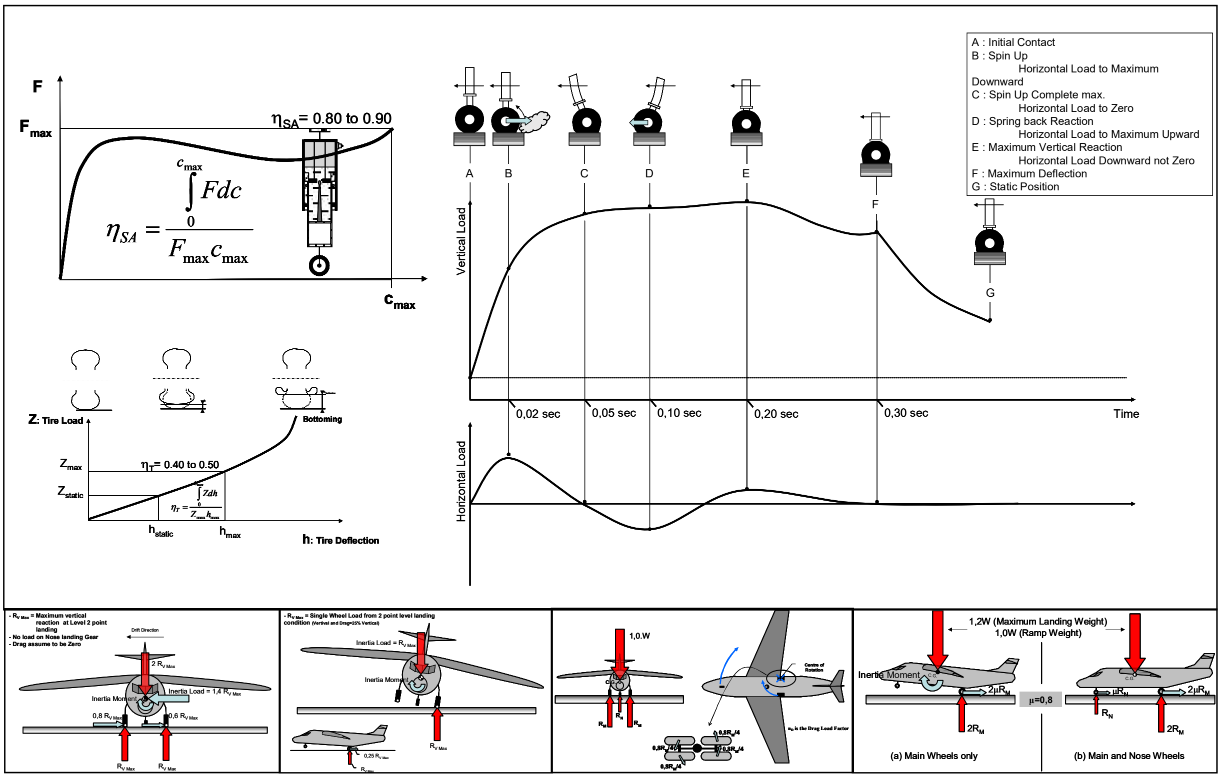
AIRCRAFT LOADS: GROUND LOADS

Landing Gear Design & Loads



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1. INTRODUCTION

1.1. Definition of Aircraft Loads Analysis

Aircraft loads analysis is that part of the aircraft design process which provides with Structural Design Data, Stiffness and Life from the analysis of flight and ground behaviour and the environment.

Structure design data takes the form of Bending Moment, Shear Force and Torque diagrams and Discrete Loads.

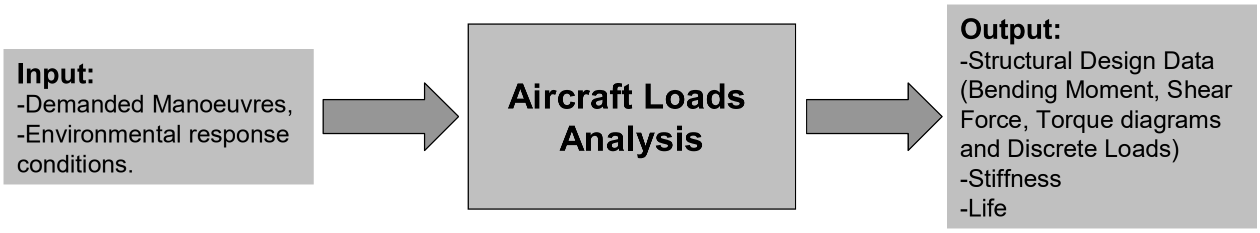


Figure 1-1 : Aircraft Loads Analysis

1.2. Airworthiness and Requirements: The input data for Aircraft Loads Analysis

As designing an absolutely safe aircraft would be prohibitively expensive, unacceptably heavy and impracticable, standard for design are necessary.

The fundamental input data for Aircraft Loading analysis is contained in the particular Specification and General Requirements for a vehicle, based on many years of experience. They are issued by appropriate Airworthiness Authorities.

1.2.1. Design Requirements for Military Aircraft

In France, the standard reference is the “Air 2004E”, but within Europe, the most complete one is the United Kingdom Def. Standard 00-970 which covers all aircraft intended for service in the Royal Air Force and Royal Navy.

The corresponding United States requirements are contained in the MIL series.

1.2.2. Design Requirements for Civil Aircraft

The main sets of requirements for civil aircraft are:

- USA Federal Aviation Regulations –FAR of which the important sections are :
  - FAR 22 for gliders
  - FAR 23 for light aeroplanes
  - FAR 25 for large aeroplanes

- FAR 27 and 29 for rotorcraft

- The European Commission has adopted on 16 May 2006 a new Regulation (Ref: COMMISSION REGULATION (EC) No 736/2006, published in the Official Journal L 129/10 of 17 May 2006) regarding new working methods of the European Aviation Safety Agency for conducting standardisation inspections. The main sections are:

  - CS 22 for gliders
  - CS 23 for light aeroplanes
  - CS 25 for large aeroplanes
  - CS 27 and 29 for rotorcraft

1.3. Between the main categories of Load cases: Ground cases

One of the more fundamental aspects of aircraft design is the landing gear design, which encompasses numerous engineering disciplines such as structure, weight, runway design etc. According to Conway [1], it is "the essential intermediary between the aeroplane and catastrophe".

Two types of requirements must be considered from the point of view of landing gear design. The first is about the aircraft static and manoeuvring on the ground; the second is concerned with the absorption of vertical energy in a landing. Landing loads are the result of the vertical deceleration which occurs when the aircraft lands or when it encounters a runway irregularity.

2. LANDING GEAR DESIGN

2.1. *Generalities*

Landing gear design and the associated ground loads are important aspect of aircraft design. Landing gears are the source of high concentrated loads which require considerable features in the structure such as dedicated heavy frame or spars to receive and spread these loads.

The landing gear design is well documented in Currey [2] and is experience based. The following deals mainly with wheel landing gears which are the most common ones.

2.2. *Functions of the landing gear*

The most important function of the landing gears if of course to allow the smooth landing of the aircraft, absorbing its vertical kinetic energy. But this “small” device contains many other functions that make it one of the most complex systems of the aircraft.

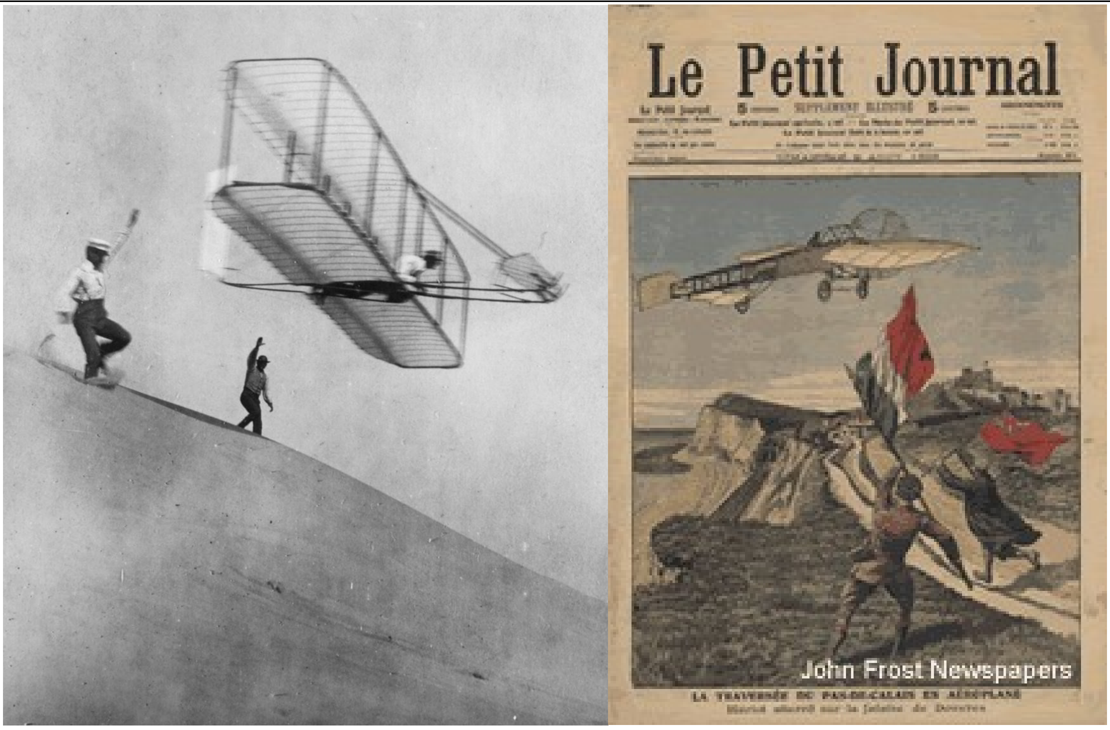
These functions are:

- To Taxi and Take off,
- To allow smooth landing by absorbing vertical kinetic energy,
- To house the main braking system,
- To provide retraction for flight,
- To provide steering system (nose landing gear),
- To house anti-crash devices,
- To allow catapult launching (for Navy aircraft),
- Etc.

2.3. *Landing Gear Types and Configurations*

2.3.1. Landing gear configurations

Few years after the Wright Brothers flight without wheeled landing gears in December 1903, appeared the first aircraft with wheeled landing gears such as the Bleriot aircraft when he crossed the Channel in July 1909. See Figure 2-1.

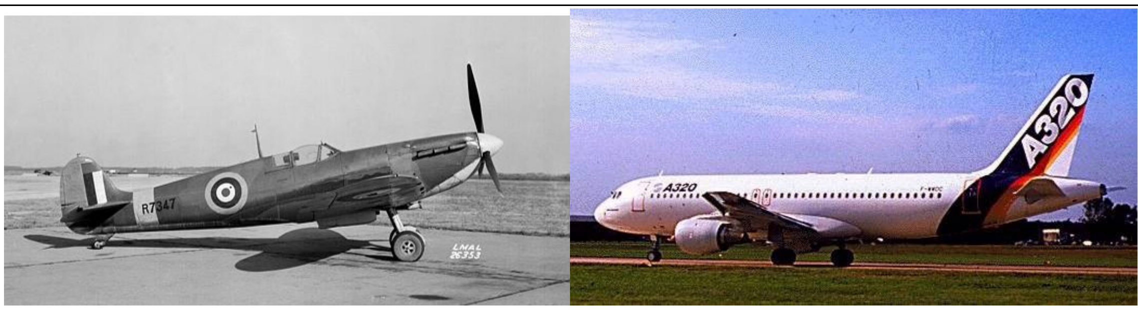


(a) (b)

Figure 2-1: (a) Wright Brothers Flight without wheeled landing gears in December 1903 and (b) Bleriot crossed the Channel with a wheeled landing gear aircraft in July 1909

The first aircrafts were more or less all designed with tail wheel landing gear. That was the time of WWI and WWII. Figure 2-2(a) shows a WWII Spitfire which was designed with a retractable tail landing gear configuration.

