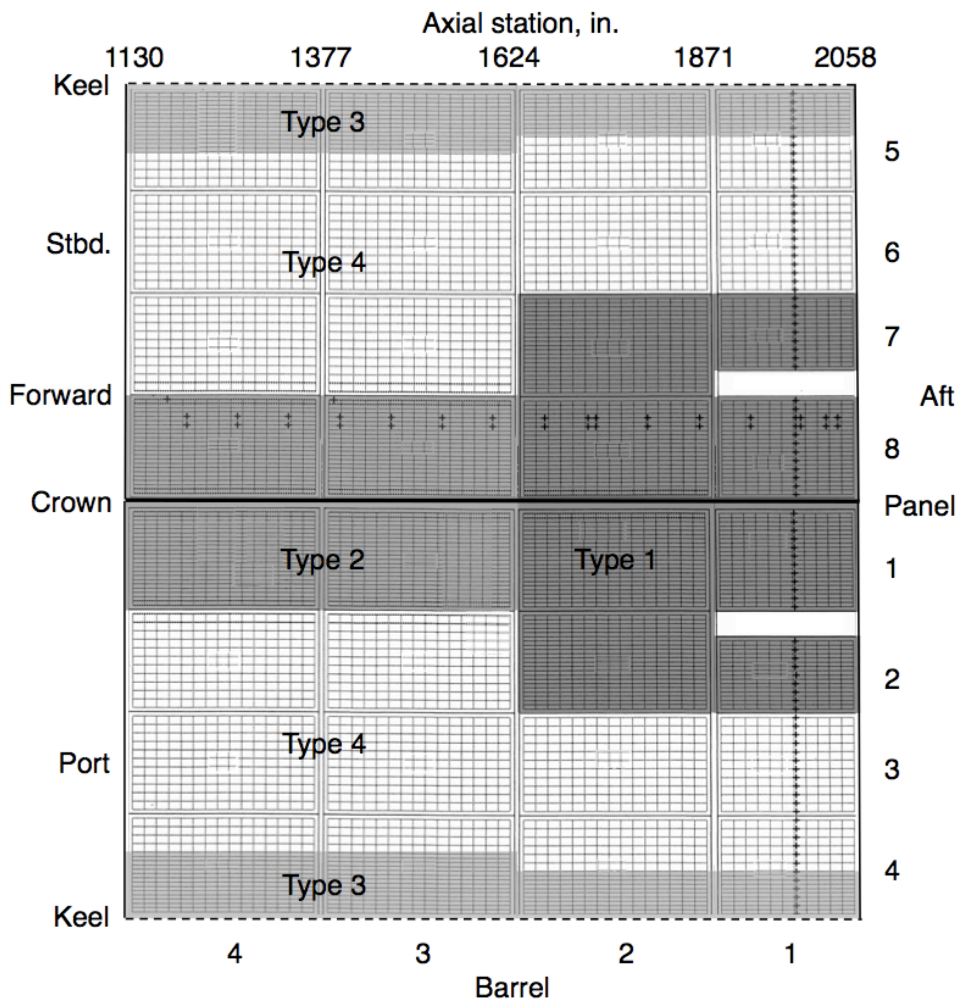

Figure 10. Orthogrid unit cell type locations.

A spreadsheet model for the weight of an orthogrid unit cell is then developed from this basic geometry. Using an assumed material density of 0.098 lb/in^3 for Al-Li 2195, the weight of each unit cell type is calculated, along with their corresponding areal weights. The unit cell type weights are presented in Table 2, with their respective locations shaded in Figure 10. Note that panels 4 and 5 on either side of the tank keel contain both unit cell types 3 and 4, as noted above. A coarse estimate of the panel weight is then calculated as the product of the appropriate orthogrid unit cell areal weights and panel planform areas. These predicted panel weights are shown only on the upper (starboard) side of the tank planform view in Figure 11, and are by definition symmetric to panels across the tank diameter.

