

ANALYTICAL WEIGHT ESTIMATION OF UNCONVENTIONAL LANDING GEAR DESIGNS

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Abstract

Landing gear weight calculations can be carried out using statistical or analytical methods. Statistical methods were used in the past and offered quick group weights, however, they are not capable of computing with accuracy the weight of unconventional landing gears which have special geometries and performances. In this work, landing gear weight is computed using analytical methods.

The procedure established by Kraus and Wille is acquired as a baseline so as to create a program able to deal with landing gear weight calculations. This software has been designed to be as much flexible as possible, giving the user the freedom to modify many options and parameters.

1 Introduction

Designing a landing gear involves awareness of the weight belonging to it. Previous studies, such as the one carried out by McDonnell Douglas [1, 2] notices that statistical studies do not differ much from the analytical ones. The main reason for this fact is that landing gear designs have varied little from the conventional cantilever over the years. The main problem stated in this paper about statistical methods is the limited amount of parameters appearing in the equation. In order to be more precise when designing, analytical methods must be used.

Particular aircraft main landing gears have been studied: F-15 Eagle, F-16A, T-45A, and AV-8B. These are cases previously studied by

McDonnell Douglas in which Point-to-Point Analysis was done to find the loads applied in the structure. In the present study, though, a bending moment analysis is used to find out the loads affecting the structure and be able to compute the weight afterwards. When using the bending moment analysis, landing gears have been simplified caring only about the most important components of each one such as pistons and main bars. The simplification includes avoiding small bars and other components that do not take part in the load analysis.

The tool consists of a program which allows the designer to go through a logical method using both programs Microsoft Excel® and CATIA® to find the weight of its design. The designer is allowed to introduce the parameters of every single point and varying its values, giving valuable results for a correct design. The process' goal includes not just computing the weight of the simplified landing gear, but also to cooperate with the designer and make his work easier. Another target is to make a robust program that can be extended in a future with other landing gears or complemented with other important elements for the designer.

2 Case study

The cases treated take into account four specific landing gears that correspond to various military aircraft. Simplified landing gear models of F-15E, F-16A, T-45A and AV-8B are considered and studied further. All landing gears considered are with a single-wheel or a double-wheel configuration. Understanding how the whole structure

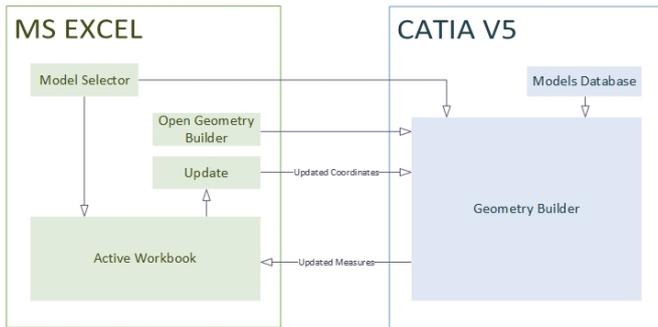


Fig. 1 : General Program Diagram

Material	σ [MPa]	ρ [kg/mm ³]
Ti-6Al-4V	950	4,43E-06
Ti-5Va-5Mo-5Al-3Cr	1236	4,65E-06
Ti-10V-2Fe-2Al	1170	4,65E-06
AerMet100	2080	7,89E-06
AerMet310	2170	7,97E-06
Aluminium	450	2,80E-06
Steel	1450	7,80E-06

Fig. 2 : Materials Database Sheet

works is the main step to know how to simplify the structure. When considering the stroke, it is important to bear in mind that there is a part of the cylinder inside. The stroke of the inner part will be different depending on the loads applied, it means that, if the plane is in the air (landing gear extended) the stroke of the cylinder due to the lack of loads will be longer than when on the ground (landing gear compressed). For this particular reason, three parameters have been created. First of all the parameter s makes reference to the distance of the bar that goes from the outside part of the stroke until the bottom of the bar. The parameter g takes into account the longitude of the bar inside the stroke itself. Eventually the parameter f consists in a factor taking into account the percentage of s that is inside the stroke. Considering this percentage, the designer has the freedom to choose a value for this factor corresponding to the compression of the stroke due to a particular weight of the aircraft.

