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Introduction

Fully reusable launch vehicles (RLV's) are being studied by NASA for future space transportation systems. Single-stage-to-orbit (SSTO) vehicles offer the potential for reduced Earth-to-orbit launch and operations costs, leading to more cost-effective access to space. Typically, SSTO vehicles are very sensitive to variations in weight. Small variations in the weight of the structure can lead to substantial changes in the weight of the vehicle. Therefore, vehicles with lightweight structures have a greater potential for improved performance.

One proposed concept for a single-stage RLV is a wing-body design (ref. 1), shown in figure 1. This concept includes an integral liquid hydrogen (LH2) tank, located in the aft part of the vehicle, that must carry the high axial and bending loads generated during flight. The LH2 tank for the wing-body vehicle in figure 1 may be built using methods similar to those used for fabrication of the LH2 tank of the Space Shuttle External Tank (ref. 2). The cylindrical portion of the tank is made up of several barrels with integrally machined stiffeners. The barrel ends are welded to major ring frames, and minor ring frames are mechanically attached to the stiffeners at intervals along the barrel length. The stiffeners and ring frames are necessary to prevent buckling of the tank under the applied axial and bending loads. Each barrel is assembled from eight 45-degree circumferential sections, which are welded together along their longitudinal edges.

The purpose of this study is to compare the structural efficiency of three stiffened panel concepts which may be used for the RLV fuel tanks. The three stiffened panel concepts compared here are a panel with uniformly spaced T-stiffeners, a panel with a single blade stiffener centered between each pair of T-stiffeners, and a panel with two identical blade stiffeners equally spaced between each pair of T-stiffeners. Optimization and analysis of the panels are performed with PASCO (Panel Analysis and Sizing Code, refs. 3-4), a linked-plate code for linear bifurcation buckling of panels with prismatic cross-sections. A version of PASCO for personal computers is used to perform the analyses (ref. 5). Panel analysis models are generated with MacPASCO, a personal computer-based graphical preprocessor (ref. 6) for PASCO.

PASCO analyses are used to determine optimized designs for the three stiffened panel concepts under nominal panel compressive loads from 3184 to 4450 lb/in. To provide a basis for comparison between concepts, areal weights are computed for the optimized panel designs. Total tank and barrel weights are then computed for two different tank design approaches. In the first design approach, each 45-degree circumferential section of the barrel is designed to carry the same maximum compressive load. In the second design approach, each 45-degree barrel section is designed to carry the highest compressive load in that section. The first approach is typically used for axisymmetric launch vehicles, while the second may be more appropriate for the wing-body vehicle tankage, which experiences asymmetric loads. Finally, optimized panel designs and areal weights are determined for a range of panel lengths and skin thicknesses at the maximum compressive load of 4450 lb/in. These analyses are performed to provide an estimate of the panel weight sensitivity to variation of the panel length and skin thickness.

Stiffened Panel Concepts

Three stiffened panel concepts are compared in this study. The first concept, shown in figure 2a, has identical T-stiffeners which are uniformly spaced along the panel width. Each T-stiffener is comprised of a shear web which is perpendicular to the panel skin, and a flange which is attached to the top of the web and is parallel to the skin. The stiffeners stabilize the skin and increase the panel buckling load, but also increase the panel weight. The Space Shuttle External Tank LH2 tank is fabricated from panels with uniformly spaced T-stiffeners (ref. 2). The second concept, shown in figure 2b, has a single blade stiffener centered between each pair of T-stiffeners. The blade stiffener is parallel to the T-stiffeners, and perpendicular to the skin. Panels which use this stiffener arrangement are designated as T/Blade-stiffened designs. The lightweight blade stiffener is intended to stabilize the skin between the T-stiffeners and decrease the panel weight, while still maintaining its strength. The third concept, shown in figure 2c, has two identical blade stiffeners between each pair of T-stiffeners. Panels with this stiffener arrangement are designated as T/Blade/Blade-stiffened designs. The spacing between the T-stiffeners and the blades is equal to the spacing between the two blade stiffeners. One possible variation of this concept is one in which these two dimensions are allowed to vary independently. However, this option is not examined in this study.

Tank Geometry and Loads

Tank Geometry

A representative tank barrel is shown in figure 3. Each barrel is assembled from eight separate sections, which are defined as a 45-degree sector of the tank barrel circumference. Continuous, integral stiffeners are cut out as each section is machined from plate stock. The barrel in figure 3 has major ring frames located at each end of the barrel. In addition, three minor ring frames are equally spaced along the barrel to decrease the effective column length of the stiffeners and to provide stability. The region between ring frames in a section is defined as a panel. These panels are modeled as flat, stiffened plates in PASCO. Each barrel section in the figure is comprised of four panels. The panel length is defined as the panel dimension parallel to the barrel axis of revolution; a nominal panel length of 36 inches is chosen for this study.

A representative LH2 tank for the wing-body vehicle is shown in figure 4. Structural weights will be computed for this tank configuration using results from the PASCO analyses. The length of the cylindrical portion of the tank is 684 inches, and the diameter is 336 inches. The tank cylinder is made up of three separate barrels; the length of barrel 1 is 144 inches, the length of barrel 2 is 288 inches, and the length of barrel 3 is 252 inches. The tank barrels are connected by major ring frames, also located at each end of the tank cylinder where the ellipsoidal bulkheads are attached. The tank in figure 4 has four major ring frames and sixteen minor ring frames.

Tank Loads

Tank loads are computed using flight loads from a representative ascent trajectory for the wing-body vehicle. The axial force and bending moment both vary along the length of the tank during the flight. Therefore, the equivalent compressive loads are different for each barrel in the tank. The maximum axial force in the tank is approximately 4 x 10^6 lb, and the maximum bending moment is approximately 63 x 10^6 in-lb. The axial forces are resolved into equivalent line loads by dividing the axial force by the tank circumference. The bending moments along the tank are also resolved into equivalent line loads, which vary circumferentially around the barrel. The axial loads are then added to the bending loads to determine the resulting compressive loads. Because of the direction of the bending moment, the maximum compressive load occurs at the "belly" (point a in fig. 3) of the vehicle, and decreases around the circumference towards the "spine" (point e). Points a and e are on the vertical symmetry plane of the vehicle, and points b, c and d are equally spaced at 45-degree intervals along the barrel circumference. These five points are located at the weld seams where two sections are joined.

The resultant compressive loads on the three barrels at points a through d are given in table 1. These loads are the maximum value observed along the length of each barrel section. The maximum load of 4450 lb/in occurs at point a on barrel 2, and the minimum load of 3184 lb/in occurs at point d on barrel 3. The load on the spine of the vehicles is not required because the load at point d is higher, and will size the panel between points d and e. The loads are assumed to be identical for right and left sides of the vehicle. Two effects are not modeled in this study which affect the loads in an actual tank. Circumferentially, the tank internal pressure is resisted by hoop tension in the skin, which results in biaxial loading of the panel. Longitudinally, the internal pressure also reduces the compressive load on the entire tank through an extensional force which is reacted through the tank bulkheads. Exclusion of these effects does not affect the comparison between the three stiffened panel concepts in this study.

