SPACE SHUTTLE ORBITER THRUST STRUCTURE

DESIGN PROJECT 1

Final Report

AEE 471 | Davidson

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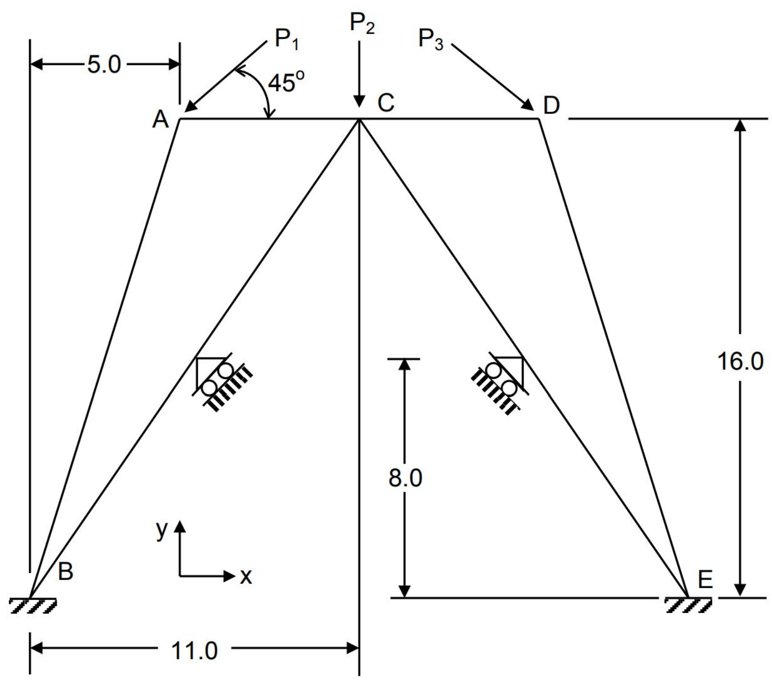
PROVIDED INFORMATION

This project encompasses the design of a space shuttle orbiter upper thrust structure. This structure is simplified and shown below in *Figure 1.* The end goal of this project is to appropriately design the idealized upper thrust structure as seen in *Figure 1* featuring minimum weights..

Figure 1

Davidson, AEE 471 Handout, 8/31/18



Each engine (with 3 in total) generates 375,000 lbf of thrust and can gimbal up to 8°. The forces *P1, P2, and P3* are shown below for each case, where cases 2 and 3 account for anticipated gimbal.

Table 1 *(Davidson, AEE 471 Handout, 8/31/18)*

	CASE 1	**CASE 2**	**CASE 3**
P1	101,196 lbf	120,000 lbf	88,391 lbf
P2	227,655 lbf	227,655 lbf	227,655 lbf
P3	104,196 lbf	88,391 lbf	120,000 lbf

Each beam will be designed from Ti-5AL-2.5Sn Titanium and B4/N5505 Boron/Epoxy, which feature the following properties:

Table 2 (Davidson, AEE 471 Handout, 8/31/18)

	Titanium	**Boron**
Modulus, E (msi)	15.500	29.600
Poisson's ratio ν	0.330	0.210
Yield stress, σ_{ys} **(ksi)**	110.000	n/a
Ultimate Strength in tension, σ_{uts} **(ksi)**	115.000	183.000
Ultimate Strength in compression, σ_{ucs} **(ksi)**	115.000	363.000
Density (lb/in^3)	0.162	0.072

For initial constraints, stuts AC and CD are to be I-beams with a maximum outer depth of four inches. Struts AB and DE are to have thin-walled circular cross sections with a maximum outer radius of four inches. Finally, struts BC and CE are to have square or rectangular cross sections featuring a maximum outer depth of six inches.