The following load cases are modeled for this case study[3]:

1. Two/Three Point Landing
2. Tail Down Landing
3. Lateral Drift Landing
4. Braked Roll
5. Ground Turning
6. Pivoting

2.1 General Diagram

The Figure 1 provide a clear overview of the program structure and functioning. First of all, it can easily be seen that the program is using two kinds of software (Excel® and CATIA®). The user will mainly work in the Excel® workbook but it may consult the CATIA® document as well.

2.2 Materials Database Sheet

The Materials Database sheet is simply a table containing the most used materials for landing gears giving two main parameters that are needed when sizing; the density and the elastic stress [4, 5, 6, 7, 8]. These parameters will be directly loaded into the Excel Workbook on the user's choice (Figure 2).

2.3 Geometry Builder Functioning

Once the parameter $type$ has been modified in order to select the desired baseline geometry, the desired model will be instantiated. In this case the T45-A (Figure 3) geometry has been instantiated, therefore inside the *Instantiate* folder, inside the *Geometry* element, all the exported co-ordinates from Excel®.

Besides from the geometry coordinates, the *Instantiate* folder also contains the measures of the longitudes and angles required in order to calculate external reactions and bending moments. Once the geometry is updated from Excel® the measurements are recalculated and sent back to the Excel Workbook. Methodologies presented by Munjulury [9] are used for the geometry build up and automation.

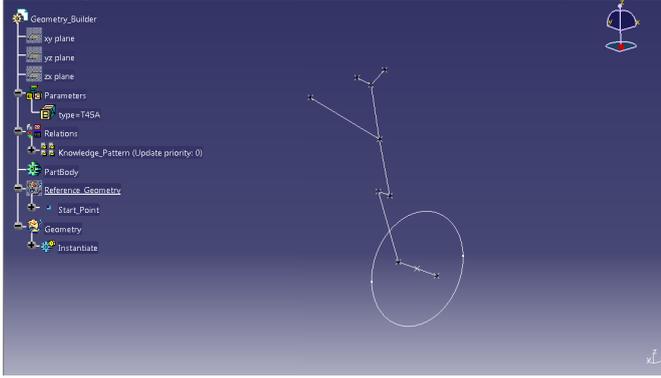


Fig. 3 : Screen With an Instantiated Geometry

3 Analytical Development

In this chapter the mathematical development used to solve the structural problem is explained step-by-step for each landing gear model. A structural simplification of the models is made in order to ease the mathematical approach. Once the model is simplified the process is as follows:

1. External reactions calculation
2. Bending moments calculation
3. Tubes sizing
4. Weight calculation

3.1 External Reactions

In this section the external reactions for the simplified landing gear models are obtained. Each subsection presents the mathematical approach for respective model.

3.1.1 F15-E

In this case, the structure is simplified as a cantilever. Also, since in the side view a drag brace is used, the structure is simplified by considering it as an applied force.

The approach to the problem is formulating a system of six equations (3 for the front view and 3 for the side view) based on forces and moments summation. Solving this system the external reactions, drag brace force and bending moment at the cantilever are obtained (Figure 4).

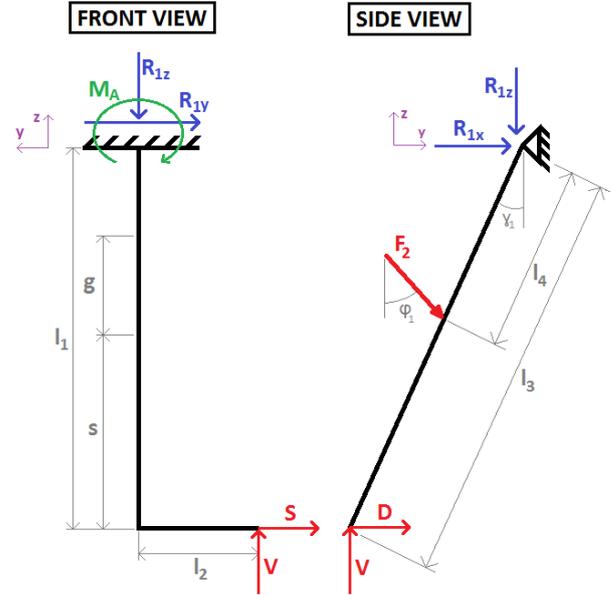


Fig. 4 : F15-E Simplified Model

Note that considering the stroke of the piston, a parameter f is introduced. It can be varied by the user and corresponds to the % of the stroke that will be reduced from the entire length of the vertical bar once the landing gear is on the ground, because of the aircraft weight.