Most of the modern aircraft are now designed with nose wheel landing gear configuration (See Figure 2-2(b)).



(a) (b)

Figure 2-2: (a) A Tailed-Wheel Aircraft (Spitfire) and (b) a Nose Wheel Aircraft (A320)

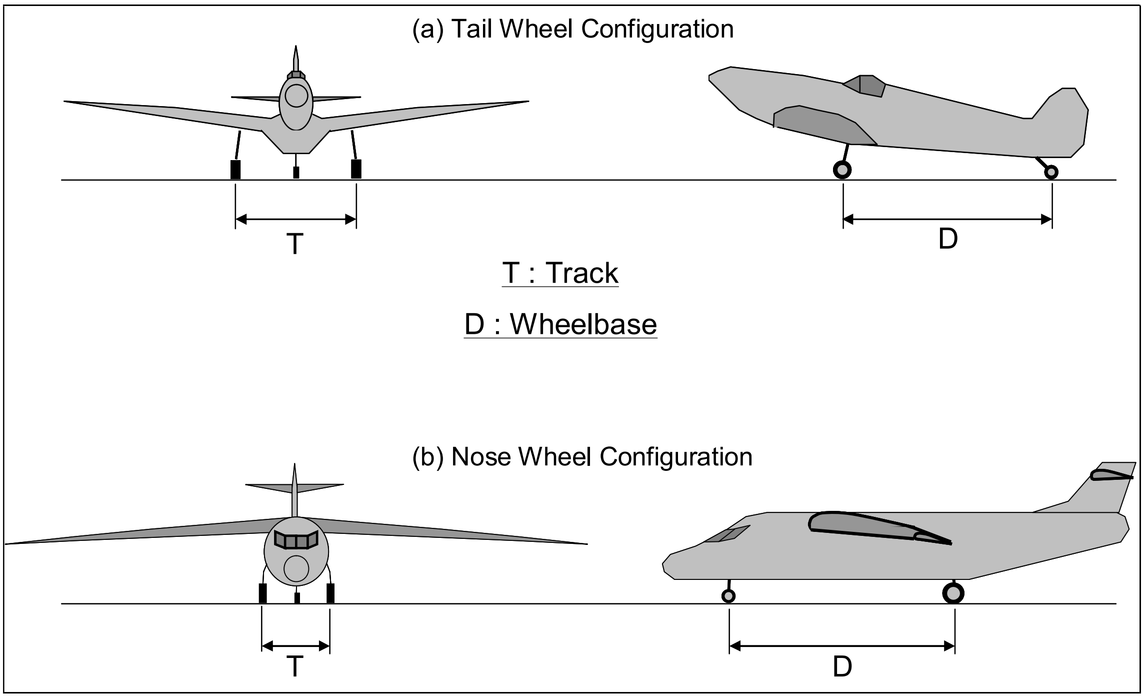


Figure 2-3: Track and Wheelbase

Whatever the configuration, the distance between the two main landing gears span wise is the Track and the distance between the landing gears longitudinally is the Wheelbase. See Figure 2-3.

2.3.2. Landing gear types

Landing gears are categorized by the number of wheels and their arrangement. Figure 2-4 shows the main types of landing gears.

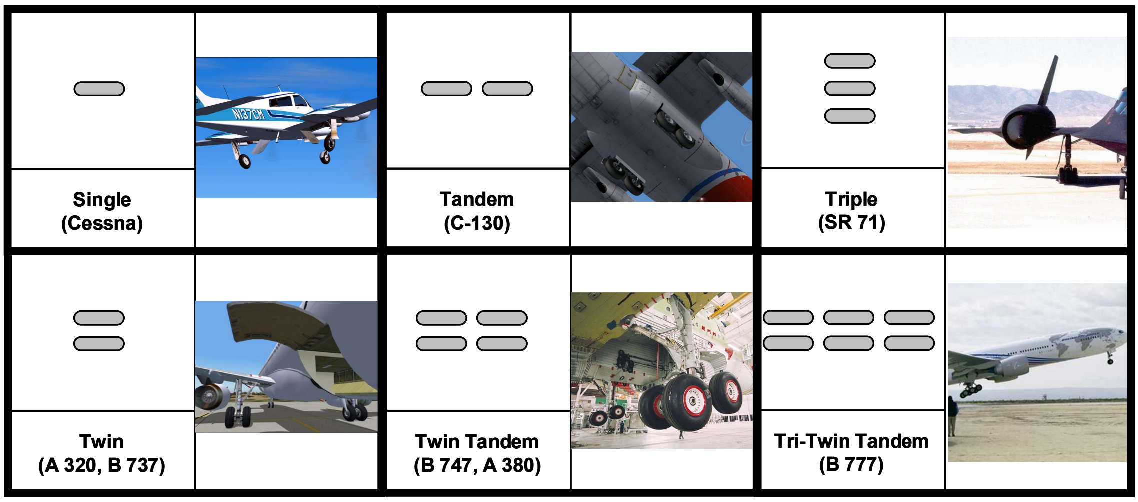


Figure 2-4: Standard Landing Gear Types

The choice of the landing gear type is often a flotation issue. The total static pressure of each tyre on the ground must be reasonable for the airfield to support it. In the past decades, the single wheel loading didn't stop to increase – At about 5 to 10 tons per wheel for the DC-3 and DC-4 in the 1940's, it is today commonly said that the aircraft load per wheel is around 30 tons. The Boeing B777 the maximum take off weight of which is 300 tons required 10 tyres; a 12 tyres (2 x 6) has been chosen. The Airbus A380 the maximum take off weight of which is 560 tons required 19 tyres; a 20 tires (2 x 6+2 x 4) has been chosen.

2.4. Landing Gears Location

The exact location of the landing gears is usually defined late in the design process, but some empirical rules allow the designer to locate roughly the landing gears at the first iterations. The following gives some basic methods to longitudinally and laterally locate the landing gears of a contemporary tricycle-nose-wheel-gear aircraft.

2.4.1. Longitudinal Location

The input data required to locate the landing gears are the Mean Aerodynamic Chord (MAC) and the forward and aft centre of gravity (c.g.) limits. See Figure 2-5.

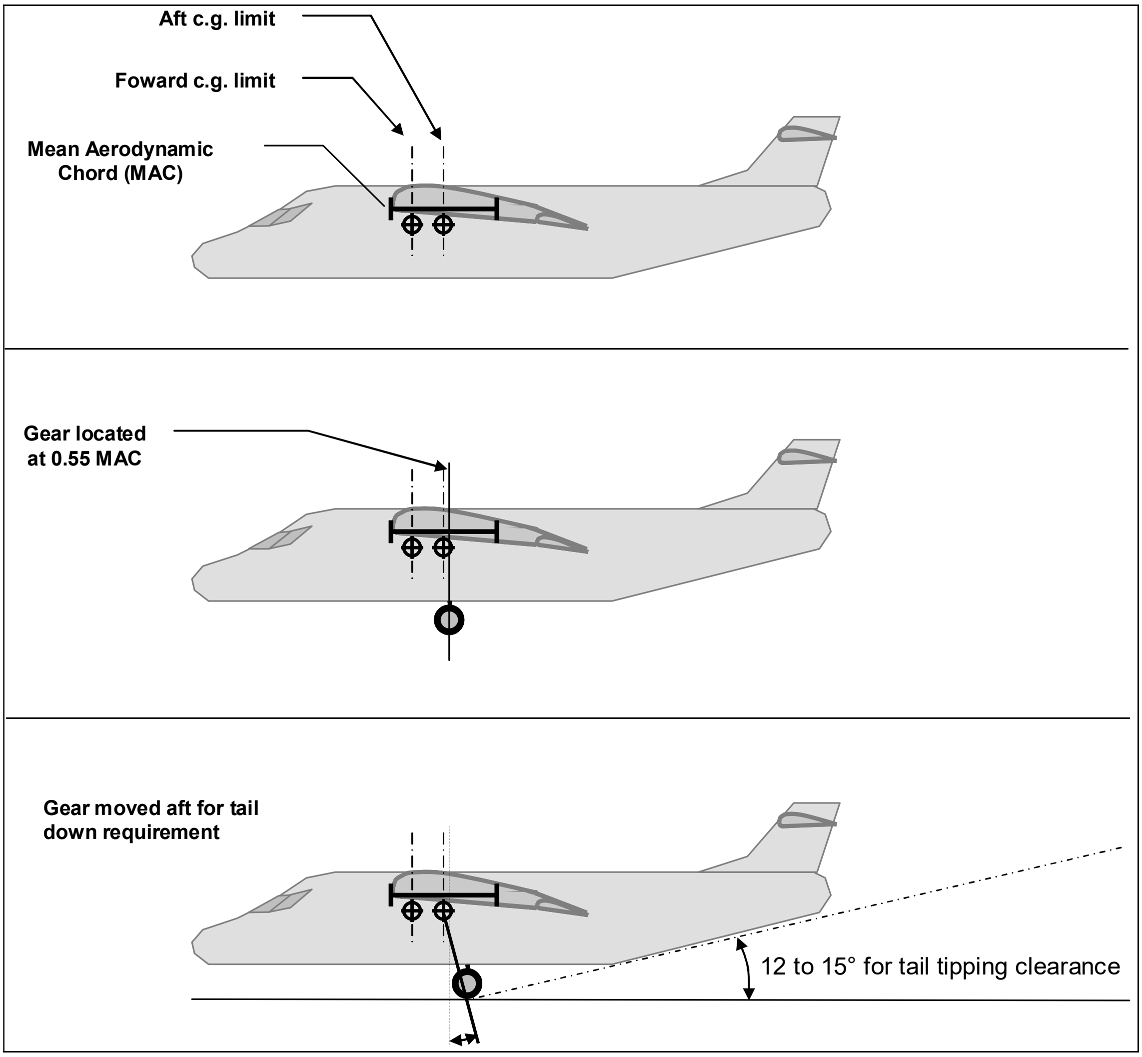


Figure 2-5: Longitudinal location

The main landing gear must of course be located behind the aft c.g. limit, but, according to Currey [2], it should be between about 50-55% of the MAC. Moreover, many years of experience led to another criterion: the static ground line must be behind the intersection of the ground with the line passing through the aft c.g. at 15° from the vertical. This is mainly to avoid tail tipping.

Other details must be considered such as the presence of a rear spar to attach the landing gears. On swept-wing aircraft, the aft c.g. limit might be behind the rear spar. In such a case, a third spar might be added aft of the rear spar.