LIMIT AND DESIGN LOADS

First in this design process comes calculating limit and design loads. These will later lead to calculating appropriate factors of safeties of various failure modes. Limit loads are the internal forces experienced by each strut for each load case. The maximum limit load will be picked from the appropriate load case, and this will continue to be a driving force for further design conditions as the design develops. Design loads will be calculated, by multiplying the limit loads by a factor of safety of 1.5, or in the case of a yield stress will be a 1.25 factor of safety. Results for this aspect of the design are shown below in *Tables 3 and 4.* Design loads and peak limit loads are in *Table 4*, with the limit loads for each load case are in *Table 3.* Calculations for this are shown in Appendix A, where numbers are calculated in Appendix m in MATLAB.

Table 3 *(Appendix A and M)*

		No Gimbal (Case 1)	Gimbal Right (Case 2)	Gimbal Left (Case 3)
Load Cases and Limit Loads	P1 (lbf)	101,196	120,000	88,391
	P2 (lbf)	227,655	227,655	227,655
	P3 (lbf)	104,196	88,391	120,000
Load in Strut (lbf)	AC	50,589 (T)	58,262 (T)	42,915 (T)
	CD	50,589 (T)	42,915 (T)	58,262 (T)
	AB	77,211 (C)	88,922 (C)	65,499 (C)
	DE	77,211 (C)	65,499 (C)	88,922 (C)
	BC	138,120 (C)	151,670 (C)	124,570 (C)
	CE	138,120 (C)	124,570 (C)	151,670 (C)

Table 4 *(Appendix A and M) (T=Tension, C=Compression)*

Strut	Load Case	Peak Limit Load (lbf)	Design Load (lbf)
AC	Gimbal Right (2)	58,262 (T)	87,392 (T)
CD	Gimbal Left (3)	58,262 (T)	87,392 (T)
AB	Gimbal Right (2)	88,922 (C)	133,380 (C)
DE	Gimbal Left (3)	88,922 (C)	133,380 (C)
BC	Gimbal Right (2)	151,670 (C)	227,500 (C)
CE	Gimbal Left (3)	151,670 (C)	227,500 (C)

DESIGN CONDITION ONE

-Appendix B, C, and D, Appendix M for calculations in MATLAB (lines 70-209)

This section utilizes all Titanium Struts, utilizing the material properties available in *Table 2.*

Total Weight **(Design Condition 1 Only)** **= 620.837 lbs**

Given By Equation 1:

$$Total\ Weight\ =\ 2*Weight_{BC,CE}+2*Weight_{AB,DE}+2*Weight_{AC,CD}\quad \textbf{(1)}$$

STRUTS AB and DE, CIRCULAR CROSS SECTIONS (Tubes)

-Appendix B, Appendix M for calculations (lines 118-160)

-In Compression

Figure 2

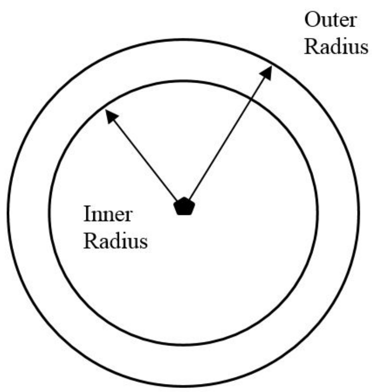


Table 5

Requirements	
Limit Load (lbf)	88,922.000
Design Load (lbf)	133,380.000
Design Geometry	
Outer Radius (in)	4.000
Inner Radius (in)	3.811
Length of strut (in)	201.156
Analysis Information	
Cross-sectional area (in^2)	4.638
Moment of Inertia I (in^4)	35.391
Correlation coefficient (γ)	0.810
Cylindrical Buckling coefficient k_x	28,729.000
Failure Predictions	

Critical Load-Euler Buckling (lbf)	133,800.000
Critical Load-Cylindrical Buckling (lbf)	1,682,700.000
Critical Load-Ultimate Failure (lbf)	533,350.000
Critical Load-Yielding (lbf)	510,170.000
Factors of Safety	
Euler Buckling	1.505
Cylindrical Buckling	18.924
Ultimate Failure	5.998
Yielding	5.737
Weight of each Strut (lbs)	**151.135**

