AOE 3024 FALL 2017 - AERO PROJECT

Figure 1: The Boeing 787

A major aerospace company is designing a new airplane, similar to the one shown in Figure 1, and the engineering staff needs your help with the design of a new wing and fuselage. For the purposes of this project, it will be assumed that the wing spar (the main structural member of the wing) carries the entire load. The skin, the ribs, the leading and trailing edges simply transmit loads to the spar. This will allow us to use our thin walled structures theory to analyze the spar. Furthermore, the loads on the fuselage from the wing and tail will be assumed to be point loads, and the distributed loads from payload and fuel with be piecewise-constant. The company's loads group has provided us with the results from their aerodynamic analysis and wind tunnel testing.

Initial data given to us by the company:

Aircraft:

Weight during take-off: 550000 lbs (This includes everything, i.e. gear, engines, structural weight, fuel, passengers, cargo, etc.)

Max torque produced by rudder: 5390000 lbs-ft

Cruise Velocity: 490 knots

Cruise Altitude: 35,000 ft

Landing Gear Weight: Main = 4320 lbs each, Nose = 2160 lbs (All gear 10,800 lbs)

Total tail weight: 8360 lbs

Engine:

Type: Pratt & Whitney PW4000 series (112-inch) Gas Turbine engine

Weight: 10000 lbs

Max thrust: 90000 lbs

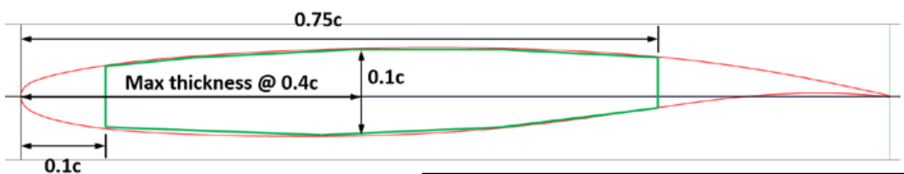
Wing parameters:

Length: 95.8 ft/Cos(θ_{sweep}) = 117.84 ft (fixed design variable)

Max. Wingbox Breadth: 65% chord
Max. Wingbox Height: 10% chord at 40% chord
Material used: Aluminum 6061 T6 (Subject to change and refinement)
Wing Area: 2062.4 sq. ft.
Root chord: 38.94 ft.
Chord at 28.7% wing length: 24.9 ft.
Tip chord: 9.735 ft.

Note: 3 chord values are given, so the wing consists of 2 trapezoids.

Sweep: 35.61°
Overall lift coefficient: 0.3925 at 3° AoA (load factor N=1)
Overall drag coefficient: 0.0948 at 3° AoA
Overall zero lift drag coefficient: 0.008755
Overall moment coefficient: -0.0370 at 3° AoA
Overall Maximum lift coefficient 1.1263 at 11° AoA
Overall Maximum negative lift coefficient -1.1294 at -13° AoA
Airfoil: Boeing Airfoil J[1] - http://airfoiltools.com/airfoil/details?airfoil=bacj-il
Moment chord: 25% chord