Panel Analysis and Design

Analysis Tools

Two computer programs are used in this study. The panel analysis models are generated with MacPASCO, a graphical preprocessor for personal computers (ref. 6). Panel geometry, design variables, boundary conditions, and nominal compressive load are all defined in MacPASCO, which is then used to generate an input file for PASCO. PASCO, a linked-plate code for linear bifurcation buckling, is used to perform the analysis and optimization of the stiffened panel concepts (refs. 3-4). PASCO consists of two modules, a VIPASA eigenvalue analysis module and a CONMIN non-linear optimizer. VIPASA is used to compute buckling loads and mode shapes for a given panel configuration. CONMIN is used to minimize the panel weight index, defined as the panel weight divided by the product of the panel planform area and length (ref. 3). PASCO attempts to minimize the panel weight index while keeping the computed buckling loads at or above the nominal load defined in MacPASCO. For these analyses, PASCO is assumed to have successfully converged if the computed buckling loads are within 95 percent of the nominal load from table 1; this typically requires about ten optimization cycles in CONMIN.

The panel weight index from PASCO is multiplied by the panel length to determine the areal weight (weight per unit area) of the panel. Panel and barrel weights are then calculated from the computed areal weights using the following equations.

$$\text{Panel weight} = (2\pi rL/8) \times (\text{panel areal weight}) \quad (1)$$

In equation (1), r is the radius of the barrel, L is the panel length, and the areal weight is determined from the PASCO optimization. Note that the weight in equation (1) is for one panel of one section of a tank barrel.

$$\text{Barrel weight} = (\Sigma \text{ panel weight}) \times (\text{number of panels}) \quad (2)$$

In equation (2), the sum of the panel weights is the total of the panel weights of each of the eight sections around the barrel circumference. The number of panels is the number of panels in each section of the barrel.

Analysis Models

Design variables for the three stiffened panel concepts are the width and thickness of the T- and blade-stiffeners, and the stiffener spacing. Design variables for each concept are shown in table 2. Upper and lower limits for these variables are listed, and the variables are allowed to take on any value within the specified range. The skin thickness is equal to 0.082 inches, and is not a design variable because it is sized by internal tank pressures. The lower limit on stiffener thickness is determined by minimum gage limits from fabrication. The upper limit on stiffener height is often determined by the availability of standard plate thicknesses.

The design variables for the T-stiffened panel in figure 2a are the spacing between the T-stiffeners, the height and thickness of the web, and the width and thickness of the flange. The repeating element defined in MacPASCO is the shaded portion of figure 2a. The panel analysis model consists of ten of these repeating elements and is shown in figure 5a.

The T/Blade-stiffened panel concept (fig. 2b) has the same design variables as those used for the T-stiffened panel, with the addition of the height and thickness of the blade-stiffener. In this case, the stiffener spacing is defined as the distance between the T- and the blade-stiffeners. The blade-stiffener is centered between the T-stiffeners. The repeating element used is the shaded portion of figure 2b. Ten repeating elements are used to form this panel (see fig. 5b). Note that the panel for this concept is asymmetric because the repeating element from MacPASCO is asymmetric. The left side of the panel has a T-stiffener next to the panel edge, but the right side of the panel has a blade only which does not provide as much transverse stiffness.

The design variables for the T/Blade/Blade-stiffened panel concept (fig. 2c) are the same as those used for the second panel concept. The stiffener spacing for this concept is the same for the distance between the T- and blade-stiffeners, as well as the distance between the two blade stiffeners, as shown in figure 2c. The repeating element generated in MacPASCO is the shaded portion of figure 2c. Eight repeating elements are used to form the panel analyzed for this design (fig. 5c).

All of the panel designs have several common features. The designs all have simply supported edges, and a nominal panel length of 36 inches is chosen for the distance between ring frames. Tank components are assumed to be machined from Aluminum-Lithium (Al-Li) 2195 alloy. Nominal room-temperature material properties for Al-Li 2195 are listed in table 3. The tank experiences a wide range of temperatures during operation, which will cause the material properties in table 3 to vary. However, a valid comparison between the panel concepts may be made at a single temperature. Therefore, all analyses presented here are performed with the room temperature properties shown. In addition, the stiffened panel concepts in this study are all modeled as flat panels, a representation which neglects stiffening due to the curvature of the barrels. However, the ratio of barrel radius to skin thickness is over 2000 which suggests that curvature effects should be small.

Tank Design Approaches

Tank barrel weights are estimated for two different design approaches. The first approach, designated as a uniform approach, is to design each barrel section for the same maximum compressive load in the barrel. The same panel design is then uniformly replicated around the circumference of the tank barrel. This uniform approach is typically used on expendable launch vehicles, since it is advantageous for vehicles which have high production rates, which may lead to lower manufacturing costs through economies of scale. The Space Shuttle External Tank LH2 tank is built using a uniform design approach (ref. 2). One potential disadvantage of this approach is the fact that a large part of the structure is overdesigned (and therefore heavier), because every section is capable of carrying the maximum load in the barrel.

In the second approach, designated as the tailored approach, the highest compressive load in a 45-degree circumferential section of a barrel is used to design the panels in that section. Since loads are assumed to be identical for right and left sides of the vehicle, there are four unique panel designs in each barrel. Because stiffer panels are required to carry higher loads, the bending neutral axis of the barrel is shifted towards the side of the barrel which experiences the higher loads. However, this effect is not modeled in this study and the bending neutral axis is assumed to remain at the geometric center of the barrel cross-section.

The tailored design approach may save weight on vehicles like the wing-body concept which experience asymmetric loads, since this approach results in a structure which more closely matches the applied loading. Design, engineering and manufacturing costs will almost certainly be higher for tanks designed with a tailored approach, since four different panel designs are required for each barrel. However, the extreme sensitivity of RLV's to increases in structural weight makes circumferential variation of panels an option which should be considered.

Comparison of Tank and Panel Weights

Optimized Panel Designs and Areal Weights

PASCO optimization analyses are performed for the three stiffened panel concepts at each of the twelve compressive loads in table 1. The areal weights of these optimized designs are shown in tables 4a-c. Corresponding dimensions for the optimized panel designs are presented in Appendix A. For each of the twelve load cases, the T/Blade-stiffened panel has the lowest areal weight of the three panel concepts. Areal weights for the T/Blade-stiffened panels range from 1.57 to 1.73 lb/ft^2. In nearly every case, the T-stiffened panel has the next lowest areal weight, and the T/Blade/Blade-stiffened panel has the highest areal weight. For each stiffened panel design, the computed buckling load (from Appendix A) is plotted against the corresponding areal weight in figure 6. Also shown in the plot is a line (generated from linear regression through the data) for each stiffened panel concept which represents a linear relationship between the panel buckling load and the areal weight. These best-fit-lines in the figure may be used during preliminary design to predict an areal weight for a panel which must carry a given buckling load.