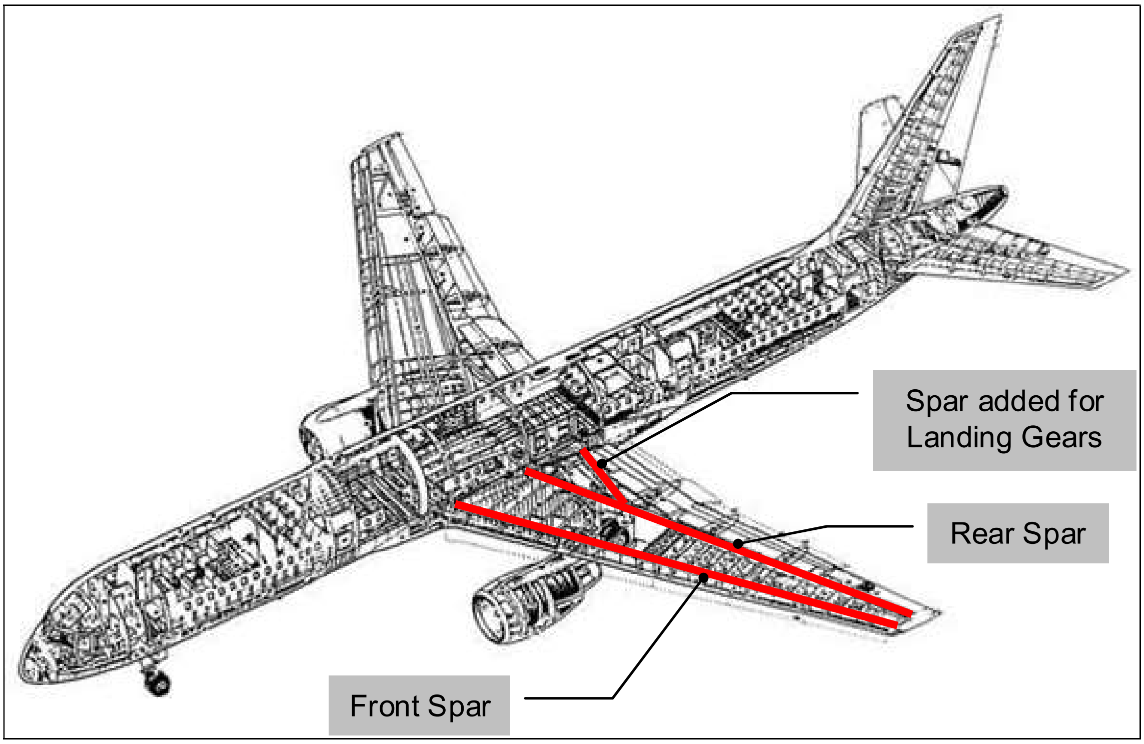


Figure 2-6: Third Spar added for Landing Gears

Concerning the nose landing gear, it should be located as far forward as possible to minimize its load. However, the load must not be too light for steering efficiency.

Figure 2-7: ...what may happen when the pilot does not take care of mass distribution

2.4.2. Lateral Location

The lateral location of the main landing gear is determined via the turnover angle θ (See Figure 2-8). According to Currey [2], this angle must not be more than 63° for land-based aircraft or 54° for carrier-based aircraft.

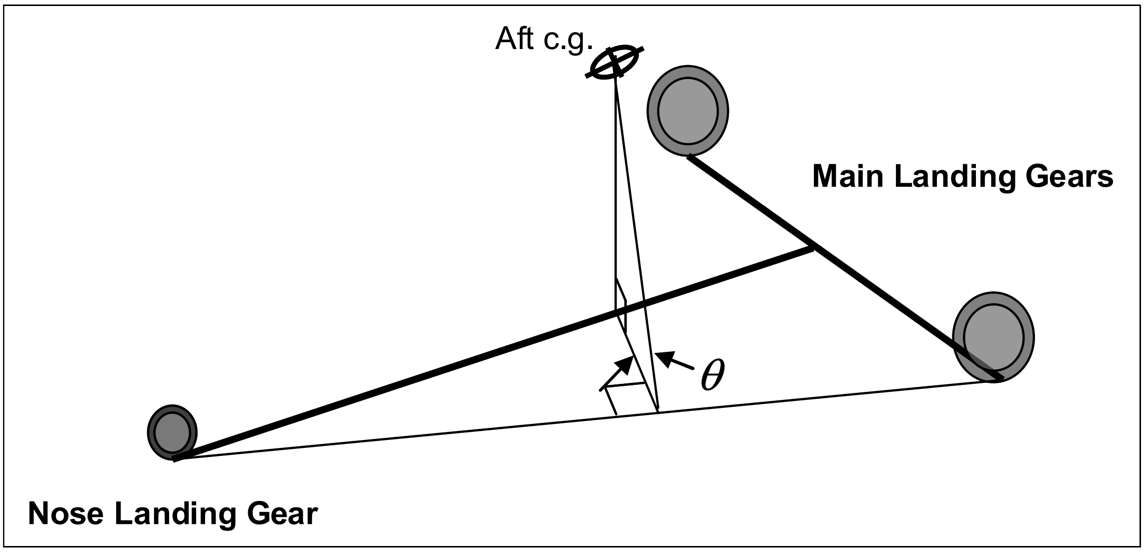


Figure 2-8: Turnover angle

2.5. Landing Gear Mounting on Airframe

Two main requirements pilot the landing gear mounting on the airframe.

The first one is a kinematic requirement: the landing gear must retract and extend easily in flight.

The second one is a load requirement: one must know perfectly how the loads sustained by the landing gear are transmitted to the airframe. Since the landing gear loads are large, there can be severe weight penalties in the use of indeterminate structural load paths – an indeterminate structure is one in which a given load may be reacted by more than one load path, the distribution being subject to the relative total stiffness of these load paths.

A solution which is generally adopted to cope with these requirements is the isostatic mounting. One pivot axis – realised by 2 attachment points fitted with spherical knee joint – is associated with a strut fitted with 2 knee joints. The strut is also used for retraction. See Figure 2-9.

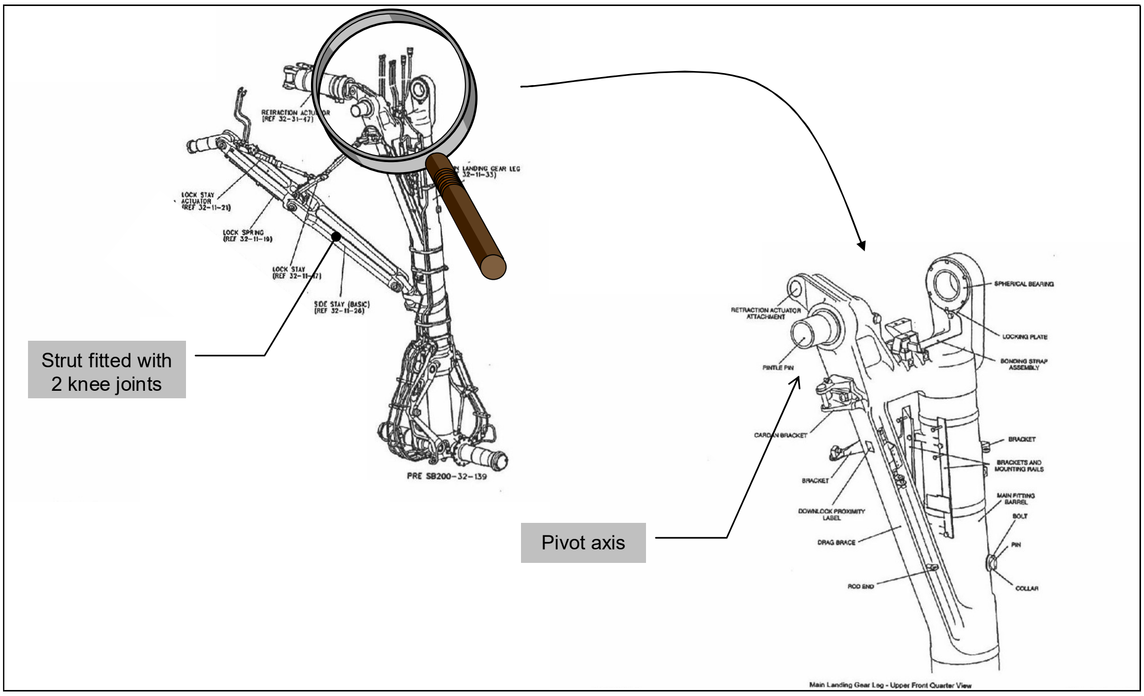


Figure 2-9: Airbus A320 main landing gear

2.6. Landing Gear Load Factor

Landing gear design load factor is the ratio between the maximum load acceptable in the shock strut – dynamic load – divided by the static load – often at MTOW. It must not be mistaken with aircraft load factor which results from manoeuvre or atmospheric disturbances.

Typical landing gears factors are [1]:

- For Fighter Aircraft: 3 to 5
- For Small Aircraft: 2 to 3
- For Large Aircraft: 0.7 to 1.5

Contrary to aircraft load factor, landing gear load factor does not govern the aircraft structure design, except locally where the landing gears are attached (main frame, Spar, etc.).

2.7. *Shock Absorber*

2.7.1. Generalities

Known as the most important component in a landing gear, the shock absorber is also the one item common to all landing gear.

Its basic function is to absorb the kinetic energy during landing so that the accelerations undergone by the airframe are reduced to a tolerable level and provide with smooth taxiing for passenger comfort. The two main functions of an efficient shock absorber are the Spring and the Damping function (See Figure 2-10).

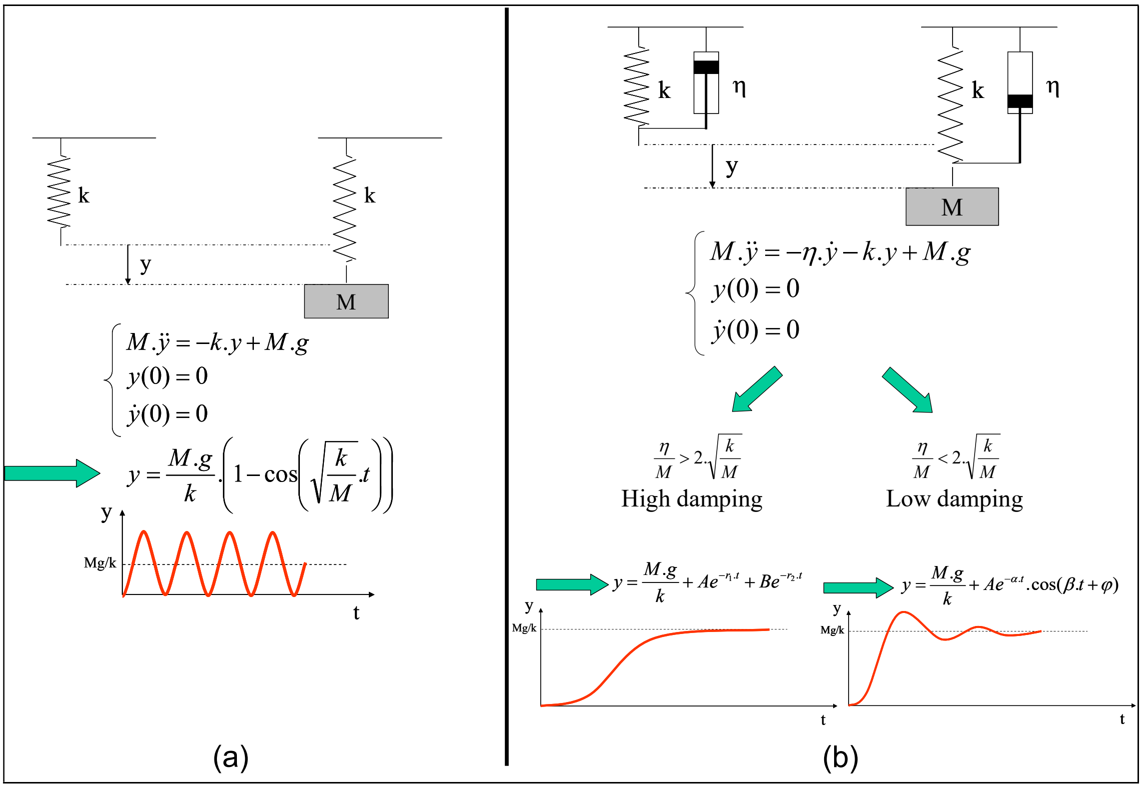


Figure 2-10: (a) Spring Function – (b) Spring and Damping function

Even though oleo pneumatic shock absorber efficiency is discussed in §2.6.4, the definition of the efficiency is given below to help for the understanding the discussion. Shock absorber efficiency is given by the following formula:

$$Efficiency = \frac{A}{L \times S}$$

Where A is the area beneath the strut loadstroke curve, L the maximum load and S the maximum Stroke (See Figure 2-11).