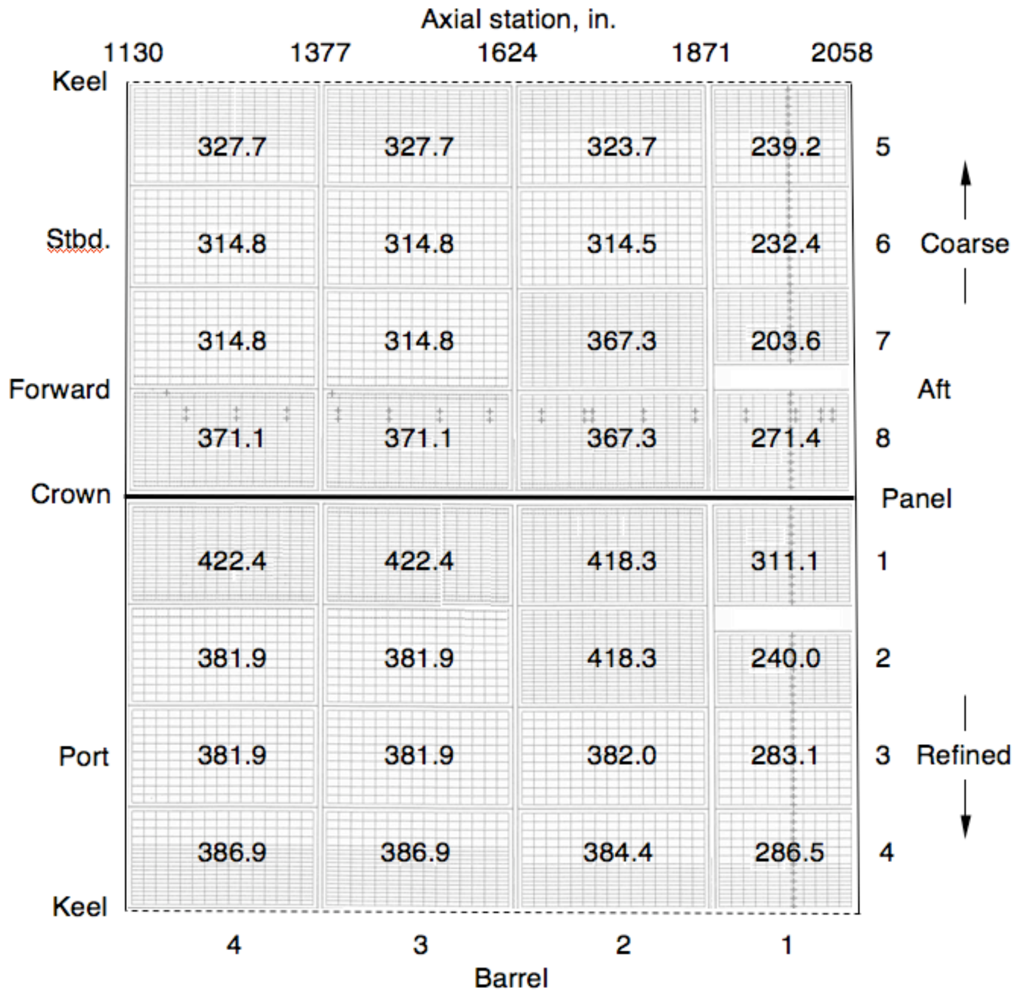

Figure 11. Predicted panel weights, lbs.

A more detailed panel edge model with weld lands and skin and stiffener transition details, shown in Figure 12, is developed to add additional fidelity to the panel weight estimates. The orthogrid region areas in the panel centers are subtracted from the panel planform areas, and the resulting weighted average panel edge widths are calculated as 10.75 in. along the tank axis of revolution, and 10.20 in. for the circumferential direction. These surrounding edge widths are then equally divided between a 0.325 in.-thick weld land, and a 0.160 in.-thick skin transition zone between the orthogrid cells and the weld land. Each blade stiffener is transitioned down to the weld land with a triangular piece bridging the skin transition zone.

This panel edge model and the unit cell weights developed previously are then combined to develop a more refined panel weights estimate. The total orthogrid weight for each panel is calculated by multiplying the appropriate unit cell weight (or weights, in the case of the keel panels) by the number of orthogrid cells in that panel. Predicted weights for the skin and stiffener transitions and weld lands are also calculated using a spreadsheet. The predicted orthogrid and panel edge weights are then added together to get the refined panel weight estimates shown on the lower (port) side of the tank planform view in Figure 11. As noted above, these predicted weights are symmetric across the tank diameter. Comparison of the coarse and refined predicted panel weights in the figure shows an average percentage difference of approximately 17 percent, with the coarse weights being consistently lighter than the corresponding refined values.