Barrel and Tank Weights

Tables 5a-5c compare barrel and tank weights for the uniform and tailored construction approaches described above. The barrel weights in these tables were computed using equations (1) and (2). For the three panel concepts examined, the tailored tank comprised of T/Blade-stiffened panels has the lowest total weight of 8258 lb. The T-stiffened panel shows the largest weight savings of 314 lb or 3.6 percent for a tailored approach over a uniform approach. An average weight savings of 3.4 percent is predicted for tanks if the tailored approach is used. Thus, a significant weight savings may be achieved by varying the panel designs around the circumference.

Table 6 presents a comparison of the stiffener concepts in terms of the barrel weights. The barrel weights given are computed using a tailored design approach. Use of the T/Blade stiffened panel design results in the lowest tank weight in this study. The weight of 8258 lb for the T/Blade-stiffened tailored tank represents a weight savings of 435 lb, or 5.0 percent, over the 8693 lb weight of the uniform design with T-stiffeners (which is similar to the Space Shuttle External Tank LH2 tank construction). The total tank weight for the T-stiffened panel with one blade is 1.5 percent lower than the T-stiffened panel and 2.3 percent lower than the T-stiffened panel with two blades. Note that the total tank weights presented in this study do not include the weight of the forward and aft bulkheads. Also, these analyses do not reflect weight savings from vehicle resizing, which can be up to 4 times the structural weight savings for this class of vehicle.

Variation of Nominal Panel Length and Skin Thickness

The analyses described above are performed for constant panel length and skin thickness. Therefore, an estimate of the weight sensitivity to variation of these two properties is necessary. Trade studies on the panel length and skin thickness are performed in order to determine the optimized panel designs for the maximum compressive load of 4450 lb/in.

Variation of Panel Length

For this portion of the study, optimized panel designs are computed for each of the three panel concepts at panel lengths from 30 to 42 inches in 3 inch increments. A PASCO analysis is performed for each combination of stiffener design and panel lengths at an applied load of 4450 lb/in. Panel areal weights are computed for each combination of panel concept and skin thickness, and are presented in table 7. A lower panel length corresponds to a lower areal weight for the panel. This result makes sense because short structures are more efficient in buckling. The optimized panel designs for the different panel lengths are presented in tables B1-B3 of appendix B.

Variation of the panel length is of interest because the panel length represents the distance between ring frames. If the ring frames are spaced further apart the panels will be longer and fewer ring frames will have to be used. However, if the panels are longer, the panel areal weight may be higher. There will have to be a tradeoff between the panel weight and the number of ring frames used. More extensive studies which include sizing of minor ring frames are necessary to determine an optimal combination of panel length and number of minor ring frames which minimizes the overall tank weight.

Variation of Skin Thickness

Optimized panel designs are computed for each of the three panel concepts at skin thicknesses of 0.074, 0.082, and 0.090 inches. A PASCO analysis is performed for each combination of stiffener design and skin thickness at an applied load of 4450 lb/in. Panel areal weights are computed for each combination of panel concept and skin thickness, and are presented in table 8. The panel areal weight is lowest at a thickness of 0.074 inches for each of the three stiffener concepts. The T/Blade-stiffened panel with a skin thickness of 0.074 inches has an areal weight of 1.64 lb/ft^2, the lowest areal weight of the nine designs considered in this portion of the study. For each of the three panel concepts, the panel areal weight is about 7 percent higher for the designs with an 0.090 inch skin than for designs with an 0.074 inch skin. The optimized panel designs for the different skin thickness are presented in tables B4-B6 of appendix B.

Analysis results indicate that stiffeners weigh less for panels with thicker skins, but the decrease in stiffener weight is offset by a larger increase in skin weight, for a net increase in panel areal weight. Evaluation of variable skin thicknesses is important, because higher yield stresses at cryogenic temperatures may allow portions of the tank which are immersed in fuel to have thinner skins. Since the skins account for the majority of the panel weight, significant savings in panel weights will result from thinner skins. So, while thinner skins are desirable, minimum skin thicknesses will still be determined by material yield stresses at operating pressures and temperatures.

Concluding Remarks

The structural efficiency of three stiffened panel concepts is compared for a range of compressive loads from 3184 to 4450 lb/in. These three concepts are a T-stiffened panel, a panel with a single blade stiffener between each pair of T-stiffeners, and a panel with two blade stiffeners between each pair of T-stiffeners. Optimized panel designs are computed for each load case for a fixed panel length of 36 inches and a skin thickness of 0.082 inch. The T/Blade-stiffened panel concept consistently shows a lower areal weight than the other two panel concepts.

Structural weights are estimated for the cylindrical portion of a representative RLV fuel tank and compared for two design approaches. A uniform approach permits each circumferential section of the tank to carry the same maximum compressive load, and results in a highly conservative design. A tailored design approach allows each 45-degree circumferential section of the tank wall to be designed by the highest compressive load in that section, and results in a structure which is approximately 300 lb lighter than the tank designed with the uniform approach. While the uniform approach is probably more economical to produce, the tailored approach results in a lighter structure that is more closely designed for the applied loading. For the representative tank with a tailored design approach, the use of the T/Blade stiffening concept results in a tank which weighs up to 200 lb less than tailored tanks which use the other stiffened panel concepts. Use of a uniform design approach and T/Blade stiffening results in a tank which weighs approximately 170 lb less than uniform tanks which use the other two concepts.

Optimized panel designs are also determined for variation of the nominal panel length and skin thickness at the maximum compressive load of 4450 lb/in. These analyses indicate that reducing the panel length and skin thickness both reduce the areal weight of the three panel concepts evaluated. As before, the areal weight of a panel with the T/Blade stiffening is always lower than the areal weight of the other two concepts. However, other issues have to be considered. While reducing the panel length results in a lower panel areal weight, the number of minor ring frames in the tank also increases. Therefore, additional analyses are necessary to determine what optimal combination of panel length and number of ring frames will minimize the total tank weight. Also, the operating pressure and temperature of the tank must be considered to size the skin thickness.

Of the three stiffened panel concepts evaluated in this study, the panel concept which has a single blade stiffener centered between each pair of T-stiffeners has the lowest areal weight for a range of loads, panel lengths, and skin thicknesses. Structural weight reductions of several hundred pounds for a representative fuel tank may generate additional empty weight reductions when the launch vehicle is resized to include the lighter tankage.