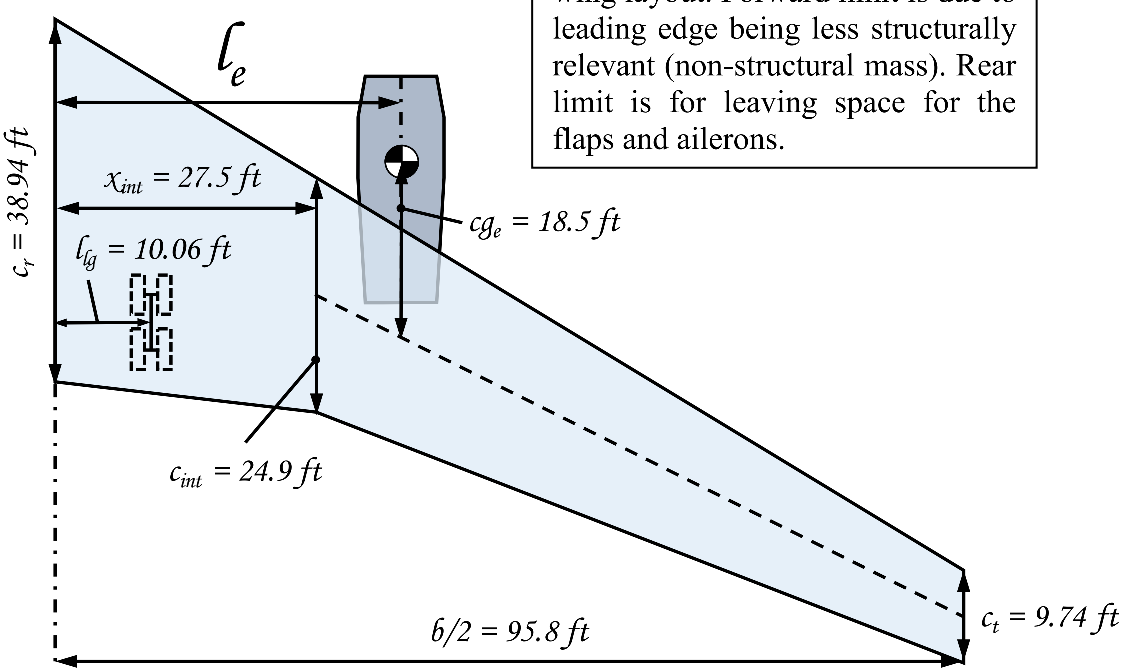


Figure 2: Usable internal space and wing layout. Forward limit is due to leading edge being less structurally relevant (non-structural mass). Rear limit is for leaving space for the flaps and ailerons.

[1] This is a supercritical airfoil, and it's designed for transonic operation. Its special shape delays the onset of drag divergence by keeping the upper surface relatively flat and using the lower surface to create most of the pressure differential responsible for lift. Consequently this moves the center of pressure backwards, near 50% chord.

Fuselage Parameters:

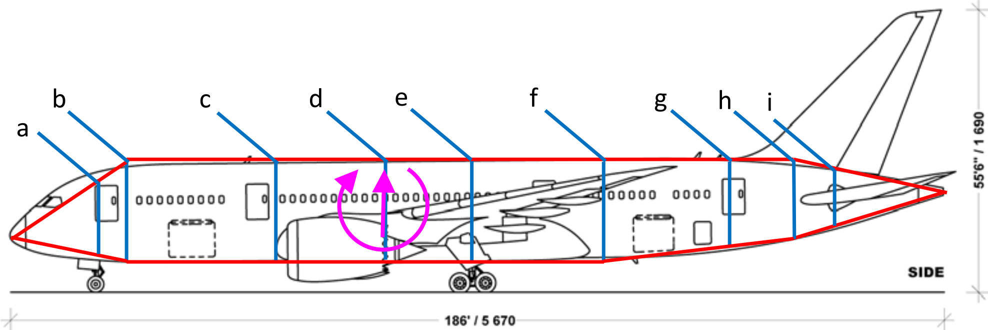


Figure 3: Dimensioned B787 drawing: "B787-800v1.0" by Julien.scavini - Own work. Licensed under CC BY-SA 3.0 via Commons. Purple arrows indicate reaction shear force and torque from the two wing roots. Assume the load transfer is via a rigid point connection.

Station data		
Key locations	ft	letter
Length	186.00	-
Root chord	38.94	-
Nose gear	17.58	a
Cockpit	22.85	b
Root Leading Edge	53.27	c
Effective wing location	74.63	d
Main gear	93.18	e
Geometry change rear 1	118.32	f
Aft cargo extent	144.42	g
Geometry change rear 2	156.11	h
Effective tail location	164.20	i
Key Diameters	full size (ft)	letter
Main body	20.04	b-f
Geometry change rear 2	15.91	i

Initial Aircraft Weight Estimation	**lbs**
MTOW	550000.00
Maximum zero-fuel weight (ZFW)	388556.79
Operating empty weight (OEW)	289441.93
No. of passengers	242.00
passenger weight	177.91
Total passenger weight	47124.86
Cargo weight	51990.00
fuselage fuel fraction	0.40
fuel weight	244494.58
fuselage fuel weight	97797.83
Usable fuel	161443.21
Unusable fuel	83051.38
OEW+Usable Fuel+Passengers	498010.00

Distributed load lengths	ft	range
Forward cargo	35.69	b to c
Aft cargo	52.21	c+(root chord) to g
Wingbox fuel	38.94	c to c+(root chord)
Passengers	146.62	b to g

Distributed Loads	lb/ft
Cargo	591.45
Fuel	2511.50
Passengers	321.41

Wing Load Cases

Case-1: Take off.