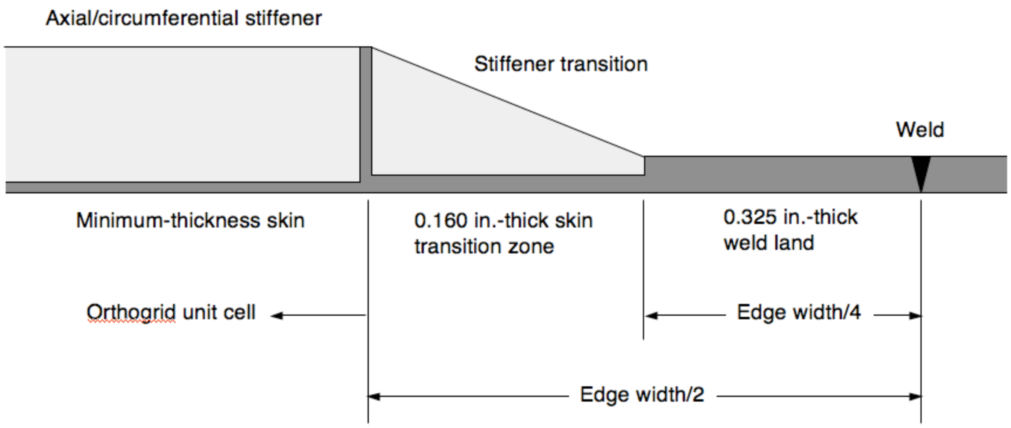

Figure 12. Panel edge model.

Panel non-optimum factors

The actual panel weights and their corresponding values predicted using the coarse and refined weights models are listed in Table 3 for the 32 panels comprising the SLWT LH_2 tank barrel assembly. The non-optimum factors (NOF) listed in the table are defined as the ratio of the actual panel weights and the predicted weights. Computed non-optimum factors range from 1.21 to 1.77 using the coarse weights model, and are shown in Figure 13 in their respective locations. Calculation of non-optimum factors using the refined weights model with additional edge details results in values between 1.02 and 1.54, as plotted in Figure 14. The average difference between the coarse and refined non-optimum factors is 21 percent. This value represents the contribution of the weld lands and skin and stiffener transitions to the overall panel weight, since those are the details captured in the refined panel weights model.

Similar overall trends are noted in both the coarse and refined non-optimum factors in Table 3. Specifically, the highest non-optimum factors observed in panels near the crown of the LH_2 tank in barrels 1 and 2 are due to the large variations in skin and stiffener thicknesses in these heavily loaded regions, as well as the subsystem attachments discussed previously. Estimates of the subsystem attachment weights, extracted from the tabulated results by comparing the non-optimum factors of panels in adjacent barrels, are similar to the previous calculations made directly from the panel weights. As expected, panel 8 in barrel 1 has the highest non-optimum factor of all the panels due to its many subsystem attachments.

The lowest non-optimum factors are observed in the 16 tank acreage panels, which are removed from the crown regions and barrels 1 and 2, where the Orbiter and subsystem attachments are located. The acreage panels weigh an average of 24 percent more than the coarse weights model predictions, and 3 percent more than the refined predictions. Their computed standard deviations are approximately 2 and 1 percent, respectively.

Barrel-panel identifier	Actual panel weight, lbs	Coarse pred. weight, lbs	Coarse NOF	Refined pred. weight, lbs	Refined NOF
1 - 1	460.3	271.4	1.70	311.1	1.48
1 - 2	316.9	203.6	1.56	240.0	1.32
1 - 3	317.1	232.4	1.36	283.1	1.12
1 - 4	312.0	239.2	1.30	286.5	1.09
1 - 5	312.6	239.2	1.31	286.5	1.09
1 - 6	317.0	232.4	1.36	283.1	1.12
1 - 7	319.0	203.6	1.57	240.0	1.33
1 - 8	479.1	271.4	1.77	311.1	1.54
2 - 1	592.8	367.3	1.61	418.3	1.42
2 - 2	619.7	367.3	1.69	418.3	1.48
2 - 3	389.6	314.5	1.24	382.0	1.02
2 - 4	393.1	323.7	1.21	384.4	1.02
2 - 5	391.1	323.7	1.21	384.4	1.02
2 - 6	389.6	314.5	1.24	382.0	1.02
2 - 7	619.2	367.3	1.69	418.3	1.48
2 - 8	602.8	367.3	1.64	418.3	1.44
3 - 1	456.4	371.1	1.23	422.4	1.08
3 - 2	399.1	314.8	1.27	381.9	1.05
3 - 3	389.6	314.8	1.24	381.9	1.02
3 - 4	397.8	327.7	1.21	386.9	1.03
3 - 5	397.9	327.7	1.21	386.9	1.03
3 - 6	389.6	314.8	1.24	381.9	1.02
3 - 7	398.7	314.8	1.27	381.9	1.04
3 - 8	482.4	371.1	1.30	422.4	1.14
4 - 1	464.5	371.1	1.25	422.4	1.10
4 - 2	398.2	314.8	1.26	381.9	1.04
4 - 3	392.3	314.8	1.25	381.9	1.03
4 - 4	398.8	327.7	1.22	386.9	1.03
4 - 5	399.7	327.7	1.22	386.9	1.03
4 - 6	392.2	314.8	1.25	381.9	1.03
4 - 7	398.5	314.8	1.27	381.9	1.04
4 - 8	488.9	371.1	1.32	422.4	1.16