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Table 1: Nominal Load on Each Barrel (lb/in)

	point a	point b	point c	point d
Barrel 1	3950	3826	3525	3225
Barrel 2	4450	4249	3763	3277
Barrel 3	4400	4191	3688	3184

Table 2: Design Variable Ranges for Stiffened Panel Concepts— Maximum and Minimum Dimensions For:

	T-Stiffened	T/Blade	T/Blade/Blade
stiffener spacing (in)	6.000/2.000	3.000/1.000	8.000/1.000
height of web (in)	2.000/1.000	2.000/1.000	2.000/1.000
thickness of web (in)	0.100/0.040	0.100/0.040	0.100/0.040
width of flange (in)	2.000/0.000	2.000/0.000	2.000/0.000
thickness of flange (in)	0.100/0.040	0.100/0.040	0.100/0.040
height of blade (in)	N/A	1.700/0.000	1.700/0.000
thickness of blade (in)	N/A	0.100/0.040	0.100/0.040

Table 3: Material Properties for AL-Li 2195

Young’s modulus (lb/in^2)	11,000,000
Shear modulus (lb/in^2)	4,135,000
Density (lb/in^3)	0.098
Poisson’s ratio	0.33
Yield stress (lb/in^2)	79,000
Ultimate stress (lb/in^2)	82,000

Shear stress (lb / in^2)	45,000

Table 4a: Areal Weights for Barrel 1 (lb/ft^2)

	point a	point b	point c	point d
T-Stiffened	1.68	1.67	1.64	1.60
T/Blade	1.66	1.65	1.63	1.58
T/Blade/Blade	1.70	1.68	1.65	1.61

Table 4b: Areal Weights for Barrel 2 (lb/ft^2)

	point a	point b	point c	point d
T-Stiffened	1.75	1.72	1.65	1.60
T/Blade	1.73	1.68	1.64	1.59
T/Blade/Blade	1.75	1.74	1.67	1.62

Table 4c: Areal Weights for Barrel 3 (lb/ft^2)

	point a	point b	point c	point d
T-Stiffened	1.74	1.71	1.65	1.59
T/Blade	1.70	1.68	1.63	1.57
T/Blade/Blade	1.76	1.72	1.67	1.61

Table 5a: Barrel and Tank Weights for T-Stiffened Panels

	Barrel 1	Barrel 2	Barrel 3	Total Tank Weight
uniform tank design (lb)	1772	3701	3220	8693
tailored tank design (lb)	1737	3551	3091	8379
weight reduction from uniform tank design (lb)	35	150	129	314

weight reduction from uniform tank design (percent)	2.0%	4.1%	4.0%	3.6%

Table 5b: Barrel and Tank Weights for T/Blade-Stiffened Panels

	Barrel 1	Barrel 2	Barrel 3	Total Tank Weight
uniform tank design (lb)	1750	3654	3140	8544
tailored tank design (lb)	1718	3503	3037	8258
weight reduction from uniform tank design (lb)	32	151	103	286
weight reduction from uniform tank design (percent)	1.8%	4.1%	3.3%	3.4%

Table 5c: Barrel and Tank Weights for T/Blade/Blade-Stiffened Panels

	Barrel 1	Barrel 2	Barrel 3	Total Tank Weight
uniform tank design (lb)	1789	3697	3247	8733
tailored tank design (lb)	1753	3577	3120	8450
weight reduction from uniform tank design (lb)	36	120	127	283
weight reduction from uniform tank design (percent)	2.0%	3.3%	3.9%	3.2%

Table 6a: Tank and Barrel Weights for the Tailored Approach and the Weight Savings of the T/Blade Concept

	Barrel 1	Barrel 2	Barrel 3	Total Tank Weight
T-Stiffened	1737	3551	3091	8379
T/Blade	1718	3503	3037	8258
T/Blade/Blade	1753	3577	3121	8451

% savings of T/Blade over T-Stiffened	1.1%	1.4%	1.8%	1.5%
% savings of T/Blade over T/Blade/Blade	2.0%	2.1%	2.8%	2.3%

Table 6b: Tank and Barrel Weights for the Uniform Approach and the Weight Savings of the T/Blade Concept

	Barrel 1	Barrel 2	Barrel 3	Total Tank Weight
T-Stiffened	1772	3701	3220	8693
T/Blade	1750	3654	3140	8545
T/Blade/Blade	1789	3697	3247	8733
% savings of T/Blade over T-Stiffened	1.3%	1.3%	2.6%	1.7%
% savings of T/Blade over T/Blade/Blade	2.2%	1.2%	3.4%	2.2%

Table 7: Areal Weights for Variation of the Panel Length (lb/ft^2)

Panel Length	30 in	33 in	36 in	39 in	42 in
T-Stiffened	1.74	1.73	1.75	1.83	1.83
T/Blade	1.65	1.68	1.73	1.75	1.81
T/Blade/Blade	1.71	1.72	1.75	1.78	1.82

Table 8: Areal Weights for Variation of the Skin Thickness (lb/ft^2)

Skin Thickness	0.074 in	0.082 in	0.090 in
T-Stiffened	1.72	1.75	1.81
T/Blade	1.64	1.73	1.76

T/Blade/Blade	1.70	1.75	1.83

APPENDIX A: Optimized Panel Designs for Nominal Panel Length and Skin Thickness

Table A1: T-Stiffened Panel Designs for Barrel 1

	point a	point b	point c	point d
computed buckling load (lb / in)	3952	3824	3522	3225
stiffener spacing (in)	2.880	2.913	3.000	3.124
height of web (in)	1.733	1.741	1.765	1.752
thickness of web (in)	0.040	0.040	0.040	0.040
width of flange (in)	0.792	0.752	0.714	0.669
thickness of flange (in)	0.047	0.047	0.046	0.040
areal weight (lb / ft^2)	1.68	1.67	1.64	1.60

Table A2: T-Stiffened Panel Designs for Barrel 2

	point a	point b	point c	point d
computed buckling load (lb / in)	4449	4247	3762	3276
stiffener spacing (in)	2.750	2.804	2.928	3.102
height of web (in)	1.731	1.735	1.750	1.755
thickness of web (in)	0.042	0.041	0.040	0.040
width of flange (in)	0.866	0.835	0.734	0.678
thickness of flange (in)	0.050	0.049	0.045	0.040
areal weight (lb / ft^2)	1.75	1.72	1.65	1.60

Table A3: T-Stiffened Panel Designs for Barrel 3

	point a	point b	point c	point d
computed buckling load (lb / in)	4401	4188	3685	3182
stiffener spacing (in)	2.764	2.818	2.950	3.136
height of web (in)	1.741	1.737	1.756	1.752
thickness of web (in)	0.042	0.041	0.040	0.040
width of flange (in)	0.851	0.824	0.724	0.663
thickness of flange (in)	0.049	0.048	0.044	0.040
areal weight (lb / ft^2)	1.74	1.71	1.65	1.59