The shock absorber efficiency reflects the capacity of the shock absorber to absorb the kinetic energy. The higher it is, the more energy is absorbed.

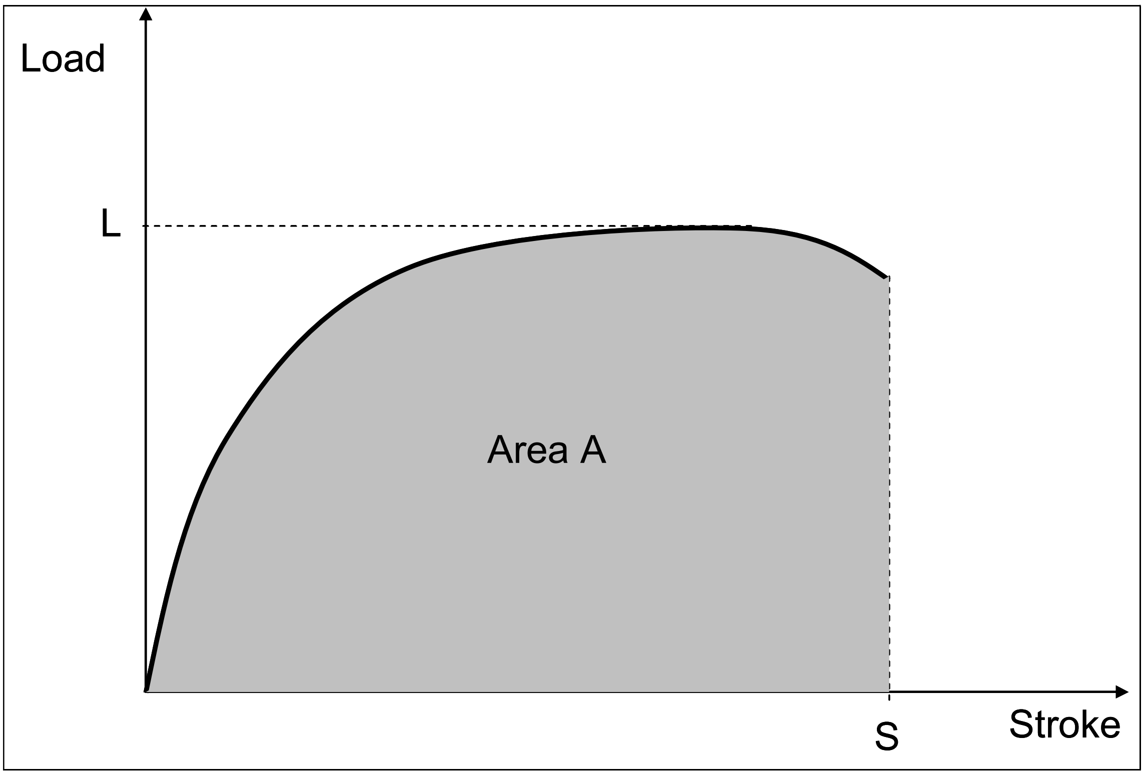


Figure 2-11: Definition of Efficiency

2.7.2. Shock Absorber Types

There are 2 families of shock absorber: the "Solid Spring family" and the "Fluid Spring family" (See Figure 2-12).

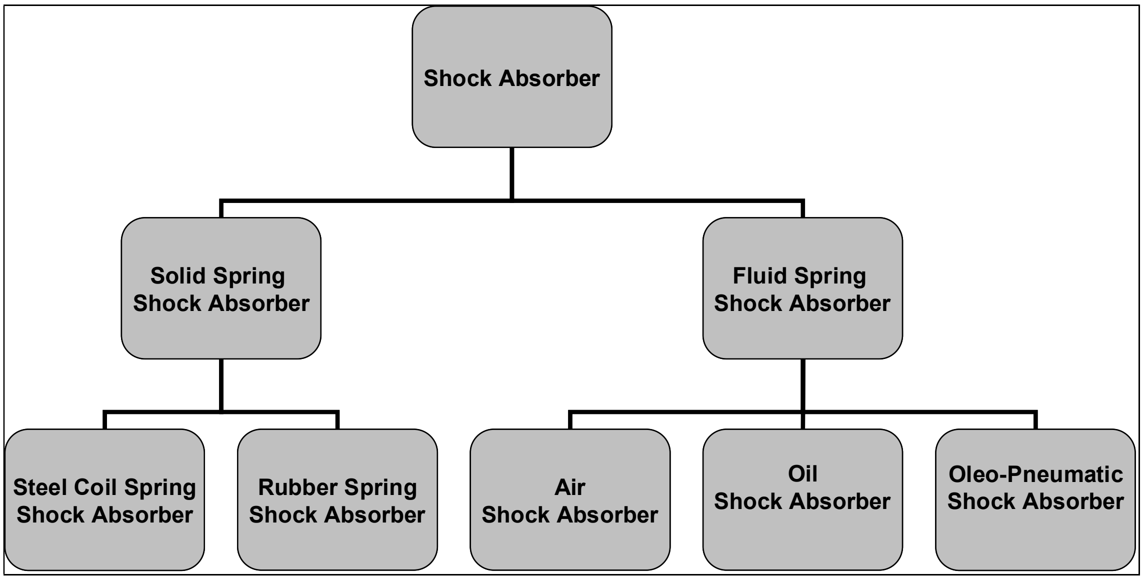


Figure 2-12: Shock Absorber Types

The efficiencies of the different types of shock absorbers are compared, in Figure 2-13, to the most efficient one, the oleo-pneumatic type.

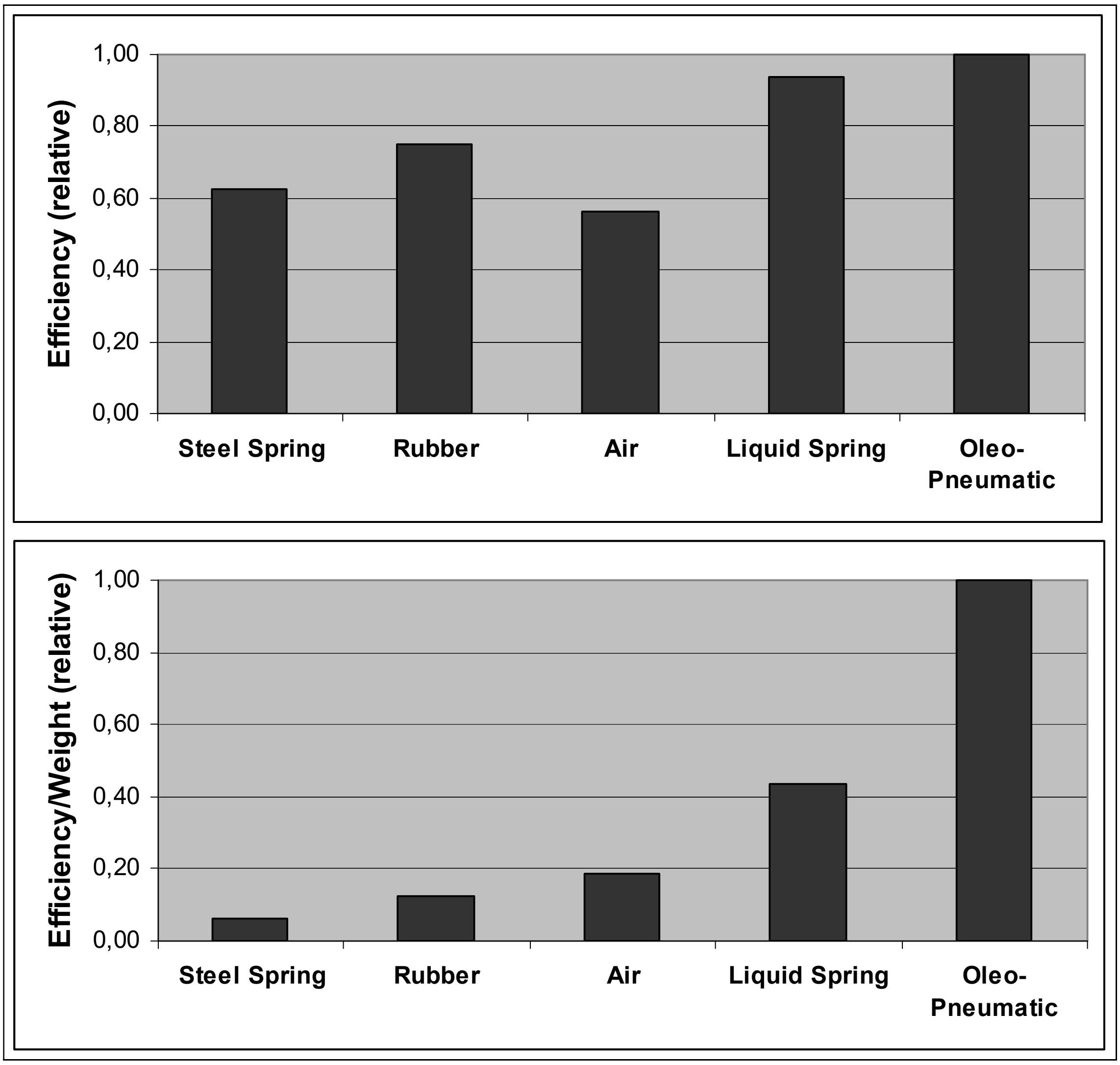


Figure 2-13: Comparison of Shock Absorber Efficiency [2]

Except in some light aircraft which are equipped with Steel Leaf Spring – ideal for its simplicity, reliability and maintenance issue –, most of today's aircraft use oleo-pneumatic shock absorbers which have the highest efficiency and the best energy dissipation. For these reasons, the following will be focused on this type of shock absorber. The reader may find more details about rubber shock absorber, leaf spring shock absorber and oil shock absorber in [1].

2.7.3. Oleo-Pneumatic Shock Absorber Arrangement

Most of today large aircraft are equipped with oleo-pneumatic shock absorber. Figure 2-14 illustrates a basic shock absorber design. It is composed of two sliding tubes, one contains oil and the other one contains oil and gaseous nitrogen. The two tubes are communicating by one orifice and the whole system is pressurised.