Table 3. Orthogrid panel weights and non-optimum factors.

These results can be used to make some general observations about the orthogrid panels evaluated here. Approximately 76 percent of an acreage panel weight is in the minimum-thickness orthogrid skin and stiffeners, 21 percent is in the panel edges and weld lands surrounding the orthogrid, and 3 percent in other design details like fillets and localized thickness variations. These proportions are relatively consistent for a variety of different orthogrid panel configurations used in the SLWT. Given a good definition of panel component basic size requirements, such as through a physical design process, the consistent acreage non-optimum factors computed here suggest that such relatively simple models can be used to accurately predict the weight of large structural components for future launch vehicles.

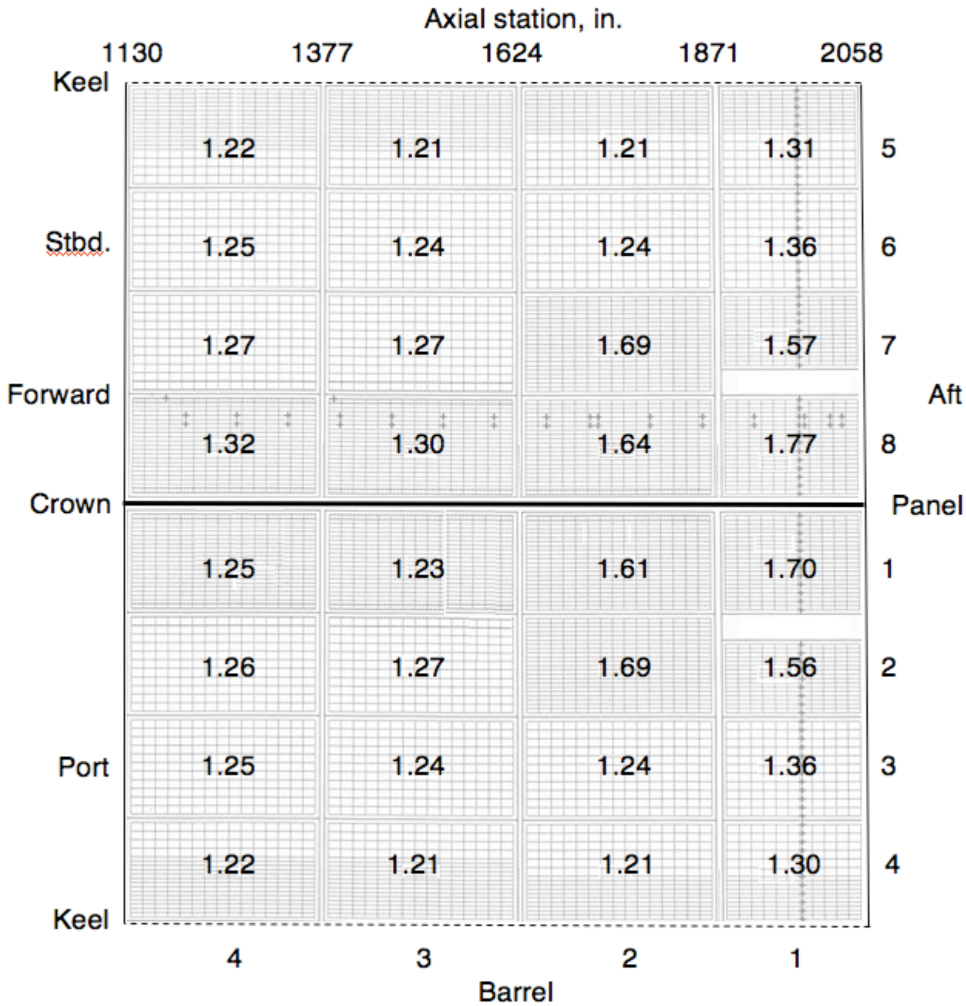

Figure 13. Panel coarse non-optimum factors.