Table A4: T/Blade-Stiffened Panel Designs for Barrel 1

	point a	point b	point c	point d
computed buckling load (lb / in)	3946	3822	3524	3224
stiffener spacing (in)	2.303	2.383	2.190	2.576
height of web (in)	1.940	1.904	1.863	1.867
thickness of web (in)	0.048	0.049	0.042	0.040
width of flange (in)	1.053	1.084	0.943	0.998
thickness of flange (in)	0.045	0.045	0.046	0.052
height of blade (in)	0.576	0.602	0.608	0.663
thickness of blade (in)	0.040	0.040	0.040	0.040
areal weight (lb / ft^2)	1.66	1.65	1.63	1.58

Table A5: T/Blade-Stiffened Panel Designs for Barrel 2

	point a	point b	point c	point d
computed buckling load (lb / in)	4430	4177	3732	3280
stiffener spacing (in)	2.067	2.472	2.372	2.465
height of web (in)	1.930	1.928	1.907	1.868
thickness of web (in)	0.050	0.047	0.045	0.041
width of flange (in)	1.049	1.196	1.108	1.033
thickness of flange (in)	0.046	0.055	0.048	0.047
height of blade (in)	0.587	0.661	0.590	0.590
thickness of blade (in)	0.040	0.040	0.040	0.042
areal weight (lb / ft^2)	1.73	1.68	1.64	1.59

Table A6: T/Blade-Stiffened Panel Designs for Barrel 3

	point a	point b	point c	point d
computed buckling load (lb / in)	4315	4008	3686	3181
stiffener spacing (in)	2.260	2.388	2.298	2.508
height of web (in)	1.919	1.959	1.928	1.860
thickness of web (in)	0.048	0.051	0.046	0.041
width of flange (in)	1.136	1.148	0.999	1.052
thickness of flange (in)	0.052	0.046	0.043	0.045
height of blade (in)	0.566	0.590	0.532	0.598
thickness of blade (in)	0.040	0.040	0.040	0.040

areal weight (lb / ft^2)	1.70	1.68	1.63	1.57

Table A7: T/Blade/Blade-Stiffened Panel Designs for Barrel 1

	point a	point b	point c	point d
computed buckling load (lb / in)	3930	3776	3482	3137
stiffener spacing (in)	1.612	1.583	1.899	1.827
height of web (in)	1.920	1.894	1.918	1.945
thickness of web (in)	0.045	0.043	0.043	0.041
width of flange (in)	1.083	1.033	1.205	1.033
thickness of flange (in)	0.050	0.053	0.051	0.046
height of blade (in)	0.548	0.514	0.689	0.626
thickness of blade (in)	0.040	0.040	0.040	0.040
areal weight (lb / ft^2)	1.70	1.68	1.65	1.61

Table A8: T/Blade/Blade-Stiffened Panel Designs for Barrel 2

	point a	point b	point c	point d
computed buckling load (lb / in)	4280	4143	3619	3255
stiffener spacing (in)	1.732	1.670	1.570	1.916
height of web (in)	1.962	1.930	1.885	1.914
thickness of web (in)	0.048	0.045	0.042	0.041
width of flange (in)	1.261	1.233	1.033	1.174
thickness of flange (in)	0.056	0.056	0.051	0.048
height of blade (in)	0.673	0.631	0.484	0.672
thickness of blade (in)	0.040	0.040	0.040	0.040

areal weight (lb / ft^2)	1.75	1.74	1.67	1.62

Table A9: T/Blade/Blade-Stiffened Panel Designs for Barrel 3

	point a	point b	point c	point d
computed buckling load (lb / in)	4235	4084	3654	3112
stiffener spacing (in)	1.690	1.733	1.823	1.838
height of web (in)	1.981	1.947	1.918	1.939
thickness of web (in)	0.047	0.045	0.042	0.041
width of flange (in)	1.232	1.186	1.163	1.037
thickness of flange (in)	0.057	0.057	0.054	0.046
height of blade (in)	0.655	0.659	0.666	0.635
thickness of blade (in)	0.040	0.040	0.040	0.040
areal weight (lb / ft^2)	1.76	1.72	1.67	1.61

APPENDIX B: Optimized Panel Designs for Variable Panel Length and Skin Thickness

Table B1: T-Stiffened Panel Designs for Varying Panel Length

Panel Length	30 in	33 in	36 in	39 in	42 in
computed buckling load (lb/in)	4447	4447	4449	4446	4451
stiffener spacing (in)	2.347	2.729	2.750	2.781	2.812
height of web (in)	1.582	1.642	1.731	1.834	1.904
thickness of web (in)	0.040	0.040	0.050	0.044	0.044
width of flange (in)	0.773	0.838	0.866	0.875	0.924
thickness of flange (in)	0.042	0.047	0.042	0.051	0.055
areal weight (lb/ft^2)	1.74	1.73	1.75	1.83	1.83

Table B2: T/Blade-Stiffened Panel Designs for Varying Panel Length

Panel Length	30 in	33 in	36 in	39 in	42 in
computed buckling load (lb/in)	4402	4447	4430	4432	4450
stiffener spacing (in)	2.059	2.229	2.067	2.296	2.091
height of web (in)	1.760	1.848	1.930	1.981	2.000
thickness of web (in)	0.048	0.048	0.050	0.048	0.047
width of flange (in)	0.985	1.077	1.049	1.253	1.248
thickness of flange (in)	0.040	0.048	0.046	0.058	0.061
height of blade (in)	0.512	0.590	0.587	0.590	0.598
thickness of blade (in)	0.040	0.040	0.040	0.041	0.040

areal weight (lb / ft^2)	1.65	1.68	1.73	1.75	1.81

Table B3: T/Blade/Blade-Stiffened Panel Designs for Varying Panel Length

Panel Length	30 in	33 in	36 in	39 in	42 in
computed buckling load (lb / in)	4448	4450	4280	4448	4446
stiffener spacing (in)	1.771	1.724	1.732	1.623	1.549
height of web (in)	1.789	1.855	1.962	2.023	2.113
thickness of web (in)	0.050	0.046	0.048	0.049	0.051
width of flange (in)	1.244	1.243	1.261	1.219	1.234
thickness of flange (in)	0.047	0.055	0.056	0.058	0.056
height of blade (in)	0.748	0.670	0.673	0.581	0.509
thickness of blade (in)	0.041	0.040	0.040	0.040	0.040
areal weight (lb / ft^2)	1.71	1.72	1.75	1.78	1.82

Table B4: T-Stiffened Panel Designs for Varying Skin Thickness

Skin Thickness	0.074 in	0.082 in	0.090 in
computed buckling load (lb / in)	4434	4449	4446
stiffener spacing (in)	2.419	2.750	3.098
height of web (in)	1.691	1.731	1.795
thickness of web (in)	0.047	0.042	0.042
width of flange (in)	0.857	0.866	0.861
thickness of flange (in)	0.042	0.050	0.050
areal weight (lb / ft^2)	1.72	1.75	1.81