Using a wind tunnel and computational fluid dynamics, the aerodynamic loads on the wing were determined for this maximum, ultimate loading case (worst case flight condition based on V-N diagram at sea level or at cruising altitude, i.e. check positive and negative load factors) which will serve as one of our design requirements (Note: the total lift on the spar should be half of the weight of the aircraft for a load factor of 1). A simplified schematic of the spar for this loading case is shown in Figure 4, where we have replaced the actual elliptical lift distribution with a quadratic one. The maximum dimensions of the spar are determined by the selected airfoil. There is a Pratt & Whitney PW4000 series (112-inch) Gas Turbine engine, with all the accessories and cowling, that is hanging from the spar. This results in a 10,000 lb point load hanging from the wing. This load is offset from the shear center and will thus produce a point torque. In addition, the engine thrust can generate an "out-of-page" force which will also affect the net engine torque. The engine CG is 18.5 ft in front of the mean chord line (see Figure 2) and 3 ft below the mean wing thickness. Assume the line of thrust passes through the engine CG. In addition to the engine, the stowed landing gear will provide a point force of 4320 lbs at 10.5% span and 67% chord. The aircraft can carry a maximum of 223,378 lbs of fuel, 30% of which we will assume is in an individual spar/wing design space. Fuel tanks can span the entire wing and usable volume, but it is unlikely all this space will be used due to the weight limit. Assume the fuel is Jet A with a density of 6.84 lb/US gal. As a worst case approximation, you can assume that a negligible amount of fuel is used in getting to the cruising altitude and speed. Also assume that the drag per unit span $p_z(x)$, is given by:

$$-p_z(x) = \left(\frac{1}{2}\rho_\infty V^2 S C_{D_0}\right)/L + \frac{[p_y(x)]^2}{\left(\frac{1}{2}\rho_\infty V^2 S\pi e AR\right)/L}$$

where L in the equation is the full length of spar and the Oswald efficiency factor, e, should be taken to be 0.862. Thus the total drag produced over the half span is 12,723 lbs corresponding to an L/D at cruise (i.e. load factor of N=1) of 21.6. At some point you will

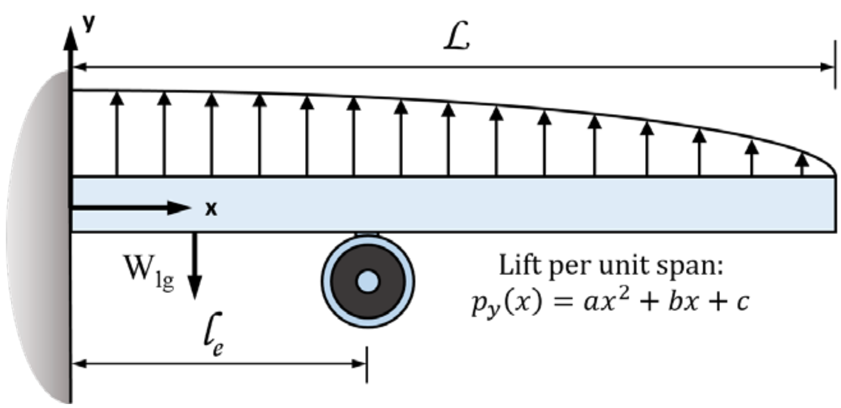


Figure 4: Loading on the wing for Case 1: Take off. $p_y(x)$ is the lift force per unit span. Assume the top of the engine is aligned with the neutral axis.

also want to consider the torque due to the fuel load along with aerodynamic twisting moment.

Case 2: One of the engines malfunctioning during cruise.
This is a very dangerous flight condition where one of the engines does not function. The thrust produced by the other engine produces a torque about the center of gravity which causes the aircraft to yaw (keep turning round and round). To prevent this, the pilot uses the counter-torque produced by the rudder of the aircraft to fly it in a straight line (Figure 5). You must be sure that the engine placement does not adversely affect the pilot's ability to control the plane in the engine out condition.