Application to Ares V LH_2 tank

To illustrate the application of the methods presented in this paper, structural weights are predicted for a representative acreage panel on the Ares V (Figure 15, Ref. 12) launch vehicle's core stage LH_2 tank barrel assembly. While still in the conceptual design phase, it is likely that this structure would be built using manufacturing techniques and orthogrid wall constructions that are similar to the ones used to build the SLWT, thus taking maximum advantage of the experiences gained during the Space Shuttle program.

A finite element model of the LH_2 tank is shown in Figure 16 with a representative panel. Load cases with tank pressurization and flight loads at liftoff, maximum axial acceleration, and maximum bending moment (maximum q-alpha condition) are used to size the panel described above. Credit for 20 psig of pressure stiffening with an ullage pressure of 35 psig is used in the flight load sizing conditions. This pressure and fuselage bending are the largest contributors to structural loads.

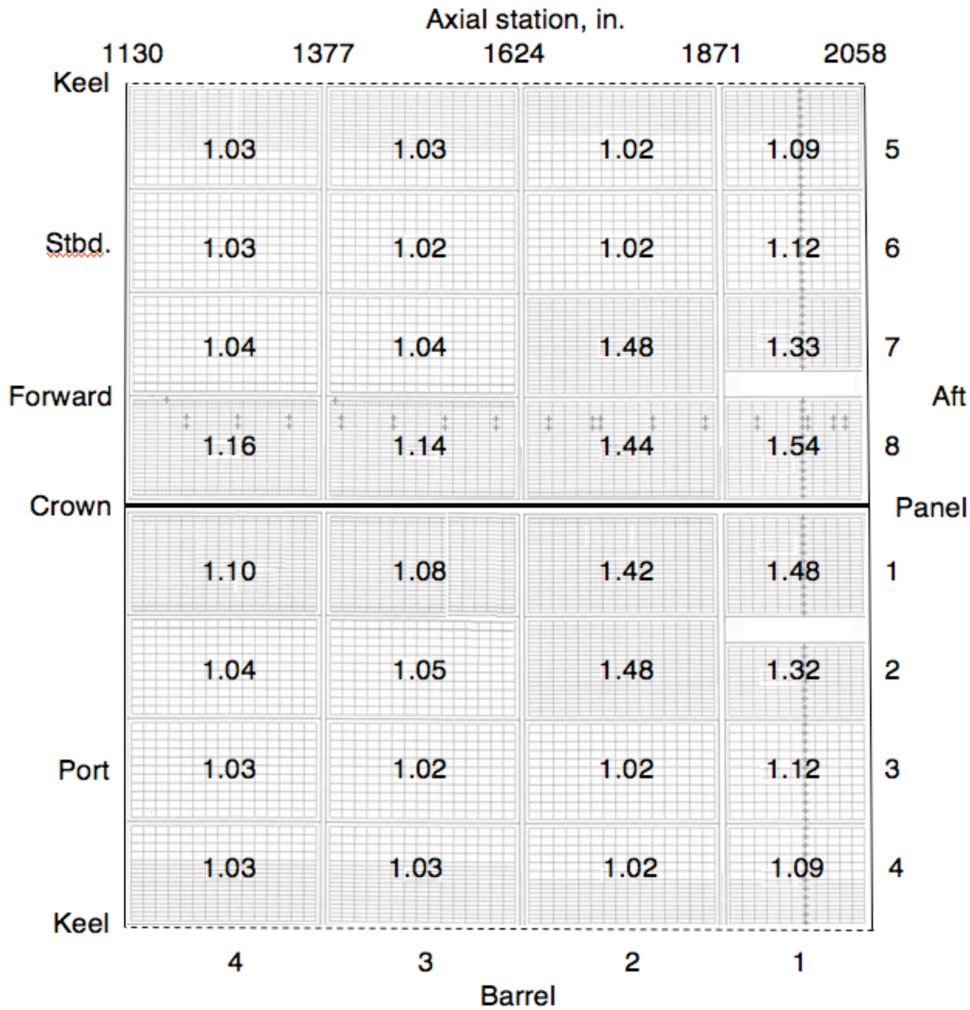

Figure 14. Panel refined non-optimum factors.