• Front View

$$\Sigma F_z = 0 \rightarrow -R_{1x} + V = 0 \rightarrow R_{1x} = V \quad (1)$$

$$\Sigma F_y = 0 \rightarrow -R_{1y} - S = 0 \rightarrow R_{1y} = -S \quad (2)$$

$$\Sigma M_A = 0 \rightarrow S \cdot l_1 + V \cdot l_2 - M_{1x} = 0 \rightarrow M_{1x} = S \cdot l_1 + V \cdot l_2 \quad (3)$$

Note: For cases 4 to 6, l_1 refers to:

$$l_1 = l_1 - s \cdot f$$

• Side View

$$\Sigma M_B = 0 \rightarrow F_2 = \frac{(V \cdot \sin(\gamma_1) - D \cdot \cos(\gamma_1)) \cdot l_3}{l_4 \cdot (\sin(\phi_1) \cdot \cos(\gamma_1) + \cos(\phi_1) \cdot \sin(\gamma_1))} \quad (4)$$

$$\Sigma F_x = 0 \rightarrow R_{1x} = -D - F_2 \cdot \sin(\phi_1) \quad (5)$$

$$R_{2x} = F_2 \cdot \sin(\phi_1) \quad (6)$$

$$R_{2z} = F_2 \cdot \cos(\phi_1) \quad (7)$$

Note: For cases 4 to 6, l_3 refers to:

$$l_3 = l_3 - \frac{s \cdot f}{\cos(\gamma_1)}$$

3.1.2 F16-A

In this subsection, the F16-A model equations are expounded. The most noticeable topic to stand out is that, due to its geometry and simplification, the extended and retracted positions of the landing gear have to be taken into account separately. This is mainly due to the fact that the stroke does not appear directly in the equations, but it must be considered anyhow. See Figure 5 to understand the model simplification and each parameter used in the following equations.

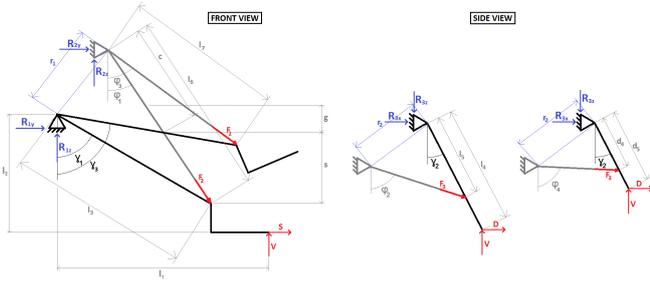


Fig. 5 : F16-A Simplified Model

• Extended Gear (Cases 1-3)

– Front View

$$\Sigma F_y = 0 \rightarrow R_{1y} = -S - F_2 \cdot \sin(\phi_1) \quad (8)$$

$$\Sigma F_z = 0 \rightarrow R_{1z} = F_2 \cdot \cos(\phi_1) - V \quad (9)$$

$$\Sigma M_A = 0 \rightarrow F_2 = \frac{(V \cdot l_1) + (S \cdot l_2)}{l_3 \cdot (\cos(\phi_1) \cdot \sin(\gamma_1) - \sin(\phi_1) \cdot \cos(\gamma_1))} \quad (10)$$

$$R_{2y} = F_2 \cdot \sin(\phi_1) \quad (11)$$

$$R_{2z} = F_2 \cdot \cos(\phi_1) \quad (12)$$

– Side View

$$\Sigma F_x = 0 \rightarrow R_{1x} = -D - F_3 \cdot \sin(\phi_2) \quad (13)$$

$$\Sigma M_B = 0 \rightarrow F_3 = \frac{l_4 \cdot (D \cdot \cos(\gamma_2) + V \cdot \sin(\gamma_2))}{l_5 \cdot (\cos(\phi_2) \cdot \sin(\gamma_2) - \sin(\phi_2) \cdot \cos(\gamma_2))} \quad (14)$$

$$R_{3x} = F_3 \cdot \sin(\phi_2) \quad (15)$$

$$R_{3z} = F_3 \cdot \cos(\phi_2) \quad (16)$$

• Compressed Gear (Cases 4-6)