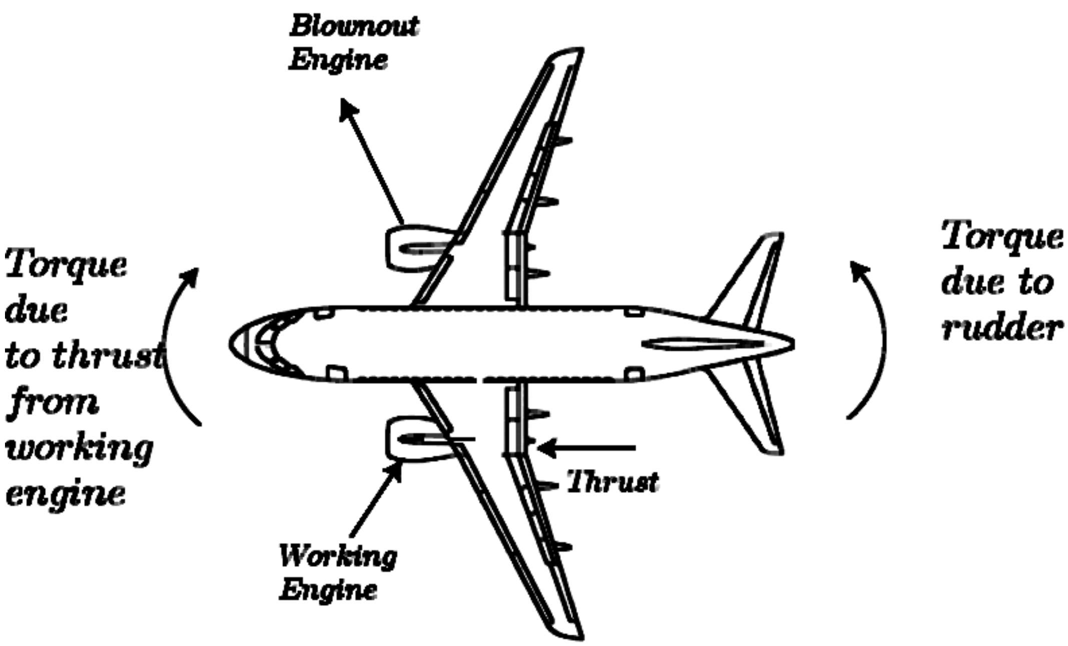


Figure 5: The case of a blown-out engine.

Case-3: Static condition

In this case the aircraft sits on the ground without any lift being produced. The only forces acting on the spar are due to the landing gear at 10.5% span, the engine hanging from it (Fig. 6), the weight of the spar, and the weight of the fuel. To accommodate ground clearance for the engine and tip, the maximum deflection magnitude, $|u_y(l_e)|$, in the no-lift case (static on the ground) should be no more than 4 ft. Use Figure 3 and the accompanying tables to determine F_{lg}. Assume the CG of the aircraft is 67 ft aft of the nose gear. Additionally, the wing tip should not hit the ground ($u_L > -7$ ft).