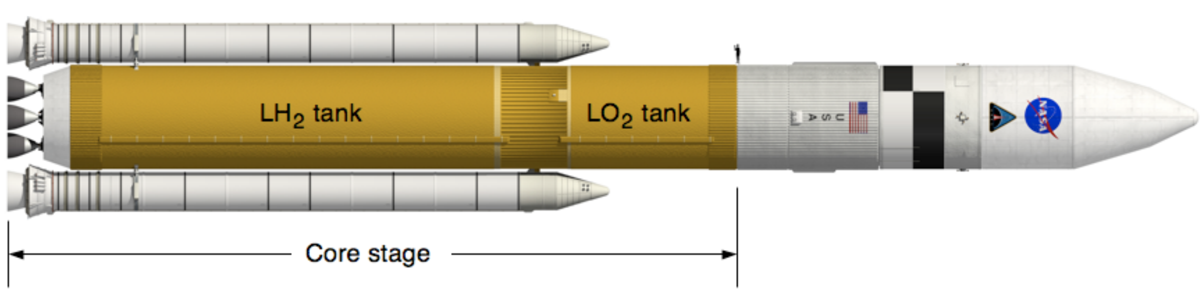

Figure 15. Ares V launch vehicle (Ref. 12).

The maximum thickness of the Al-Li 2195 plate material is assumed to be 2.000 inches, and the panel planform in Figure 17 is assumed to be 251.0 in. long by 155.5 in. around the tank circumference. The panel length between circumferential ring frames is chosen to allow six identical-length barrel sections to be welded into the tank barrel assembly. The panel width allows eight individual panels to be assembled into a 33 ft.-diameter barrel section, and is within the current capability of the Al-Li 2195 plate manufacturer (Ref. 13).

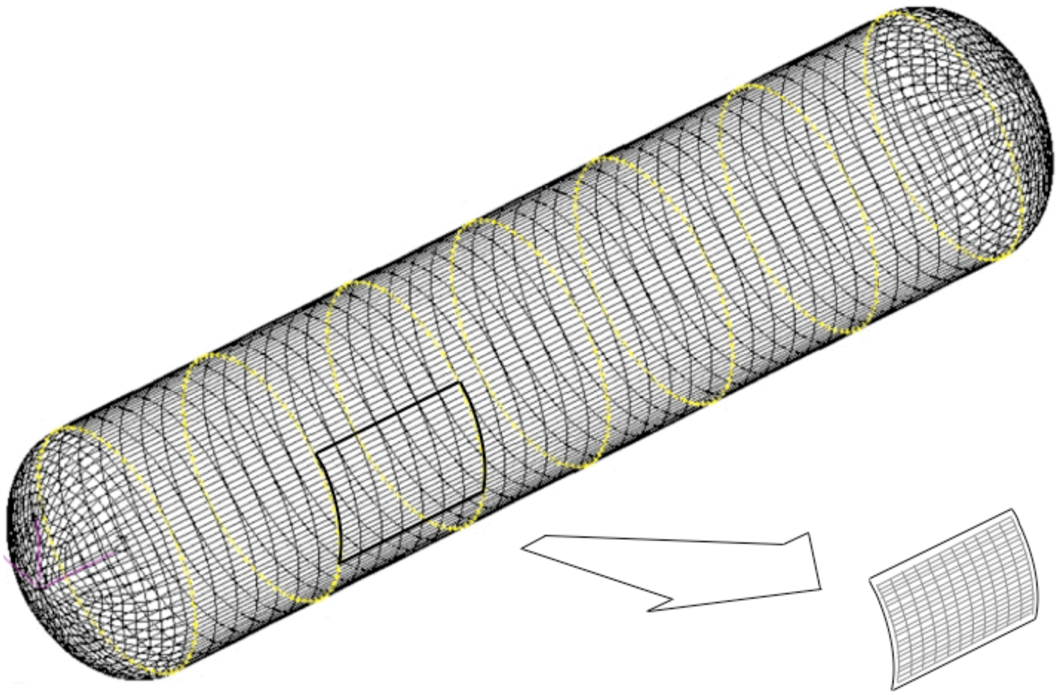

Figure 16. Ares V core stage LH_2 tank structural model and panel.