– Front View

For this case, two longitudes must be defined so as to simplify the following equations.

$$l_y = l_3 \cdot \sin(\gamma_1) + (l_2 - l_3 \cdot \cos(\gamma_1)) \cdot \sin(\gamma_3 - \gamma_1) + (l_1 - l_3 \cdot \sin(\gamma_1)) \cdot \cos(\gamma_3 - \gamma_1) \quad (17)$$

$$l_z = l_3 \cdot \cos(\gamma_3) + (l_2 - l_3 \cdot \cos(\gamma_1)) \cdot \cos(\gamma_3 - \gamma_1) - (l_1 - l_3 \cdot \sin(\gamma_1)) \cdot \sin(\gamma_3 - \gamma_1) \quad (18)$$

$$\Sigma F_y = 0 \rightarrow R_{1y} = -S - F_2 \cdot \sin(\phi_3) \quad (19)$$

$$\Sigma F_z = 0 \rightarrow R_{1z} = F_2 \cdot \cos(\phi_3) - V \quad (20)$$

$$\Sigma M_A = 0 \rightarrow F_2 = \frac{(V \cdot l_y) + (S \cdot l_z)}{l_3 \cdot (\cos(\phi_3) \cdot \sin(\gamma_3) - \sin(\phi_3) \cdot \cos(\gamma_3))} \quad (21)$$

$$R_{2y} = F_2 \cdot \sin(\phi_3) \quad (22)$$

$$R_{2z} = F_2 \cdot \cos(\phi_3) \quad (23)$$

– Side View

$$\Sigma F_x = 0 \rightarrow R_{1x} = -D - F_3 \cdot \sin(\phi_4) \quad (24)$$

$$\Sigma M_B = 0 \rightarrow F_3 = \frac{d_5 \cdot (D \cdot \cos(\gamma_2) + V \cdot \sin(\gamma_2))}{d_4 \cdot (\cos(\phi_4) \cdot \sin(\gamma_2) - \sin(\phi_4) \cdot \cos(\gamma_2))} \quad (25)$$

$$R_{3x} = F_3 \cdot \sin(\phi_4) \quad (26)$$

$$R_{3z} = F_3 \cdot \cos(\phi_4) \quad (27)$$

The γ_3 and ϕ_3 appearing in the previous equations are not physical parameters, since they correspond to the compressed position. Not having a stroke directly applied in the equations translates to the fact that those parameters must be found mathematically.

To achieve this, a system of equations shall be established. Taking a look into the Figure 5 it is easy to see that the structure is composed by several triangles. Therefore, the system of equations will be mainly composed by equations related to this geometrical shape, using relations between angles and longitudes, see Figure 6.

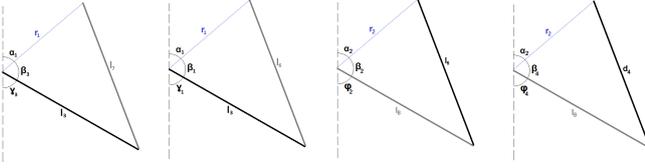


Fig. 6 : F16-A Mathematical Schematics

• Front View

The values to be obtained from the following system are: γ_3 , ϕ_3 and l_7 .

$$\begin{cases} \alpha_1 + \beta_3 + \gamma_3 = 180 \\ l_7 = c + \frac{s \cdot (1 - f)}{\cos(\phi_3)} \\ l_7^2 = r_1^2 + l_3^2 - 2 \cdot r_1 \cdot l_3 \cdot \cos(\beta_3) \\ \cos(\phi_3) = \frac{r_1 \cdot \cos(\alpha_1) + l_3 \cdot \cos(\gamma_3)}{l_7} \end{cases} \quad (28)$$

• Side View

In this case, some values must be obtained before solving the system.

$$d_3 = l_7 \cdot \cos(\gamma_3) \quad ; \quad d_4 = \frac{d_3}{\cos(\gamma_2)} \quad ;$$

$$d_6 = d_7 \cdot \cos(\gamma_3 - \gamma_1) \quad ; \quad d_5 = \frac{d_3 + d_6}{\cos(\gamma_2)}$$

The values to be obtained from the following system are: β_4 , ϕ_4 , ζ_4 and l_9 .