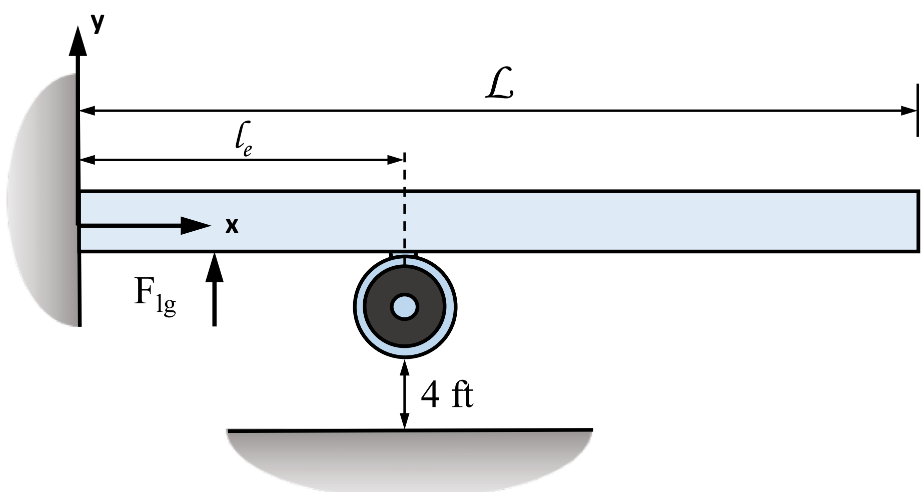
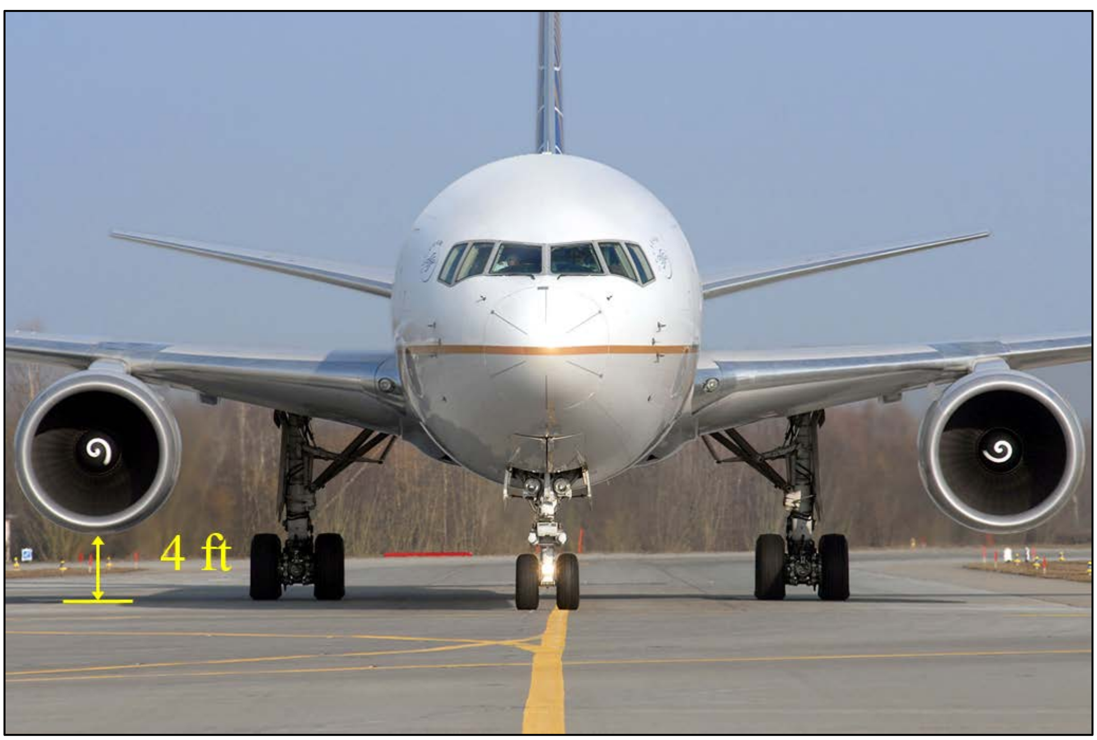


Figure 6: Diagram for Case 3: Static



Design of the wing spar:

You should strive to achieve the best wing spar design in terms of safety, weight, and cost. For this project, this means that:

- Your design must be safe for all the given flight conditions (lifting and maneuvering, static, and engine out), and should have a maneuvering envelope which allows for load factors of +2.5 and -1.5 (see FAA Regulation 25.333).
- At no given point should the values exceed the maximum values that are given, nor those that are determined by safety, e.g. the tensile or compressive yield strengths of the material you select.
- You must make sure that $\sigma_{xx}(max)$ of every cross-section of the spar is less than σ_y for your design, and if near yield, should consider if the shear stresses will cause any local yielding.
- You must make sure that $u_y(L) < 15$ ft in the lifting case.
- You must make sure that the wing tip and the engine don't touch the ground when taxiing and is within the maximum deflection limits for static loads.
- The wings must be able to produce more than enough lift to counter the maximum weight of the aircraft and additional loads during take-off and cruise associated with the positive and negative load factors.
- The dimensions of your design must fit in the green box indicated in Figure 2, and may or may not use that entire space with a single or multicell construction, and with or without stringers. Recall that the given supercritical airfoil's center of pressure is near 0.5c. You may or may not want to place your main spar accordingly.
- The stringers you develop in Part 2 (below) should not buckle. Use Euler's column buckling formula to determine the maximum allowable stringer length:

$$P_{cr} = \frac{\pi^2 E I_{min}}{L_{str}^2}$$

E is elastic modulus, I_{min} is the stringer's lowest 2nd area moment, and L_{str} is the stringer length so that ribs will be spaced according to L_{str}.

Note: Use a factor of safety of 1.15 for the design of the wing spar and fuselage. This factor has been specially approved (see FAA Regulation 25.303)

A GUIDE TO STARTING THE DESIGN PROCESS:

<u>Part 0- Place engine on the spar assuming a solid, unswept, untapered cross section.</u>

Your cross section should be based on the tip dimensions. Once you develop it, extrude it along the whole wing and use that as your beam. Determine the best location for the engine on the spar. *<u>This location must be acceptable for all the flight conditions given above.</u>*

Basically, use this step to properly code all your forces and moments on the spar without worrying too much about geometry. You are allowed to move the engine within 20 ft $\leq$ x $\leq$ 95 ft from the root of the wing. Too close to the fuselage ($\leq$ 20 ft) causes unwanted aerodynamic interference with the fuselage, and too far away could cause the airplane to Yaw too much if a single engine failed in flight (worst case 2). Also check that the tip deflection and **maximum stresses** are within the limits of this problem. Assume the dimensions of the spar given by the company and determine the position of the engine on it. Assume the material to be the one suggested by the company.

Part 1- Sweep and begin hollowing out the spar:

Now that you have the loads incorporated into your code, you can consider the wing taper, variable chord, and begin hollowing out the beam. Repeat the analysis you did in Part 0. You may wish to reconsider where the best location for the engine is.

Part 2: Reducing spar weight via tailoring the cross section of the spar for bending

For this part of the project you are required to design the cross section of the spar. Subjected to the same loading as in worst of Part-1, the spar is allowed a tip deflection of no more than 15 ft upwards. In the static case the deflection at the engine should be no more than 4 ft downwards.

As a first step, verify that the tip deflection and **maximum stresses** are within the limits of this problem for the dimensions of the spar given by the company (with the engine in the position that you determined in Part 1.). Assume the material to be the one suggested by the company.

Continue "removing" mass from the spar to reduce the weight of the beam until you reach a desirable design condition (with the engine in the position that you re-determined in Part 1.). Use caution, as you may want to check the bending in the thrust/drag direction as well. In addition to removing mass, you may want to consider moving mass to construct/place stringers within the cross section. Be sure you are within the bounds specified in Figure 2.

Finally, if you need to move your engine from the original position (that you determined in Part 1), feel free to do so in order to achieve the improved design cross section, but without exceeding any of the maximum conditions, i.e. **design is an iterative process.**

You may want to consider a variety of cross-sectional shapes, variable thicknesses in those shapes, discrete or continuous tapering of the beam outer dimensions or thicknesses, or even the use of stringers. At a minimum, place ribs at the root, tip, engine, and change-of-taper point to guarantee the wing's shape. If you do choose to include stringers, you must assure that your ribs have sufficient spacing such that the stringers do not buckle. Take rib material to be the same as spar material, and the thickness to be the minimum manufacturable value of 5 thousandths of an inch.

Please list any other factors you believe should be considered in this analysis which could impact the performance of the spar as a load-bearing member in the wing. DON'T forget to use the factor of safety of 1.15.

<u>Part 3: Choosing the right material for the spar:</u>

You are to "find" two (2) additional materials you believe would be useful for this application. Remember aircraft wings need to be light and strong and relatively inexpensive. You will need to find the same information given below for Aluminum**. Then develop a cost function that will incorporate weight of the spar and the cost of the material** and select the material you believe would best suit this problem. Note, a change in material properties may indicate a need to redesign to that material's capabilities, i.e. you *must* readjust the geometry to meet the new material's capabilities (again design is an iterative process).