Orthogrid stiffener spacings and dimensions are obtained from results of a HyperSizer analysis of the panel, and are listed in Table 4. Optimal results are obtained using a circumferential stiffener length of 6.760 inches, with axial stiffener lengths of twice this value. These axial and circumferential stiffener lengths are used to determine the integer number of orthogrid unit cells that can fit within the panel planform, as shown in Figure 17. Optimized stiffener and skin thicknesses and a uniform 1.750-in. stiffener height complete the section geometry definition. Along with the material density, these dimensions are then used to calculate the weight of a unit cell as 2.245 lbs, with an areal weight of 3.54 lb/ft^2. This areal weight is much heavier than the results calculated previously for the SLWT, which is due to the different load paths for the two vehicle configurations.

The sizing techniques developed for the SLWT panels are then applied to estimate the manufactured panel weights. Multiplication of the areal weight and panel planform area gives a coarse weight estimate of 958.2 lbs. Multiplication by the 24 percent non-optimum factor gives a predicted panel weight of 1188.2 lbs. Inclusion of 0.290 in.-thick skin transitions and 0.580 in.-thick weld lands (calculated using weld repair allowable stresses from Ref. 9) with the orthogrid weight gives a refined weight estimate of 1099.5 lbs. The predicted panel weight, after applying the 3 percent non-optimum factor, is equal to 1132.5 lbs. These predicted panel weights are within 4.8 percent of each other.

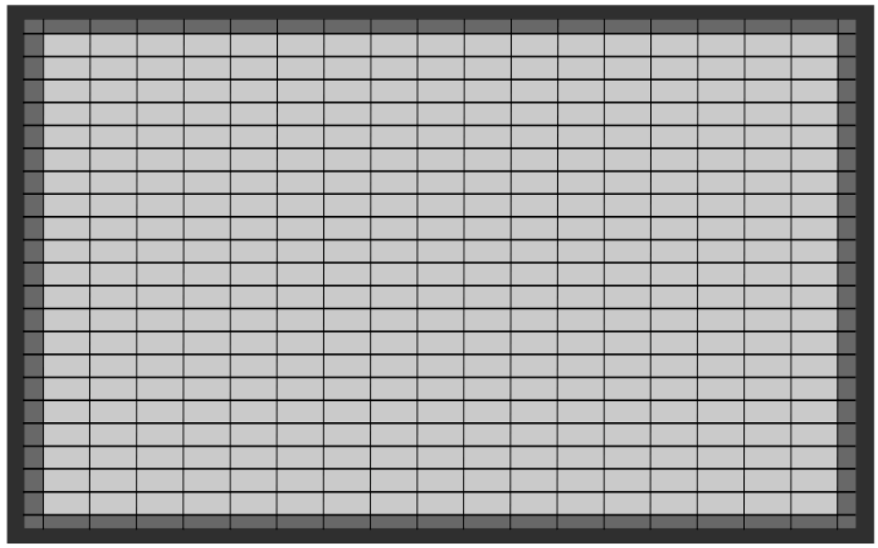

Figure 17. Ares V acreage panel layout.

Panel thickness	Skin thickness	Stiffener height	Axial stiff. thickness	Axial stiff. length	Circ. stiff. thickness	Circ. stiff. length
1.910	0.160	1.750	0.300	13.520	0.100	6.760

Table 4. Ares V orthogrid unit cell dimensions, in.

Concluding remarks

In this study, non-optimum factors are computed for the LH_2 tank barrel panels of the Space Shuttle SLWT using actual panel weights and manufacturing drawing dimensions. For acreage panels, approximately 76 percent of the panel weight is attributable to the minimum-thickness orthogrid skin and stiffeners in the center of the panel, 21 percent to the surrounding panel edges and weld lands, and only 3 percent to design details such as machining fillets, and localized skin and stiffener thickness variations. These proportions are consistent for a variety of different orthogrid configurations within the SLWT LH_2 tank barrel panels.

The consistent acreage non-optimum factors computed here suggest that relatively simple models can be used to accurately predict the weight of large portions of the structural components of future launch vehicles. Although developed for orthogrid construction, the general techniques described in this report for computing non-optimum factors should also be generally applicable to monocoque and stiffened-skin wall constructions. However, further work is necessary to determine if these processes are actually applicable to other large aerospace structural components.

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