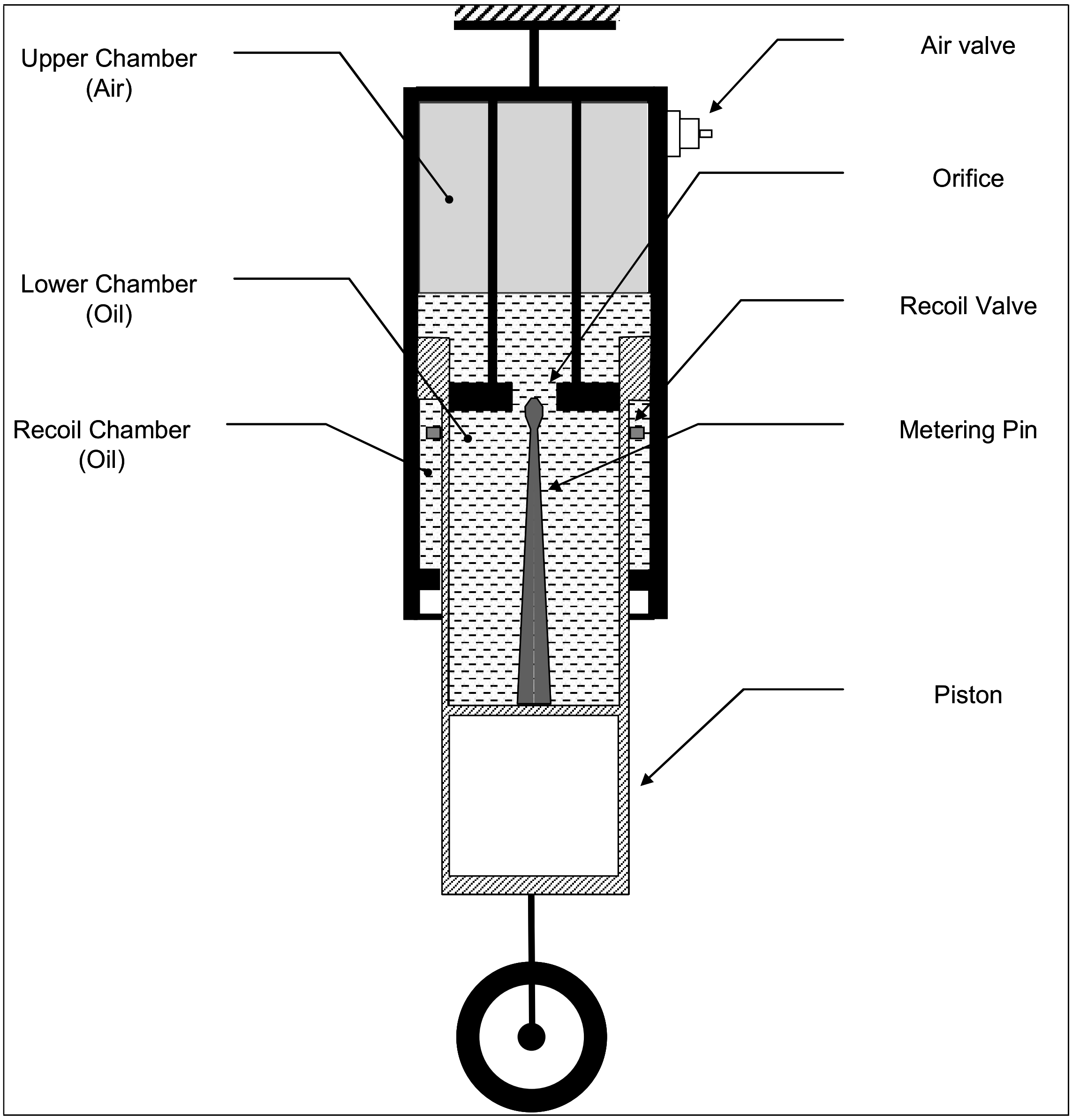


Figure 2-14: Oleo-Pneumatic Chock Absorber Arrangement

When the aircraft lands the lower tube is pushed upward forcing the oil from the lower chamber to the upper chamber. Inversely, when the landing gear is unloaded, the pressurised nitrogen forces the oil from the upper chamber to the lower chamber. The lower tube is pushed downward (See Figure 2-15).

A metering pin is often used to provide with an orifice varying in function of stroke. This has been found to maximize efficiency by leading to an almost constant strut load during dynamic loading (see §2.6.4.). The over pressure needed to force the oil to flow and the air volume reduction both lead to a rise of nitrogen pressure.

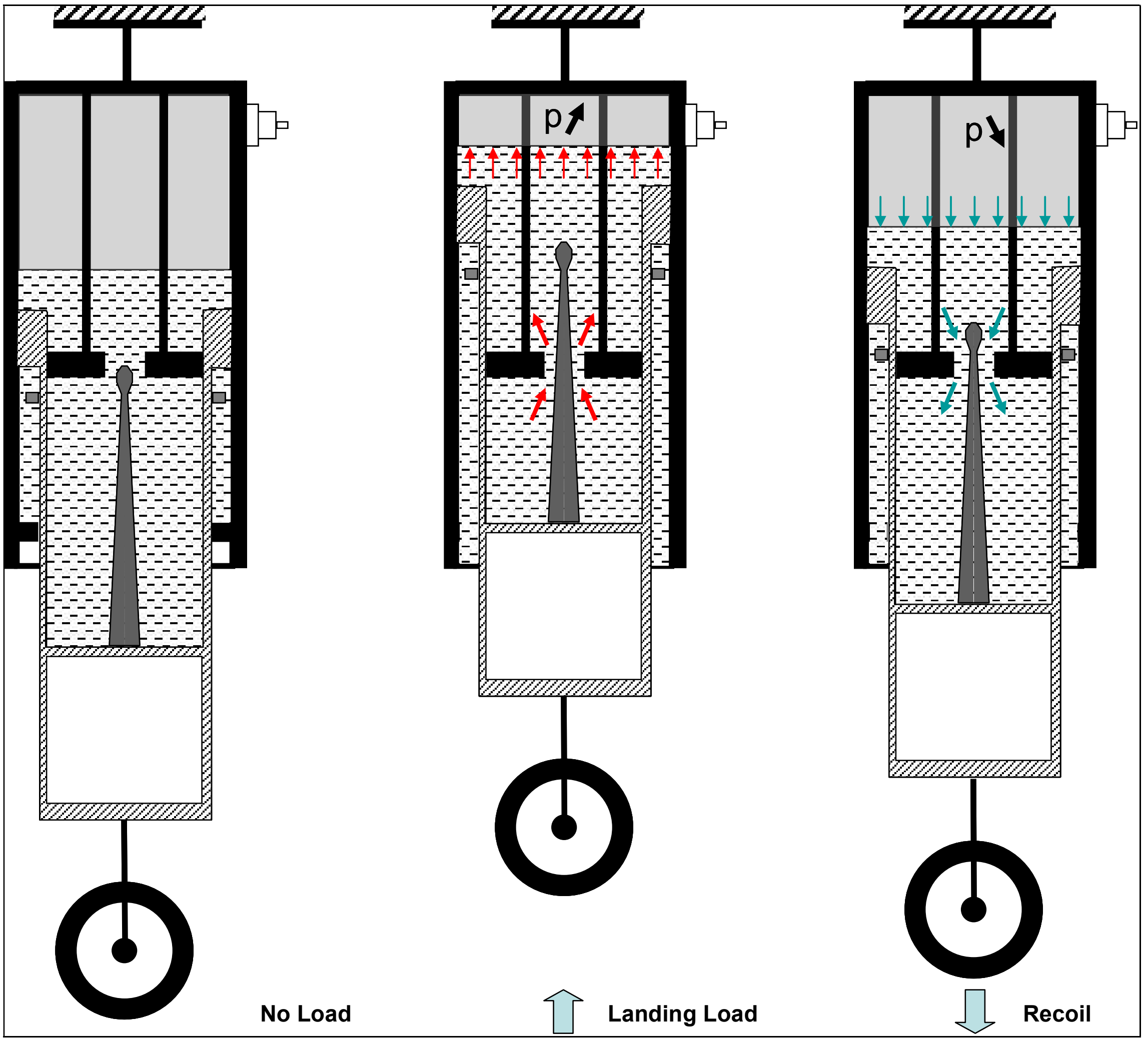


Figure 2-15: Oleo-Pneumatic Chock Absorber Principle

The Spring function of the oleo-pneumatic shock absorber is provided by the Nitrogen gas while the Damping function is providing by throttling oil through the orifice.

- **Spring Function:**

As gas does not react similarly in slow movement and fast movement, two cases must be considered.

The first case – slow movement – can be associated with normal ground handling activities. The compression is isothermal. The isothermal load-stroke curve is based on the following equations (See Figure 2-16):

:

$$P_0 L_0 S = P(L_0 - c)S$$

$$\Rightarrow F = F_0 \frac{L_0}{L_0 - c}$$

The second case – fast movement – is associated to dynamic movement such as landing or bumps on the ground. The compression is polytropic. The polytropic load-stroke curve is based on the following equations (See Figure 2-16):

$$P_0[L_0S]^\gamma = P[(L_0 - c)S]^\gamma$$

$$\Rightarrow F = F_0\left[\frac{L_0}{L_0 - c}\right]^\gamma$$

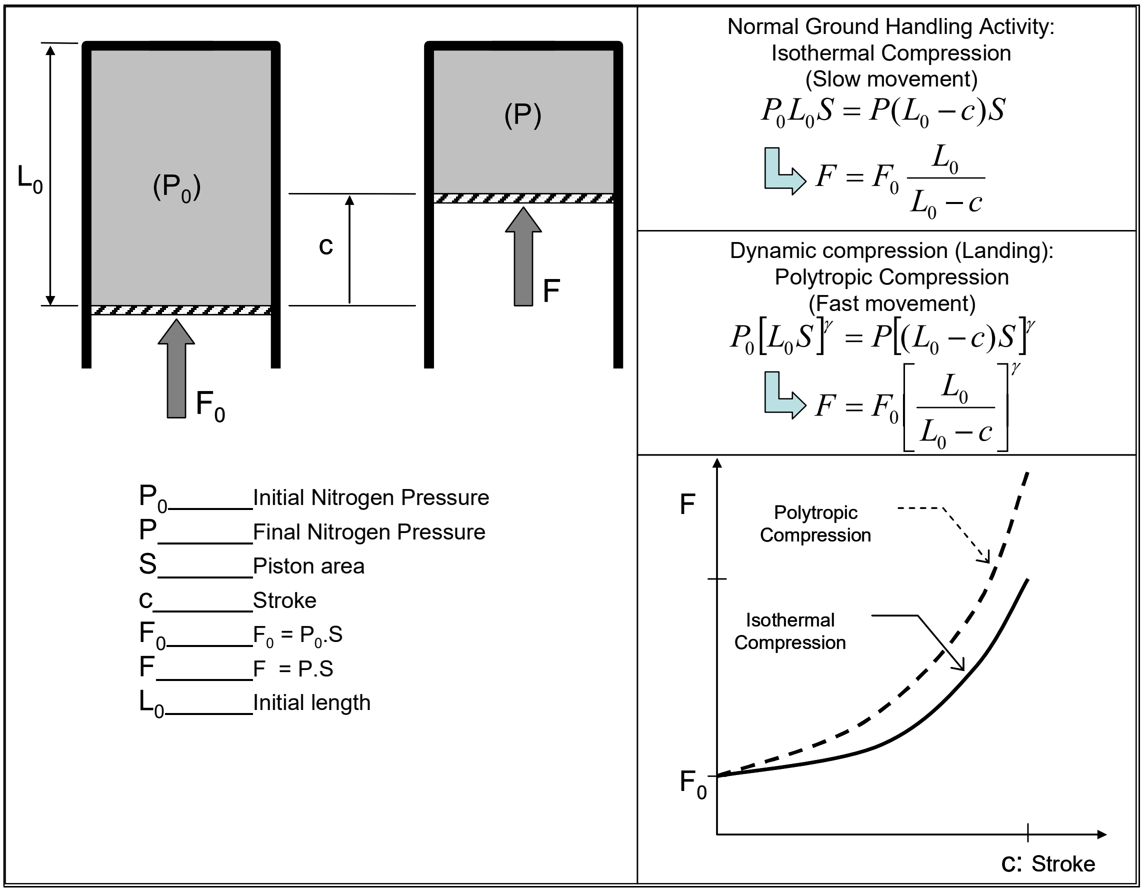


Figure 2-16: Spring Function of the Shock Absorber

Some landing gears are equipped with double-Acting shock absorber. Such shock absorbers are designed with 2 nitrogen chambers inflated at different pressure. The objective is not to enhance efficiency but to improve shock absorption characteristics during taxi conditions over rough or unpaved fields. This comfortable devices is however more expensive and usually heavier. The spring function of this type of shock absorber is shown in Figure 2-17.