Table B5: T/Blade-Stiffened Panel Designs for Varying Skin Thickness

Skin Thickness	0.074 in	0.082 in	0.090 in
computed buckling load (lb / in)	4451	4430	4308
stiffener spacing (in)	2.108	2.067	2.342
height of web (in)	1.881	1.930	1.969
thickness of web (in)	0.052	0.050	0.045
width of flange (in)	1.183	1.049	0.933
thickness of flange (in)	0.050	0.046	0.052
height of blade (in)	0.555	0.587	0.603
thickness of blade (in)	0.040	0.040	0.040
areal weight (lb / ft^2)	1.64	1.73	1.76

Table B6: T/Blade/Blade-Stiffened Panel Designs for Varying Skin Thickness

Skin Thickness	0.074 in	0.082 in	0.090 in
computed buckling load (lb / in)	4398	4280	4446
stiffener spacing (in)	1.667	1.732	1.694
height of web (in)	1.937	1.962	1.976
thickness of web (in)	0.047	0.048	0.046
width of flange (in)	1.291	1.261	1.109
thickness of flange (in)	0.060	0.056	0.057
height of blade (in)	0.742	0.673	0.574
thickness of blade (in)	0.043	0.040	0.040
areal weight (lb / ft^2)	1.70	1.75	1.83

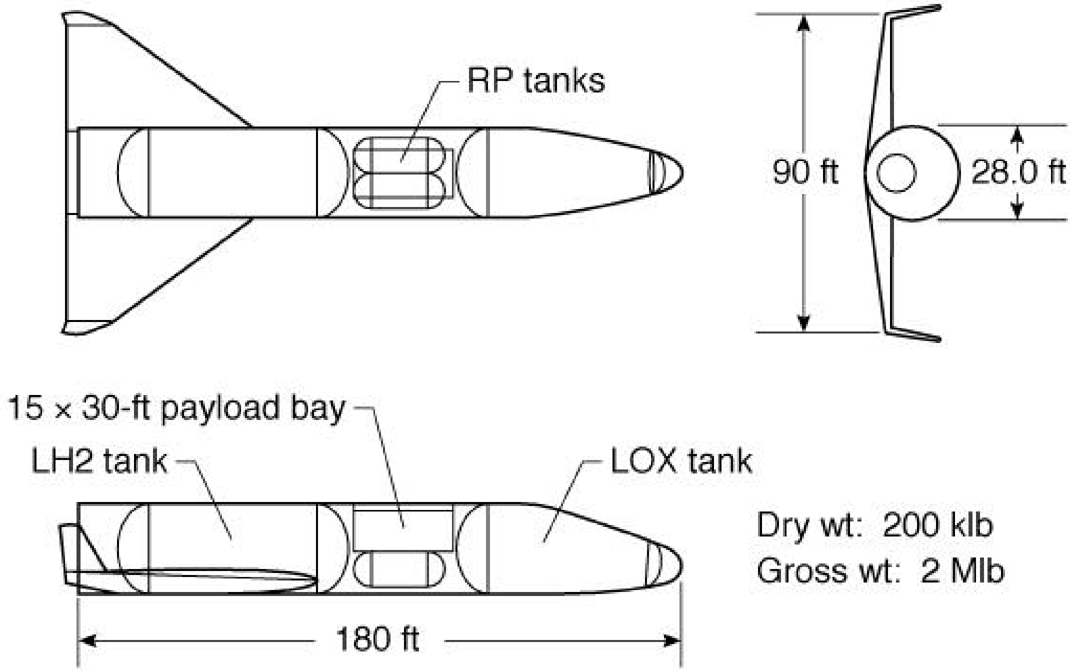
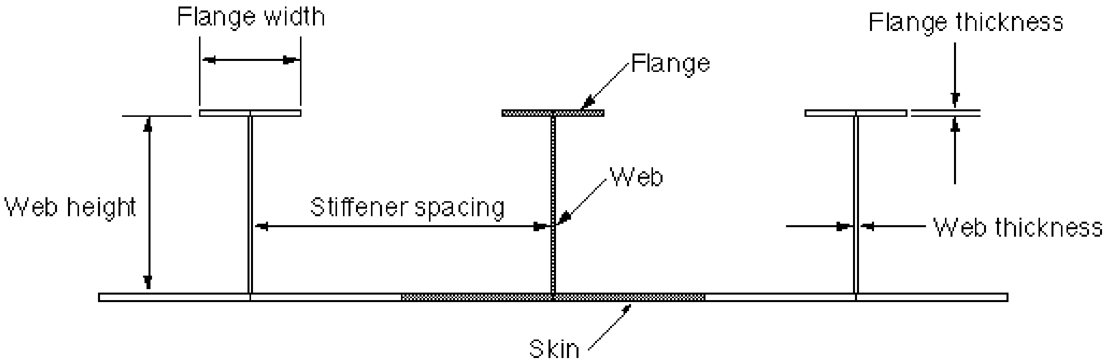
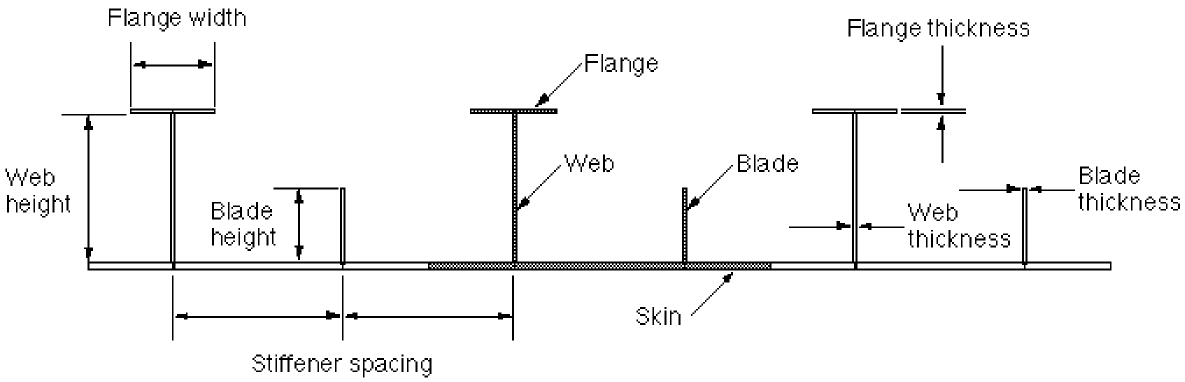