STRUTS AC and CD, I-BEAM CROSS SECTIONS

-Appendix C, Appendix M for calculations (lines 70-117)
-In Tension

Figure 3

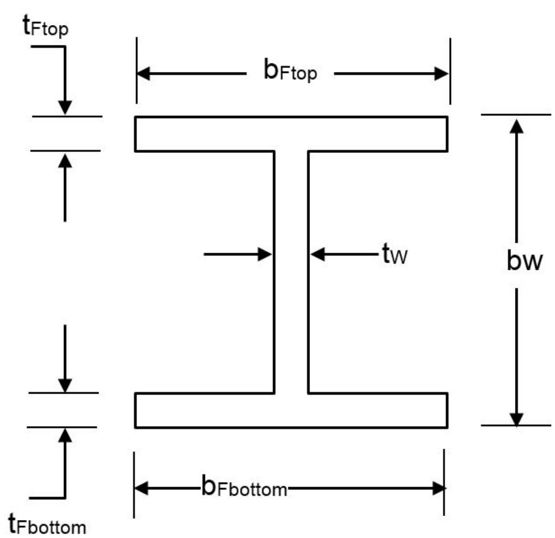


Table 6

Requirements	
Limit Load (lbf)	58,262.000
Design Load (lbf)	87,392.000
Design Geometry	
bf-bottom (in)	1.037
bf-top (in)	1.100
tf-bottom (in)	0.400
tf-top (in)	0.400
tw	0.200
bw	0.500
Length of strut (in)	72.000
Analysis Information	
Cross-sectional area (in^2)	0.795
Moment of Inertia I (in^4)	0.019
Failure Predictions	
Critical Load-Ultimate Failure (lbf)	91,402.000
Critical Load-Yielding (lbf)	87,428.000
Factors of Safety	
Ultimate Failure	1.569
Yielding	1.501
Weight of Each Strut (lbs)	9.270

STRUTS BC and CE, SQUARE/RECTANGULAR CROSS SECTIONS

-Appendix D, Appendix M for calculations (lines 161-209)
-In Compression

Figure 4

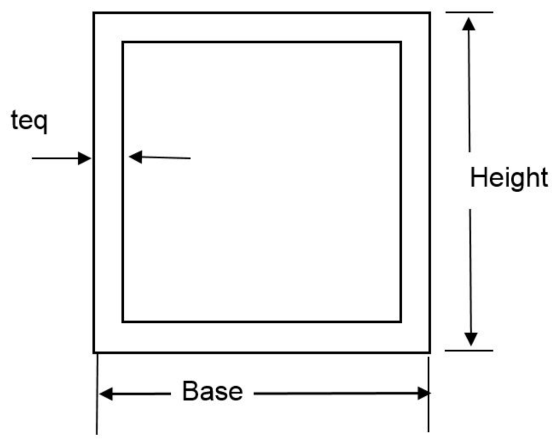


Table 7

Requirements	
Limit Load (lbf)	151,670.000
Design Load (lbf)	227,500.000
Design Geometry	
Base (in)	5.700
Height (in)	5.700
Thickness (in) *Equivalent Thickness Used*	0.180
Length of strut (in)	232.992
Analysis Information	
Cross-sectional area (in^2)	3.974
Moment of Inertia I (in^4)	20.205
Buckling coefficient k_h	4.000
Failure Predictions	
Critical Load-Euler Buckling (lbf)	227,760.000
Critical Load-Crippling (lbf)	349,750.000
Critical Load-Local Buckling	241,840.000
Critical Load-Ultimate Failure (lbf)	457,060.000

Critical Load-Yielding (lbf)	437,180.000
Factors of Safety	
Euler Buckling	1.502
Crippling	2.306
Local Buckling	1.595
Ultimate Failure	3.014
Yielding	2.883
Weight of Each Strut (lbs)	150.013

DESIGN CONDITION TWO

-Appendix E, Appendix M for calculations in MATLAB (lines 281-336)
This section utilizes all Titanium Struts, utilizing the material properties available in *Table 2.*

Total Weight (Design Condition 2 Only) = 889.029 lbs

Given By Equation 2:

$$Total\ Weight\ =\ 2 * Weight_{BC,CE_{NEW}} + 2 * Weight_{AB,DE} + 2 * Weight_{AC,CD} \qquad \textbf{(2)}$$