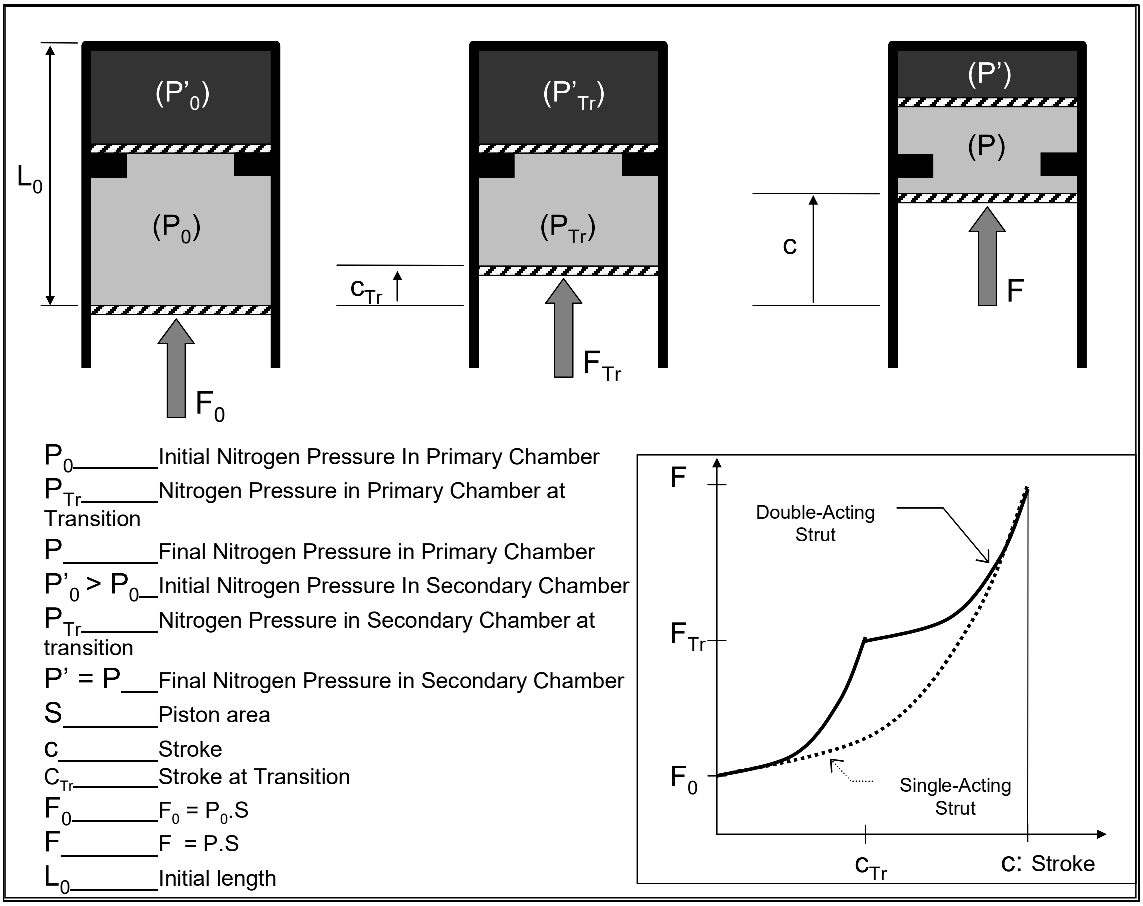


Figure 2-17: Spring Function of a Double-Acting Shock Absorber

A comparison between single and double-acting shock absorber load-stroke curves is made in Figure 2-18. A double-acting shock absorber is optimising when the static load is close to F_{Tr}, the force required to actuate the secondary chamber. In such configuration, bumps and hollows are more comfortable as approximately equal increments of load are obtained for equal increment of stroke in each direction. This is not the case for single-acting shock absorber as shown in Figure 2-18. Moreover, the local stiffness is smaller with the double shock absorber technology.

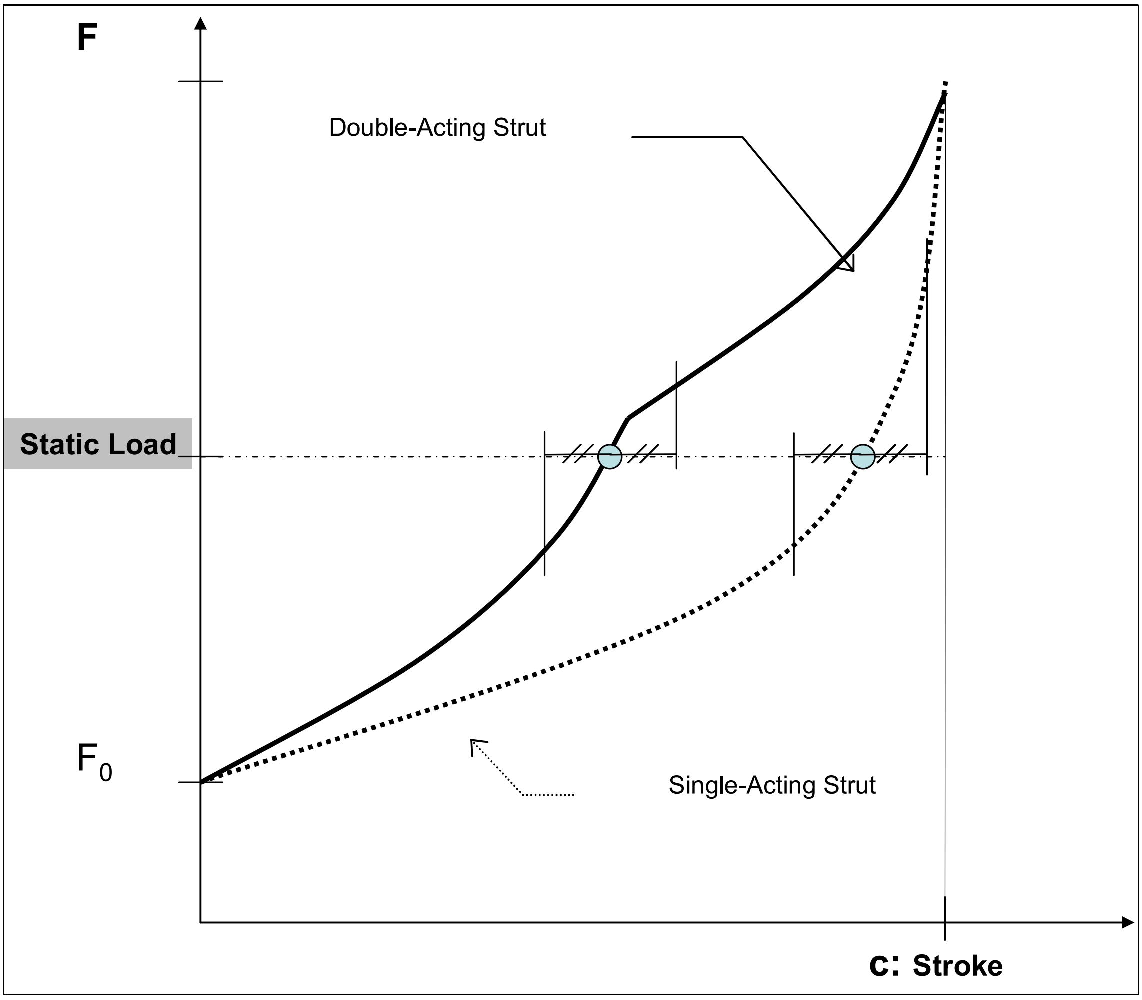


Figure 2-18: Spring Comparison of single and double

- **Damping Function:**

The overpressure required to force the oil through the orifice is roughly proportional to the square of the flow speed. The load-stroke curve – when regarding only the oil – is shown in Figure 2-19.

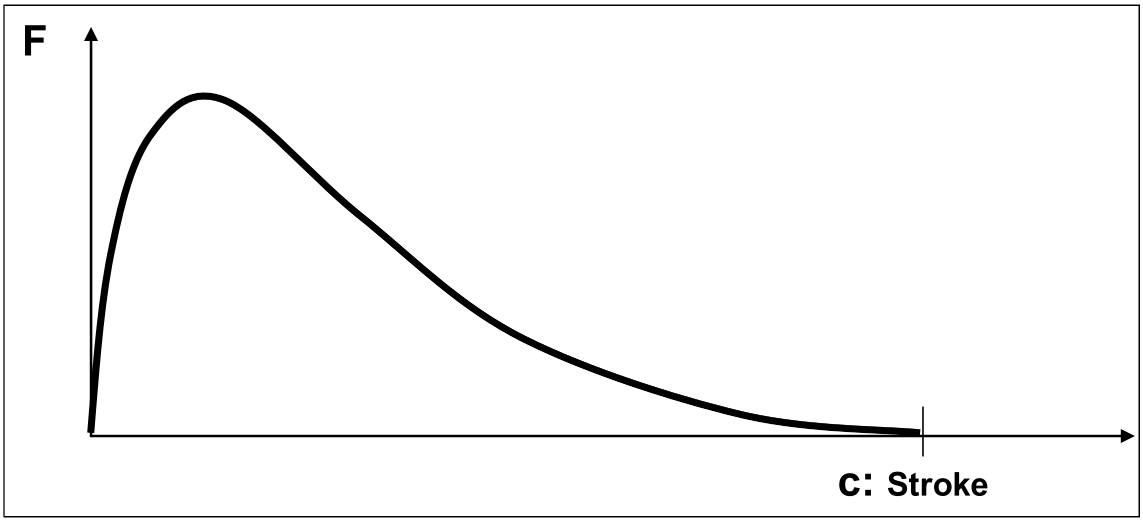


Figure 2-19: Damping Function obtained by forcing oil through the orifice

The function is decreasing when approaching c_{max} because the displacement speed is decreasing.

- **Behaviour during Landing:**

At the beginning of the landing, the lower tube moves rapidly upwards. The internal pressure increase mainly due to oil, creating a force opposed to the movement. Then speed decreases and so the effect of the damping. The spring function is then activated due to volume reduction of the nitrogen. This is shown in Figure 2-20.