Figure 1: Wing-body RLV concept



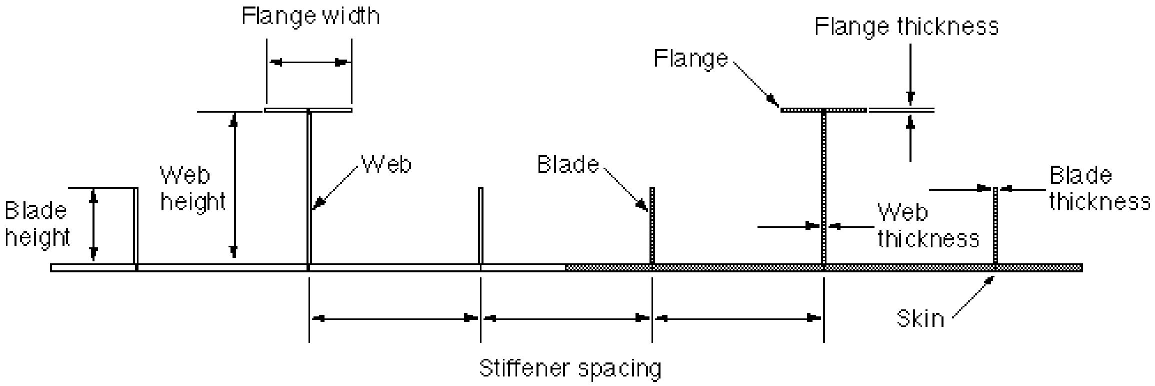
(PASCO repeating element shown as shaded portion)

Figure 2a: T-stiffened panel concept



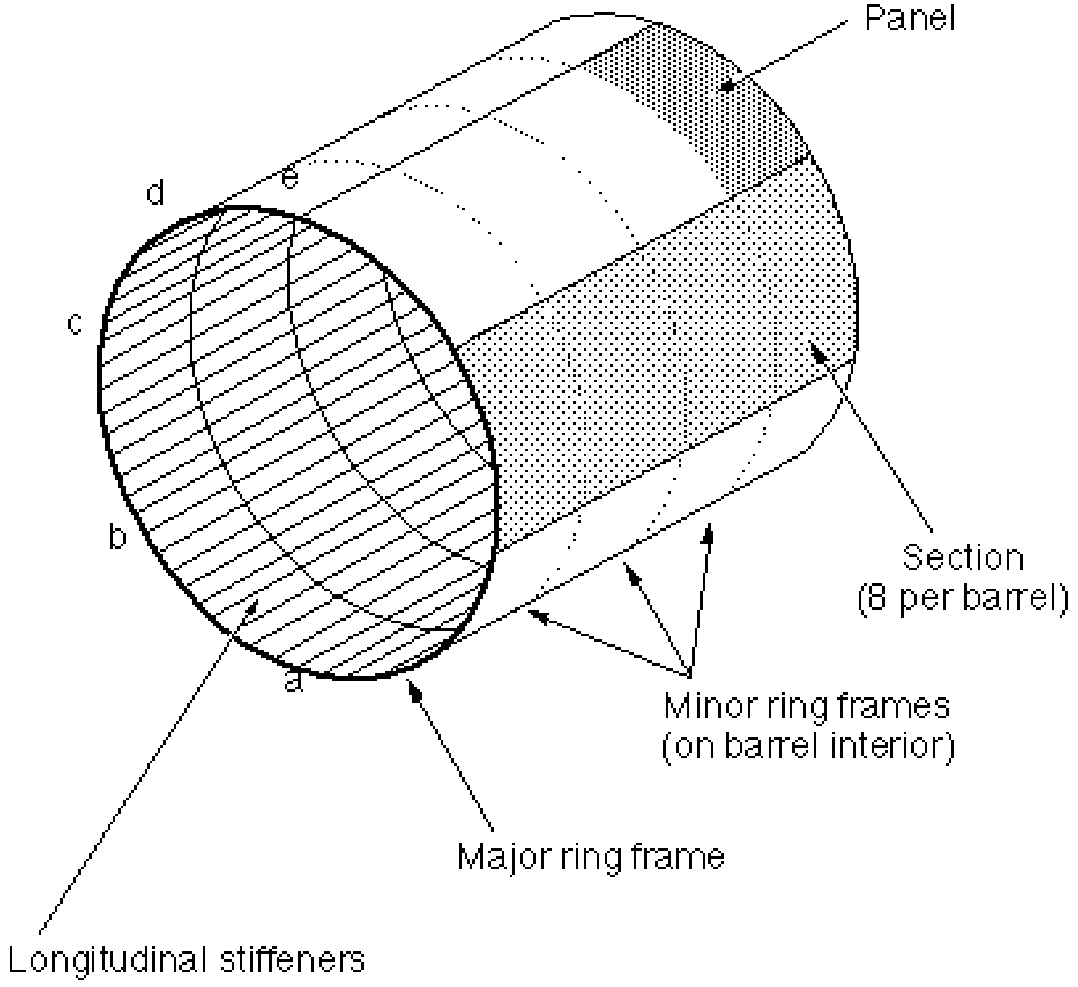
(PASCO repeating element shown as shaded portion)

Figure 2b: T/Blade-stiffened panel concept



(PASCO repeating element shown as shaded portion)