Table 8

Design Condition Two, Deflection	
Deflection BC, CE (in) (new dimensions)	0.303
Deflection AB, DE (in) (original dimensions)	0.249
Deflection - Y BC,CE (in) (new dimensions)	0.249
Deflection - Y AB,DE (in) (new dimensions)	0.237
Factor of Safety BC, CE (new dimensions)	1.503
Factor of Safety AB, DE (original dimensions)	1.579
New Information For BC, CE Struts	
Base (in)	6.000
Height (in)	6.000

Thickness (in) *Equivalent Thickness Used*	0.332
Cross-sectional area (in^2)	7.527
Moment of Inertia I (in^4)	40.441
Buckling coefficient k_h	4.000
Failure Predictions New BC, CE	
Critical Load-Euler Buckling (lbf)	455,860.000
Critical Load-Crippling (lbf)	662,390.000
Critical Load-Local Buckling	1,477,800.000
Critical Load-Ultimate Failure (lbf)	865,620.000
Critical Load-Yielding (lbf)	827,980.000
Factors of Safety	
Euler Buckling	3.006
Crippling	4.367
Local Buckling	9.744
Ultimate Failure	5.707
Yielding	5.459
Weight of Each Strut (lbs)	284.108

DESIGN CONDITION THREE

-Appendix F, Appendix M for calculations in MATLAB (lines 210-280)

This section utilizes Titanium and Boron Struts, utilizing the material properties available in *Table 2*.

Figure 5

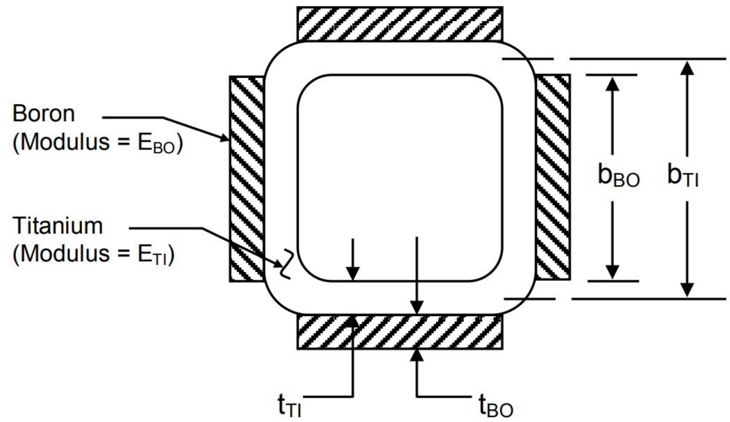


Table 9

Requirements	
Limit Load (lbf)	151,670.000
Design Load (lbf)	227,500.000
Design Geometry	
bti (in)	5.775
tti (in)	0.120
tbo (in)	0.120
bbo (in)	5.175
Length of strut (in)	232.992
Analysis Information	
Cross-sectional area (in^2)	7.516
Moment of Inertia I (in^4)	42.154
Buckling coefficient k_h	4.000
Failure Predictions	
Critical Load-Euler Buckling (lbf)	475,170.000
Critical Load-Crippling (lbf)	661,380.000
Critical Load-Local Buckling	1,340,600.000

Critical Load-Ultimate Failure (lbf)	864,300.000
Critical Load-Yielding (lbf)	826,720.000
Deflection (in)	0.303
Factors of Safety	
Euler Buckling	3.133
Crippling	4.361
Local Buckling	8.839
Ultimate Failure	5.699
Yielding	5.451
Deflection	1.500
Weight	
Titanium (lbs)	104.628
Boron (lbs)	41.670
Total Strut Weight (lbs)	146.298

FINAL DESIGN INFORMATION

Table 10

Strut	Critical Failure Mode	Factor of Safety	Weight per Strut (lbs)
AC, CD	Yielding	1.501	9.270
AB, DE	Euler Buckling	1.505	151.135
BC, CE	Deflection	1.500	146.298
TOTAL STRUCTURE	-	-	**613.410**