$$\begin{cases} \alpha_2 + \beta_4 + \phi_4 = 180 \\ l_9 = r_2 \cdot \cos(\beta_4) + d_4 \cdot \cos(\zeta_4) \\ d_4^2 = r_2^2 + l_9^2 - 2 \cdot r_2 \cdot l_9 \cdot \cos(\beta_4) \\ r_2^2 = (r_2 \cdot \cos(\beta_4))^2 + (d_4 \cdot \sin(\zeta_4))^2 \end{cases} \quad (29)$$

3.1.3 AV-8B

In this case, the structure is simplified in the front view by deleting the drag brace shown in the side view, since it only affects the performance of the structure when drag and vertical loads are applied in the side view. In the front view the restrictions applied to the bar 3 are thought to copy the desired motion of the bar when bending (Figure 7).

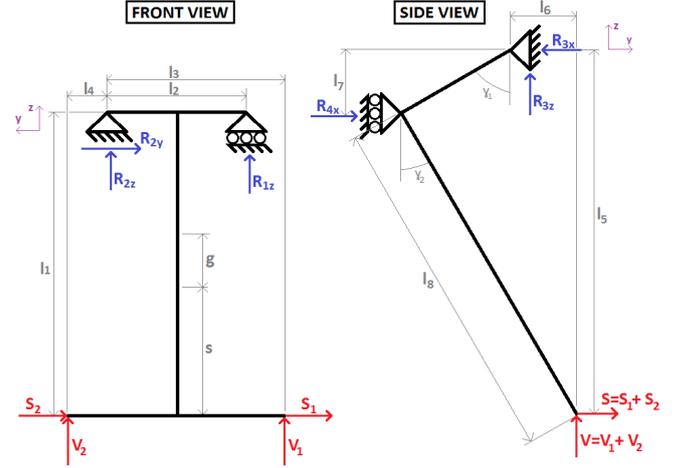


Fig. 7 : AV-8B Simplified Model

• Front View

$$\Sigma F_z = 0 \rightarrow R_{2z} = -V_1 - V_2 - R_{1z} \quad (30)$$

$$\Sigma F_y = 0 \rightarrow R_{2y} = -S_1 - S_2 \quad (31)$$

$$M_A = 0 \rightarrow R_{1z} = \frac{l_1 \cdot ((V_2 \cdot l_4) - (V_1 \cdot l_3) - (S_1 + S_2))}{l_2} \quad (32)$$

Note: For cases 4 to 6, l_1 refers to:

$$l_1 = l_1 - s \cdot f$$

• Side View

$$\Sigma F_z = 0 \rightarrow R_{3z} = V_1 + V_2 \quad (33)$$

$$M_B = 0 \rightarrow R_{4x} = -\frac{(V_1 + V_2) \cdot l_6 + D \cdot l_5}{l_7} \quad (34)$$

$$\Sigma F_x = 0 \rightarrow R_{3x} = R_{4x} + D \quad (35)$$

Note: For cases 4 to 6, l_5 refers to:

$$l_5 = l_5 - \frac{s \cdot f}{\cos(\gamma_2)}$$

3.1.4 T45-A

In this ailment, the structure is simplified in the front view by ignoring the existence of a drag brace and replacing it by an applied force directly into the main vertical bar. Also, the bar that links the drag brace with the main bar and is used to

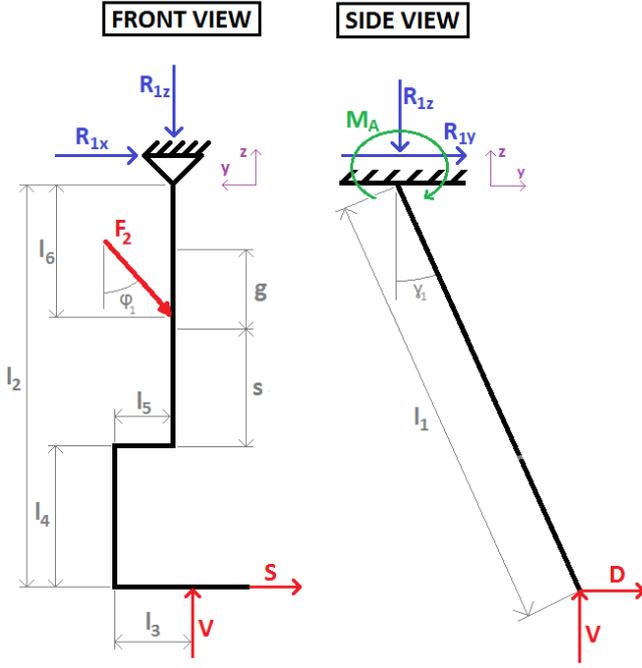


Fig. 8 : T45-A Simplified Model

guide the rotation of the landing gear is substituted by an All-DOF restriction. With respect to the side view, the model is considered as a cantilever. Figure 8 presents the simplified model schematic.