Figure 2c: T/Blade/Blade-stiffened panel concept



Loads decrease from points a to e

Figure 3: Representative tank barrel for wing-body vehicle fuel tank

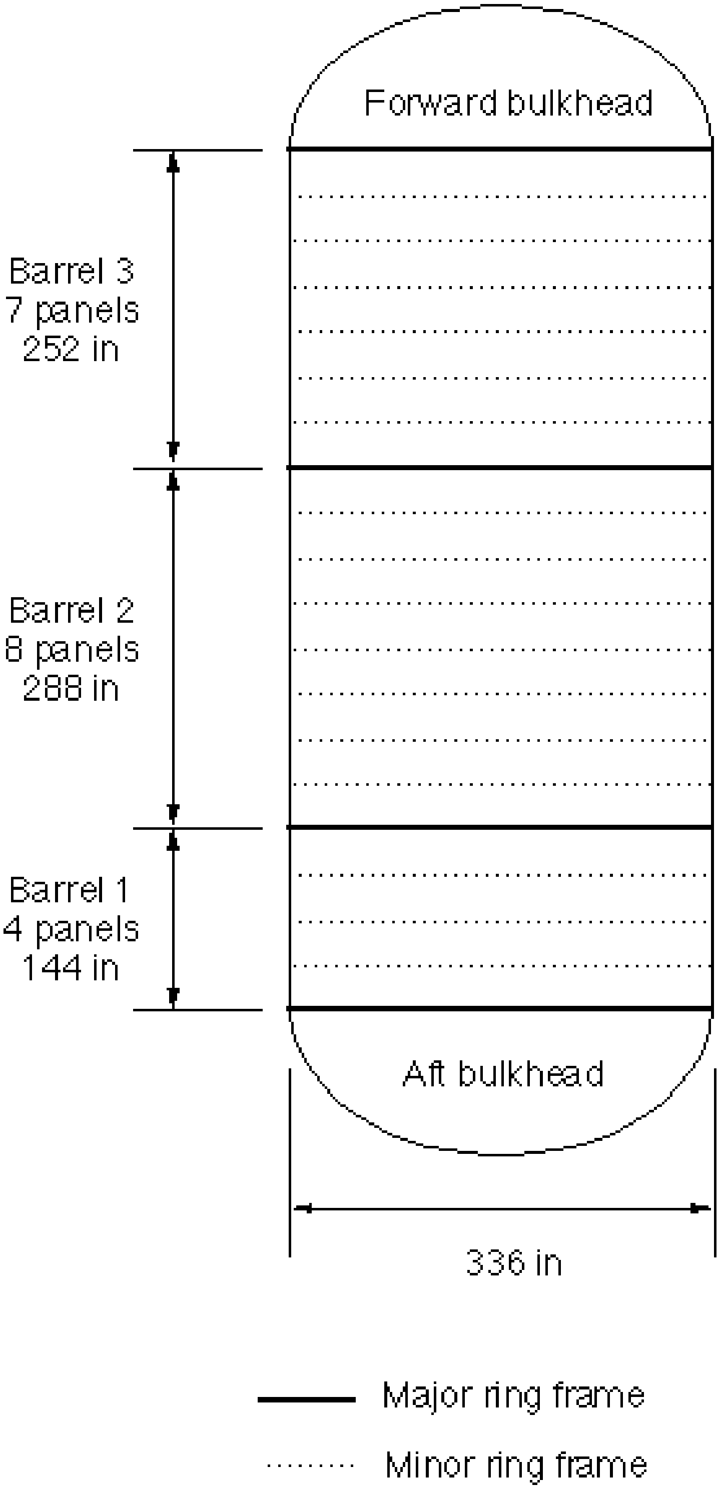


Figure 4: Representative fuel tank for wing-body vehicle

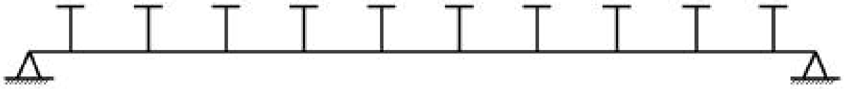


Figure 5a: End view of T-stiffened panel analysis model

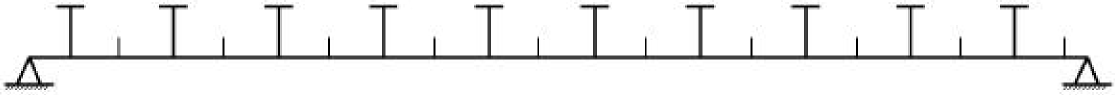


Figure 5b: End view of T/Blade-stiffened panel analysis model

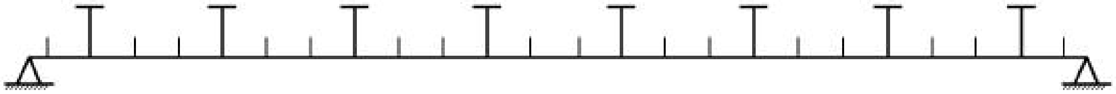


Figure 5c: End view of T/Blade/Blade-stiffened panel analysis model

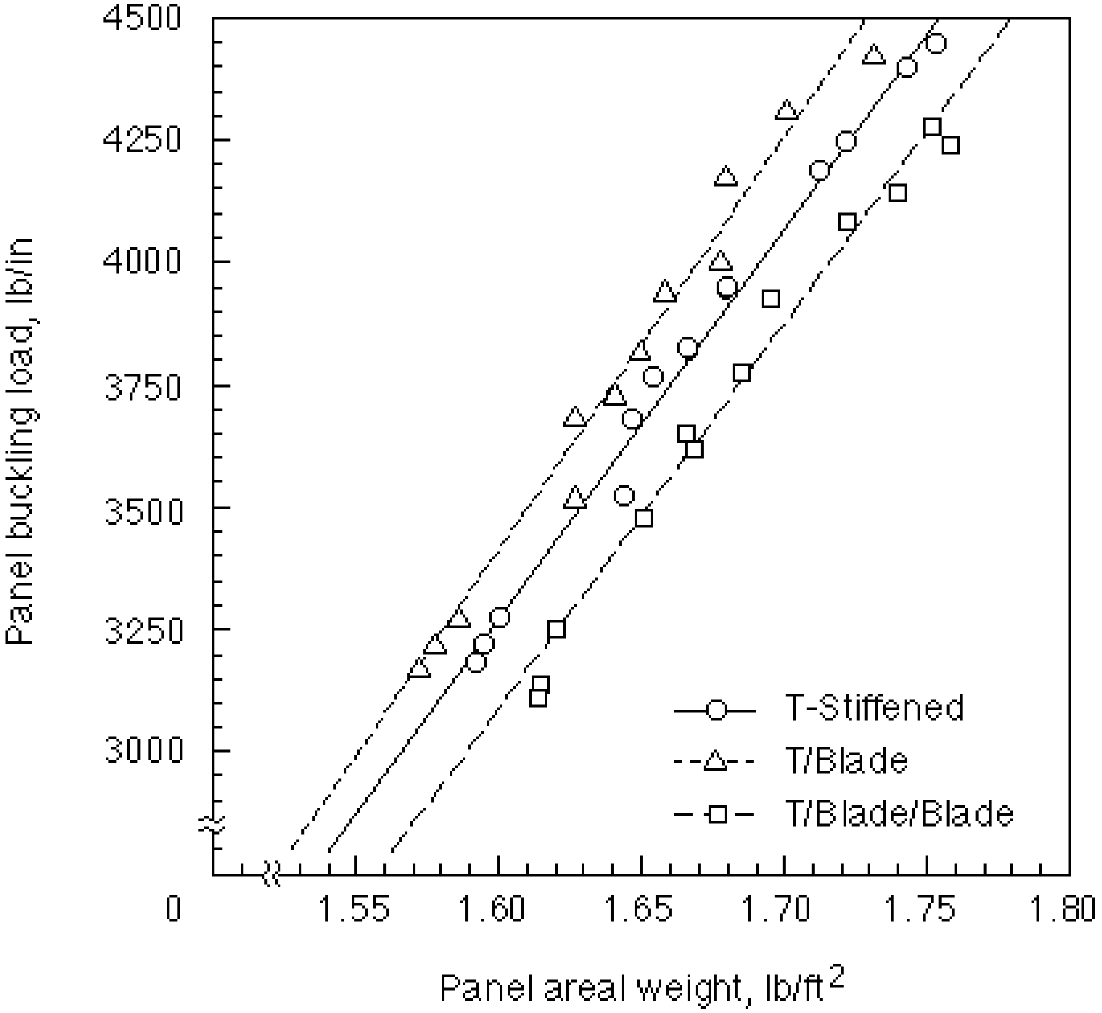


Figure 6. Panel buckling load versus panel areal weight for optimized stiffened panel designs