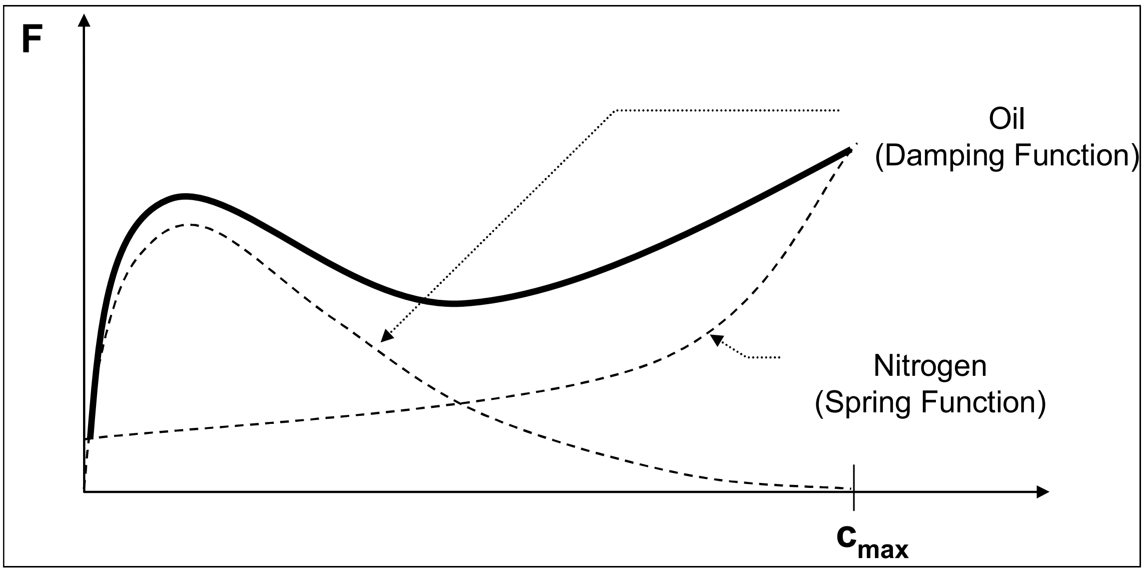


Figure 2-20: Oleo-Pneumatic Behaviour during Landing

2.7.4. Oleo-Pneumatic Shock Absorber Efficiency

As yet defined, the shock absorber efficiency, η_{SA}, is given by the following formula (See Figure 2-21):

$$\eta_{SA} = \frac{\int_0^{c_{max}} F dc}{F_{max} c_{max}}$$

Oleo-pneumatic shock absorber efficiency, the highest between the different shock absorber types, is usually around 80 to 90%. In practice it is determined by a drop test.

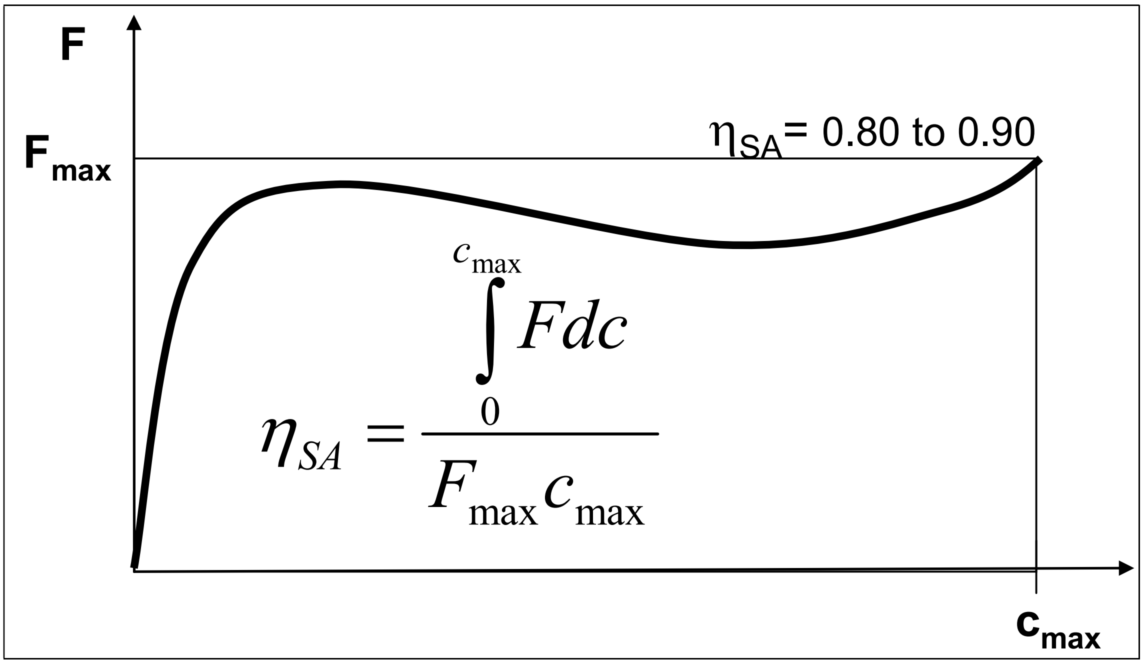


Figure 2-21: Oleo-Pneumatic Shock Absorber Efficiency

2.7.5. Remarks on Oleo-Pneumatic Shock Absorber

- Stroke: The initial stroke has to be chosen according to the load factor which seems acceptable for limit landing conditions; The total stroke for most large aircraft is about 400 – 600 mm.
- Compression ratios: Two compression ratios are normally considered: fully extended to static and static to fully compressed. According to [2]:
  - For small aircraft:
    - Static to extended____2.1/1
    - Compressed to static__1.9/1
  - For large aircraft:
    - Static to extended____4/1
    - Compressed to static__3/1

2.8. Tires

2.8.1. Generalities

Aircraft tires are subjected to a wide variety of high dynamic (Landing) and thermal loads (Braking). They are the unique interface between the aircraft and the ground and there failure can have disastrous consequences. The Concorde fatal accident in July 2000 demonstrates it. Concorde 203 taking off from Paris to New York with 100 passengers and 9 crews crashed 60 seconds after take off after suffering tire blow out –

due to foreign object on runway – that cause a fuel tank to rupture. All 109 people on board were killed and 4 people in a local hotel on the ground were also killed.

The tire characteristics which are the most relevant to the landing gear design are Load-Deflexion, Size and Weight, Loaded radius, Flat Tire radius, Rolling radius, Tire Life and Crush Load Capability.

When calculating the static ground line, the designer must consider the static tire deflection which is typically about 32%. For a given tire, this deflection is controlled by inflated pressure. Basically, the higher the deflection the higher the tire contact area and the best the flotation. However, increasing the contact area tends to reduce tire life. According to [2], "a recent USAF study did evaluate the effect of using large deflections in order to obtain higher contact areas, and hence, to improve flotation – operation on low-strength bare soil was the objective. The results showed that a 49% tire deflection was satisfactory, provided the associated reduced life was acceptable – and in a wartime emergency it probably would be".

Tire worse enemies are: under pressure and foreign objects on runway.

Figure 2-22 illustrates a typical tire with its markings, including its size which is generally defined by the maximum diameter (M), the maximum width (N) and the inside diameter (A). The standard designation is M x N – A.

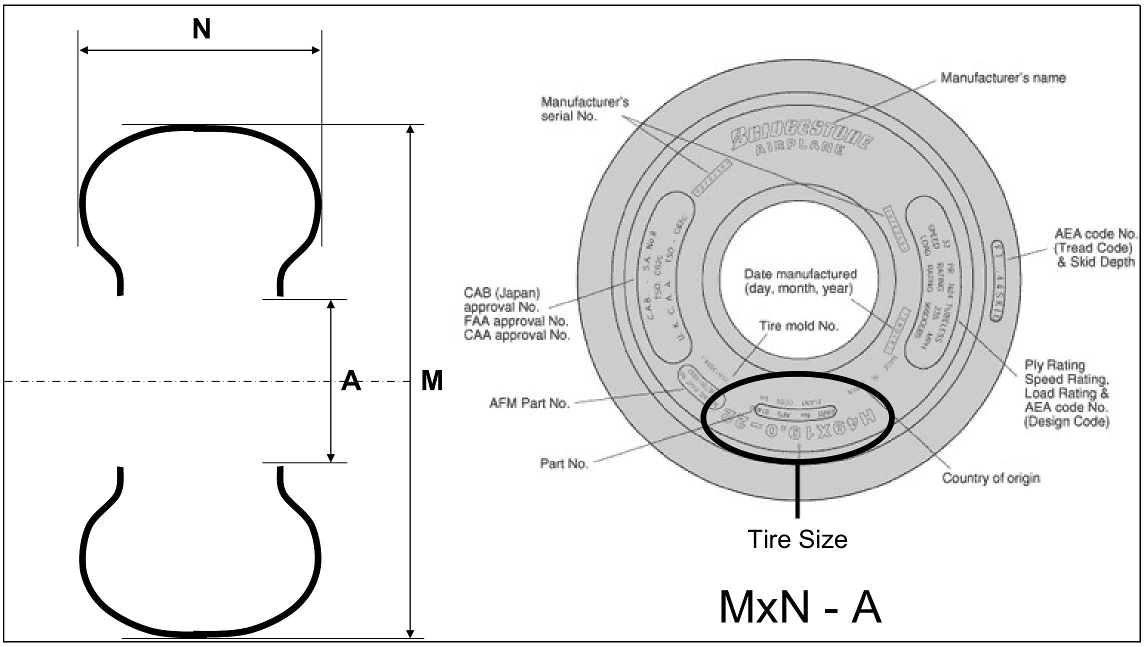


Figure 2-22: Tire Sizes [3]

2.8.2. Tires Types

The two basic tires are illustrated in Figure 2-23: Bias-Ply tire and Radial-Ply tire.

Bias-Ply tire inner casing consists of a number of layers of rubberized fabric wrapped on a bias with each each layer biased opposite to the preceding layer.

Contrary to Bias-Ply, Radial-Ply tire carcass plies are wrapped radially. That leads to higher stiffness in all direction, higher bottoming force, higher footprint (higher flotation and less hydroplanning) and higher durability when compared with current bias-ply tires.

For these reasons, radial-ply tires is becoming a standard in commercial and military aircraft.

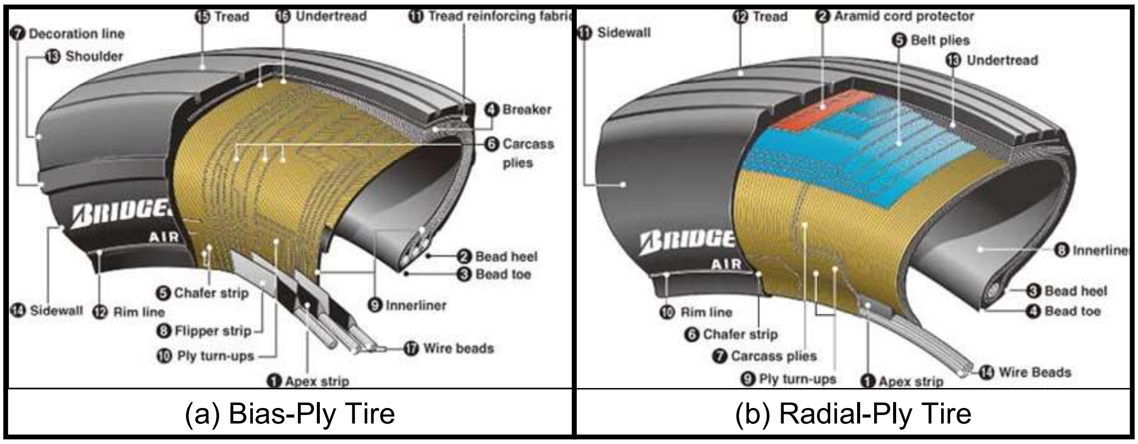


Figure 2-23: Bias-Ply and Radial-Ply Tires [3]

2.8.3. Tire Vertical Load, Tire Efficiency

When submitted to a vertical load, a tire deflects first as a quasi-linear spring; when deflection increase, the slope increases rapidly before « bottoming » (See Figure 2-24).