• Front View

$$\Sigma F_x = 0 \rightarrow R_{1x} + D = 0 \rightarrow R_{1x} = -D \quad (36)$$

$$\Sigma F_z = 0 \rightarrow -R_{1z} + V = 0 \rightarrow R_{1z} = V \quad (37)$$

$$\Sigma M_A = 0 \rightarrow M_{A1} = D \cdot \cos(\gamma_1) \cdot l_1 + V \cdot \sin(\gamma_1) \cdot l_1 \quad (38)$$

Note: For cases 4 to 6, l_1 refers to:

$$l_1 = l_1 - \frac{s \cdot f}{\cos(\gamma_1)}$$

• Side View

$$\Sigma F_y = 0 \rightarrow R_{1y} = -S - F_2 \cdot \sin(\phi_1) \quad (39)$$

$$\Sigma M_B = 0 \rightarrow F_2 = \frac{S \cdot l_2 + V \cdot (l_3 + l_5)}{l_6 \cdot \sin(\phi_1)} \quad (40)$$

$$R_{2y} = F_2 \cdot \sin(\phi_1) \quad (41)$$

$$R_{2z} = F_2 \cdot \cos(\phi_1) \quad (42)$$

Note: For cases 4 to 6, l_2 refers to:

$$l_2 = l_2 - (s \cdot f)$$

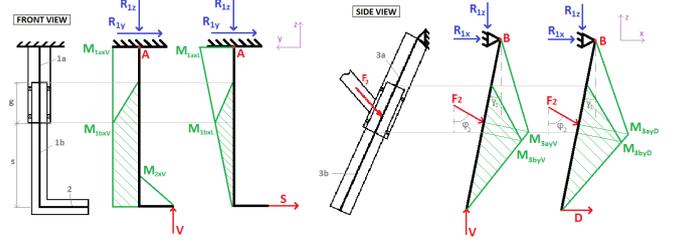


Fig. 9 : F15-E Bending Moment Diagrams

3.2 Bending Moments

In this section, the sizing bending moments for the simplified landing gear models are obtained. Each subsection develops the mathematical approach for each model, structured the same way as in the Section 3.1.

3.2.1 F15-E

When simplifying this model, the relation between the external cylinder and the piston has to be considered. Since each element must be sized, different bending moments must be taken into consideration.

In Figure 9, the different bending moments can be seen. In each view the loads have been isolated so as to simplify the representation of each bending moment along the bars.

• Front View. Vertical Loads

$$M_{2xv} = M_{1axv} = M_{1bxv} = V \cdot l_2 \quad (43)$$

• Front View. Side Loads

$$M_{2xs} = 0 \quad (44)$$

$$M_{1bxS} = S \cdot s \quad (45)$$

$$M_{1dxS} = S \cdot l_1 \quad (46)$$

Note: For cases 4 to 6, s and l_1 refer to:

$$s = s \cdot (1 - f)$$

$$l_1 = l_1 - (s \cdot f)$$

• Side View. Vertical Loads

$$M_{3byv} = -V \cdot s \cdot \tan(\gamma_1) \quad (47)$$

$$M_{3dyv} = -V \cdot \sin(\gamma_1) \cdot (l_3 + l_4) \quad (48)$$

• **Front View. Vertical Loads**

$$M_{1_{xV}} = \frac{V_1 \cdot (l_3 + l_4)}{2} \quad (59)$$

• **Front View. Side Loads**

$$M_{3_{xV}} = \frac{(V_1 + V_2) \cdot l_2}{2} \quad (60)$$

Note: For cases 4 to 6, s and l_1 refer to:

$$s = s \cdot (1 - f)$$

$$l_1 = l_1 - (s \cdot f)$$

• **Side View. Vertical Loads**

$$M_{5_{yV}} = M_{4_{a_{yV}}} = V \cdot \sin(\gamma_2) \cdot l_8 \quad (61)$$

$$M_{4_{b_{yV}}} = V \cdot \tan(\gamma_2) \cdot s \quad (62)$$

• **Front View. Drag Loads**

$$M_{5_{yD}} = M_{4_{a_{yD}}} = D \cdot \cos(\gamma_2) \cdot l_8 \quad (63)$$

$$M_{4_{b_{yD}}} = D \cdot s \quad (64)$$

Note: For cases 4 to 6, s and l_8 refer to:

$$s = s \cdot (1 - f)$$

$$l_8 = l_8 - \frac{s \cdot f}{\cos(\gamma_2)}$$

3.2.4 T45-A

Analogously to the previous cases, the relation between the external cylinder and the piston has to be kept in mind. Since each element must be sized, different bending moments must be taken into consideration.

In Figure 13, the different bending moments can be seen. In each view the loads have been isolated so as to simplify the representation of each bending moment along the bars.

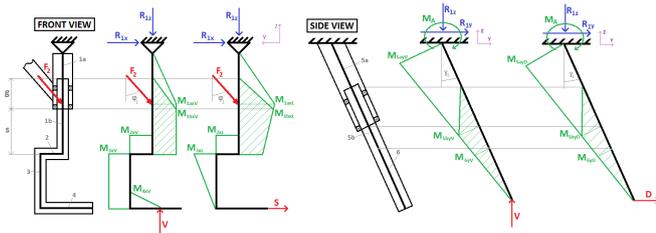


Fig. 13 : T45-A Bending Moment Diagrams

• **Front View. Vertical Loads**

$$M_{1_{a_{xV}}} = M_{1_{b_{xV}}} = M_{2_{xV}} = M_{3_{xV}} = M_{4_{xV}} = V \cdot l_3 \quad (65)$$

• **Front View. Side Loads**

$$M_{1_{a_{xS}}} = S \cdot (l_2 - l_6) \quad (66)$$

$$M_{1_{b_{xS}}} = S \cdot (l_4 + s) \quad (67)$$

$$M_{2_{xS}} = M_{3_{xS}} = S \cdot l_4 \quad (68)$$

$$M_{4_{xS}} = 0 \quad (69)$$

Note: For cases 4 to 6, s and l_2 refer to:

$$s = s \cdot (1 - f)$$

$$l_2 = l_2 - (s \cdot f)$$

• **Side View. Vertical Loads**

$$M_{5_{a_{yV}}} = V \cdot \sin(\gamma_1) \cdot l_1 \quad (70)$$

$$M_{5_{b_{yV}}} = V \cdot \tan(\gamma_1) \cdot (l_4 + s) \quad (71)$$

$$M_{6_{yV}} = V \cdot \tan(\gamma_1) \cdot l_4 \quad (72)$$

• **Front View. Drag Loads**

$$M_{5_{a_{yD}}} = D \cdot \cos(\gamma_1) \cdot l_1 \quad (73)$$

$$M_{5_{b_{yD}}} = D \cdot (l_4 + s) \quad (74)$$

$$M_{6_{yD}} = D \cdot l_4 \quad (75)$$

Note: For cases 4 to 6, s and l_1 refer to:

$$s = s \cdot (1 - f)$$

$$l_1 = l_1 - \frac{s \cdot f}{\cos(\gamma_1)}$$

3.3 Tubes Sizing

Considering the sketch shown in Figure 14, and knowing that the length and inner diameter are known values, the only parameter left to size is the outer diameter.

In Figure 14, a clear sketch of an external cylinder and a piston is shown. It is clear that the inner diameter of the external cylinder has to be equal to the outer diameter of the piston. Therefore, the piston has to be sized first by letting the

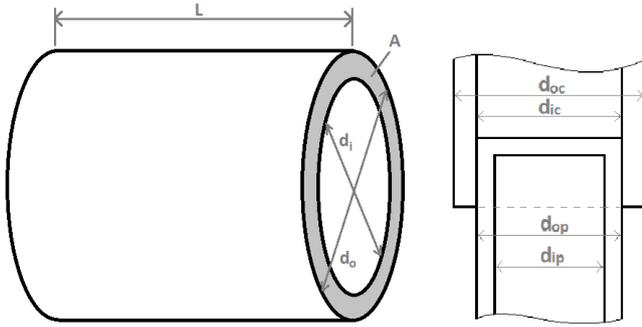


Fig. 14 : Tube Dimensions

user input the desired inner diameter. The external cylinder is going to be sized once the outer piston diameter is obtained.