Material Properties:

Material	**E (10^6 psi)**	υ	**Yield strength (ksi)**	**Density, ρ (lb/in^3)**	**Cost/lb (US $)**
Aluminum	10.2	0.33	40	0.100	$10
Titanium	16.8	0.32	110	0.1628	$50

You could also use the rule of mixtures (given below) to find an appropriate alloy of Aluminum and Titanium/Magnesium/Zinc that would help us optimize the material.

Rule of Mixtures:

$$E_c = f\,E_{al} + (1-f)\,E_{other}$$

Where E refers to any material property (such as elastic modulus or density), al refers to Aluminum, other refers to Titanium/Magnesium/Zinc, f stands for the weight % of Aluminum and (1-f) refers to weight % of Titanium/Magnesium/Zinc. You must supply references (text, journal, or website, and provide screen shots if the sources is web/software, e.g. EduPack or MatWeb.com) for material properties used.

<u>Part 4: Include torsional loads in the spar design:</u>

Starting from the chosen optimal design in Part 2, consider the torsional loads on the wing due to the engine (thrust and weight) and fuel, and due to the overall moment, M, given by $M = 1/2\,\rho_\infty V^2 S\, c c_M$. Note that c = c(x). Also note that the angle of twist induced by torsion should not exceed 2.5° as this will change the local angle of attack of the airfoil and introduce undesirable aerodynamic effects, namely divergence.

The program managers need your analysis in 9 weeks. Also awaiting your decisions is the group responsible for ordering materials, the manufacturing organization and the finance estimators.

Fuselage Load Cases (extra credit):

Case 1. Static (on ground)
Again, the aircraft is sitting on the ground. There are forces due to the wing system weight (root shear force and torque derived from static wing load case, including effect of main gear), the tail weight, the payload and fuel, the fuselage weight, and the reaction from the nose gear. Again assume the aircraft CG is 67 ft behind the nose gear. The fuselage should deflect very little, no more than 1 ft at any given location. Choose the nose gear and effective wingbox location as simple supports.

Case 2. Straight steady level flight
The fuselage must now be modeled as a free-free beam (no shear or moments at both ends, and assume everything deflects relative to CG). There will be a lift associated with the horizontal tail. Choose it such that the aircraft experiences zero net moment. Assume the aerodynamic center is 63 ft behind the nose gear. In addition, the aircraft should experience zero net vertical force. Add a correction factor to the wing lift to account for this. This will affect the moment balance and wing spar design, which in turn affects the fuselage design. Iteration will be necessary to achieve a substantially improved overall design.

Design of the fuselage:

The basic design drivers of the wing also apply to the fuselage, with the notable exception of a space constraint. Because the plane is being designed to carry a certain payload, its fuselage internal volume is effectively fixed. You can deduce the fuselage diameter distribution based on the tables in the *fuselage parameters* section.

Your main design variable is the skin thickness of the fuselage, which is primarily driven by skin buckling. Again, a code will be provided that performs buckling checks for you, but you may wish to build on it to complete a comprehensive analysis. The code will be based on Euler column and flat plate buckling. You will start out assuming uniform skin thickness, but a truly weight-optimized structure will have variable thickness depending on the stress distribution. Be sure to research common plate thicknesses that can be manufactured. These will be discrete values, so your thickness distribution will be piecewise constant.

<u>Deliverables:</u>

Spar:

- Periodic progress reports as specified in the schedule below.
- **A final report of your findings** with all calculations and explanations needed to arrive at your conclusions – use a word editor (MS Word). (Minimum 5 pages, not to exceed 10 pages including equations, figures and graphs. Bulleted summaries of procedures/key points of interest are encouraged.) It is not necessary to re-state the project description in the body of the 10 pages (you may include it as an appendix if you like), though you may highlight key constraints in your design discussion as needed. The 10 pages of design report should only contain discussion/graphs/figures/tables which make a case for your final design being the most desirable design point you were able to find. You are "selling" your design to the manager in terms of weight, cost and safety. Space is limited, so you want to consolidate the data that guided your decision processes into readily accessible charts/figures (i.e. focus should be on plotting key parameters and trend plots or stress distribution at key cross sections along the span more so than on plots of the stress distribution/deflection along the entire span; the latter can go in an appendix.)
- State assumptions and discuss your results as well as the thinking process, Do Not just turn in math or Maple/Mathematica/Matlab worksheets. (You may include these in the appendix, and should upload the working files as stated below).
- Discuss the strategy you used for modifying the design as you went through the design iterations. **NOTE:** You should do **at least 5 design iterations**: e.g. part 1, part 2, part 3, and then a redesign in light of part 4 results (i.e. go back and check engine placement, cross-section shape, and thicknesses for new materials) to yield the final design. Make trend plots of critical values (e.g. root Von Mises stress) comparing the various iterations to demonstrate the improvement. Note: You may want to document some of the discussions/decisions being made as you go through the iterations in a log, this will be very helpful when it comes to writing the final report as by that point your team may have done so much that it will be difficult to remember the details, i.e. don't leave all of the writing/explanation of iteration selection until the writing of the final report.
- **All electronic codes** used to solve the problem (Excel, Maple, Mathematica, Matlab, etc.) must be submitted in an **executable** form in order to verify results.
- A **CAD drawing** (source file) of your final design to scale as well as a scaled down version which is suitable for printing (source file and print file) in the 3D rapid prototyping machine. The maximum printer dimensions are 10in x 7in x 5in (11.5x7.5x5.8 actual max). The print file must be an .stl file.
- **A power point presentation of your results**, designed to be 10 minutes long (No more than 10 slides) illustrating the design process to achieve the final design and the key features of the final design. Your team can earn bonus points on the project grade if you upload a video of your team presenting the presentation (mp4 or avi).

- **Your final report and presentation should include the final design's dimensions, weight, cost, and V-N diagrams** (sea level and cruise altitudes) You may include this data for other designs if you think it helps make the case for your final design.

Fuselage:

- 5 page report following same general guidelines as the wing spar report. Again, be sure to justify your decision making.
- 5 page 5 minute presentation on fuselage design.

Due: Wednesday, December 13, 2017

All deliverables are to be uploaded to Canvas. Do not submit paper copies.

NOTE: Discussion is very important! You must be able to defend every step in your process. You must indicate how your analysis guided your decisions.

You are welcome to divide the labor as your team sees fit, but I would encourage interaction at each level by all team members as the parts are connected. A suggestion would be: 4 team members on the wing, 2 team members on the fuselage. Once you have the initial code, 2 wing members work on trend plots for the lifting case and 2 wing members work on trend plots for the static/taxi case. Can look at trend plots for rectangular cross section in terms of width, height, top/bottom/front/back thickness. As you start to taper, trend plots can shift to number of segments and number of stringers. It is up to you and your team as to where you want to look for weight savings.

It is strongly recommended that you develop an Excel spread sheet, Matlab program, or Mathematica/Maple routine to expedite the changing of variable parameters as you go through the design.

If you have questions, you may email them to me, or bring them to office hours.

1 page Progress Report Schedule:

- Progress Report 1 (**Friday, October 20**): Part 0 and first part of Part 1, i.e solid rectangular aluminum beam solution for static and in-flight loads ignoring torque/moment loads associated with torsion (should have shear, moment and deflection plots) and you should have explored at least one other non-solid rectangular design, e.g. the hollow cross section. You should have at least one V-N diagram done.
- Progress Report 2 (**Friday, November 10**): Minimum 3 out of 5 design iterations completed which may include cross-section shape and thickness variation as well as different materials (i.e., you should be nearly completed with Part 2 and have started Part 3). You should have explored whether stringers are a good option for your design.

- Progress Report 3 (**Friday, December 1)**: Should have analyzed the cross section selected for bending for its suitability to the applied torsional loads. Should begin assessing design modifications if necessary to be able to accommodate additional stresses due to torsion (i.e. make sure the cross section has not yielded or exceeded the angle of twist limits).
- Final Report and Presentation: (**Wednesday, December 13**) Final assessment of single/multicell design with/without stringers and appropriate rib spacing. Completed design submitted.

HINTs:

- You may want to look back at the paper discussed at the end of Lecture 1.
- You want to explore relevant trends and use decision matrices.
- What would Messerschmitt do? What was his goal?