If the length and inner diameter of a tube are known, the elastic section modulus formulas of a hollow cylinder can be used so as to obtain the outer diameter.

$$W_c = \frac{M_{max}}{\sigma_t} \quad \text{and} \quad W_c = \frac{\pi \cdot (d_o^4 - d_i^4)}{32 \cdot d_o} \quad (76)$$

By combining the expressions in Equation 76 a quartic equation is found. Since it is a 4th order equation, it has four possible solutions. Two of them will always have an imaginary part, therefore they can be discarded. The other two solutions may or may not have an imaginary component. The chosen solution is the minimum real value without imaginary part.

$$d_o^4 - \frac{M_{max} \cdot 32}{\sigma_t \cdot \pi} \cdot d_o - d_i^4 = 0 \quad (77)$$

Where,

$$\sigma_t = \frac{\sigma_e}{n}$$

Finally, once the outer diameter is obtained, the area of the tube can be calculated using the following expression for hollow cylinders.

$$A = \pi \cdot \left(\left(\frac{d_o}{2} \right)^2 - \left(\frac{d_i}{2} \right)^2 \right) \quad (78)$$

3.4 Weight Calculation

Once the area and the length of the tube are known, its volume can be easily obtained:

$$Volume = Area \cdot Length \quad (79)$$

Finally, using the definition of density, the weight of the bar is calculated.

$$\rho = \frac{Mass}{Volume} \quad \rightarrow \quad Mass = \rho \cdot Volume \quad (80)$$

4 Conclusion

The program developed is able to compute the weight of the existing bars for a particular landing gear disposition. By changing the coordinates of the start and the end of the bars, changing material properties, applied loads and other values that the user can choose, the program sizes the bar according to all of these values. These results give a chance to the designer to have both a numeric and a graphical view of the results that has been designed. The fact of having the CATIA® opened during the computations keeps the user in touch all time with a visual perspective on where the points are placed and the overall disposition of the bars.

The results obtained by the bending moment process are satisfactory. The results are really close from the ones found in the studies done by Kraus and Willie. Limitations when using the program are that, the bars that can be sized, are the ones that receive moments from the applied loads. Even though this limitation, the program is able to size the main bars of the gears for the simplifications done. If the other bars, for example, the ones that take just forces want to be sized, the method from previous studies can be used and added as an extension to the work presented.

References

- [1] Kraus, P. R., *An Analytical Approach to Landing Gear Weight Estimation*, McDonnell Aircraft Corporation, St. Louis, Missouri, 1970.
- [2] Willie, R. H., *Analytical weight estimation of unconventional landing gear designs*, McDonnell Aircraft Corporation, Alexandria, Virginia, 1989.
- [3] University, M. S., "External Loads," <http://www.coe.montana.edu/me/faculty/cairns/Introduction%20to%20Aerospace-Web/External%20Loads.pdf/>.

- [4] matweb, A., “Ti-6Al-4V,” <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTA642/>.
- [5] ResearchGate, “Ti-5Va-5Mo-5Al-3Cr,” http://www.researchgate.net/profile/Xinjin_Cao/publication/257540562_Linear_friction_welding_of_a_near-titanium_alloy/links/53d27cc60cf220632f3c9f2d.pdf/.
- [6] matweb, A., “Ti-10V-2Fe-2Al,” <http://www.matweb.com/search/datasheet.aspx?matguid=56fbc0e558dc4c958c1e5275540cf6a5&ckck=1/>.
- [7] matweb, A., “Aermet-100,” <http://www.matweb.com/search/datasheet.aspx?matguid=c68ffba520144c63937533388a51e9f9/>.
- [8] matweb, A., “Aermet-310,” <http://www.matweb.com/search/datasheet.aspx?matguid=0c4383b4e824496eb3721b8164654fc72/>.
- [9] Munjulury, R. C., *Knowledge Based Integrated Multidisciplinary Aircraft Conceptual Design*, Licentiate Thesis, No. 1661, Linköping University, Linköping, Sweden, 2014.