The energetic efficiency is given by the following formula:

$$\eta_T = \frac{\int_0^{h_{\max}} Z dh}{Z_{\max} h_{\max}}$$

Because of its quasi linear spring behaviour, the typical efficiency is about 40% to 50%.

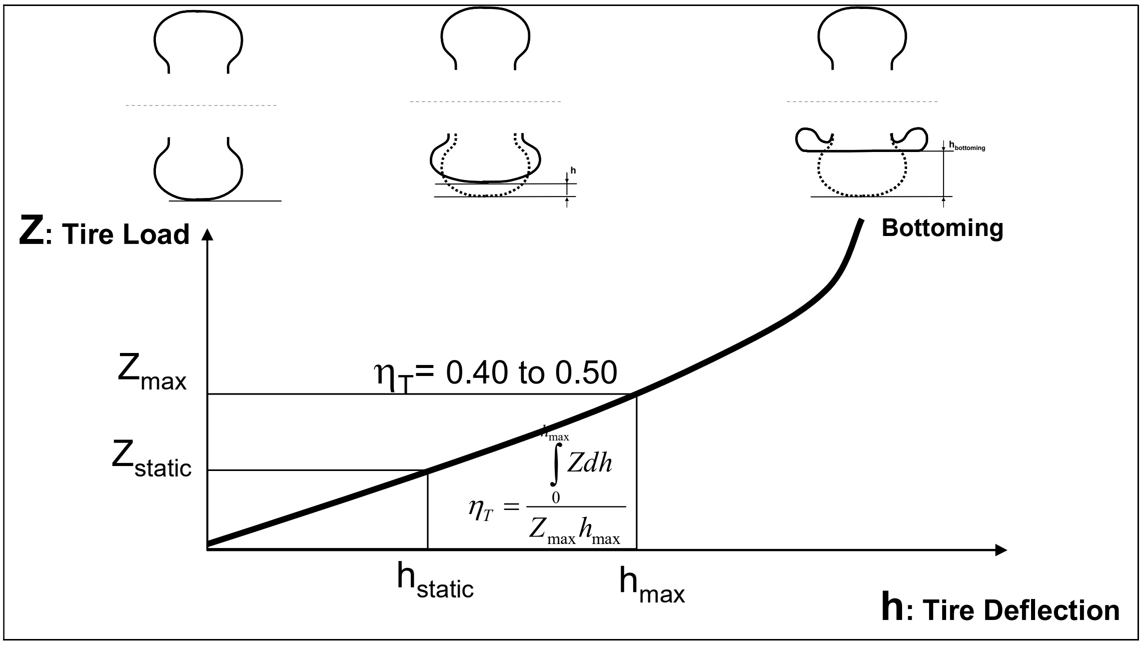


Figure 2-24: Tire Vertical Load – Deflection; Tire Efficiency

On the main gear, the vertical load applied on tires is the static load. On the nose gear, the driving load is the sum of the static load and the vertical load due to braking (10ft/s² deceleration according to standards) which makes the aircraft pitching down on its nose gear.

2.8.4. Tire Longitudinal Load

- **Tire free to roll:**

When the tire is free to roll (no braking), the friction is relatively small and is typically between 0.8% and 2% of the vertical load on dry concrete.

The rotation speed is then given by:

$$\omega_0 = V_0 / r$$

Where r=R-d/3 (d being the static deflection)

- **Braking:**

When braking is applied, the rolling radius increases: $r=R-d/3+F_X/K_X$, where F_X is the instantaneous drag and K_X the fore-and-aft spring constant.

Then: $\omega < \omega_0$. In that situation, a rearward force X appears. The friction coefficient is equal to this rearward force divided by the tire vertical force: $\mu=X/Z$.

The friction coefficient μ depends on tire material, runway and rolling speed (See Figure 2-25). Basically, its value is around 0.8 for dry concrete.

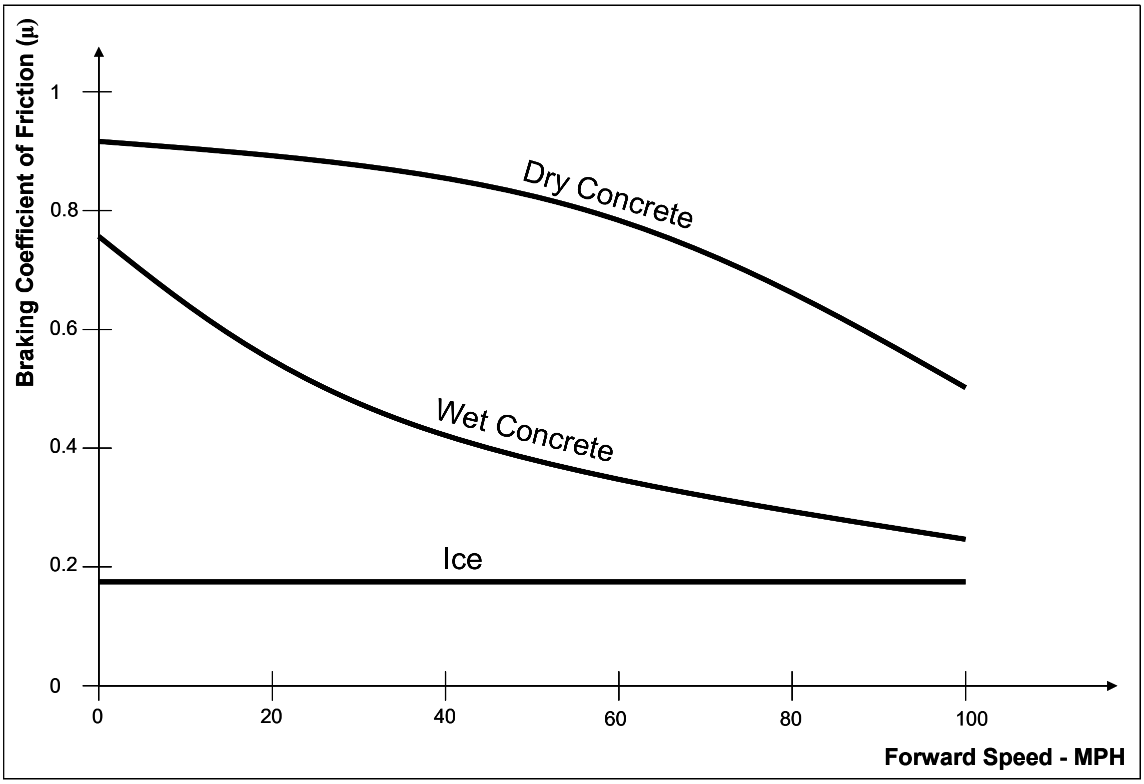


Figure 2-25: Tire Braking Friction [2]

2.8.5. Tire Lateral Load

When the tire is slipping – the tire axis form an angle ψ with direction of motion – a side force, also called the cornering force, appears. As this force is applied at a point slightly behind the tire centre line (at a distance called the pneumatic trail), a moment is applied at the centre. This moment tends to straighten the tire toward the direction of motion, this is why it is called the self aligning torque. Figure 2-26 gives details about side force and associated torque.

Such a slipping appears in landing when the aircraft lands with a slight slip angle but also sometimes in taxiing when the aircraft is turning – this is the case for co rotating wheels or in line wheels.

The cornering force and the associated torque must be considered by the landing gear designer as those loads impact the landing gear structural design.

Note that if the tire is at a yaw angle ψ, the rolling radius increases and is given by the following formula:

$$R_Y = \frac{R - d/3}{\cos\psi}$$

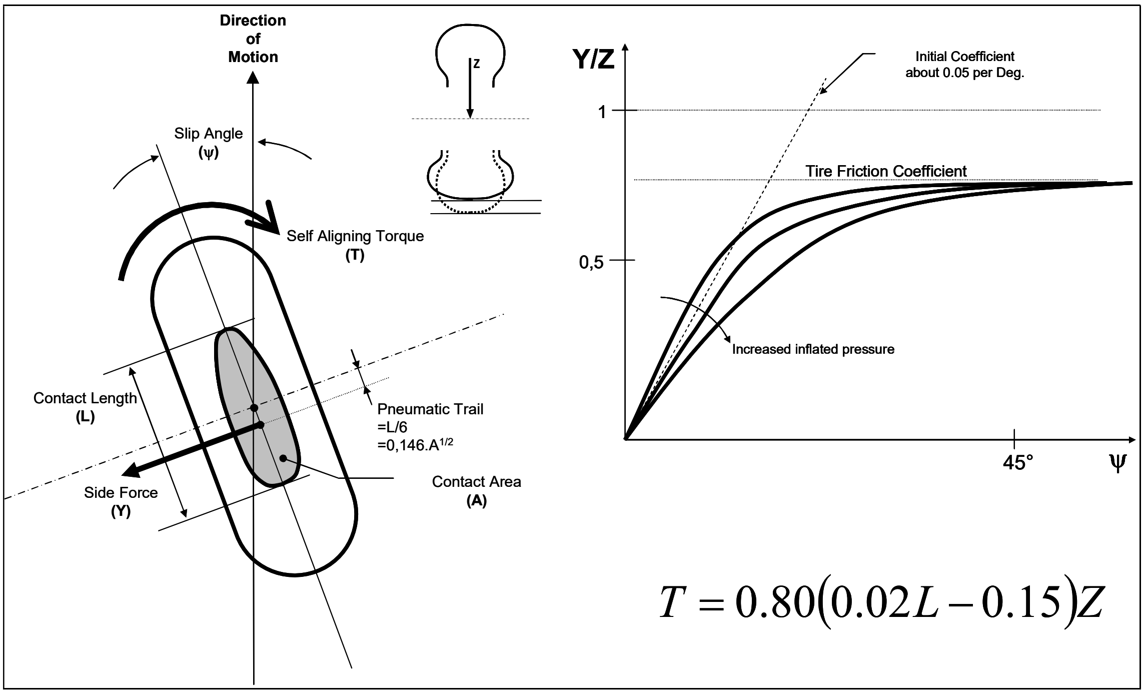


Figure 2-26: Tire Slip; Side Force and Self Aligning moment [4]

2.8.6. Tire Thermal Load

Brake action is the main source of tire thermal load.

Rejected take-off (RTO) is of course the design case for thermal loading as the tire temperature may exceed 100°C in such situation. Figure 2-27 [2] illustrates how temperature rises in tire bead and brake during a Rejected Take Off.

One can see that the tire bead temperature reaches its maximum few minutes after the RTO, generally when taxiing back. A fusible plug is generally used to prevent from any tire blow-out – which would cause serious damage to the aircraft structure but above all to people on the ground.

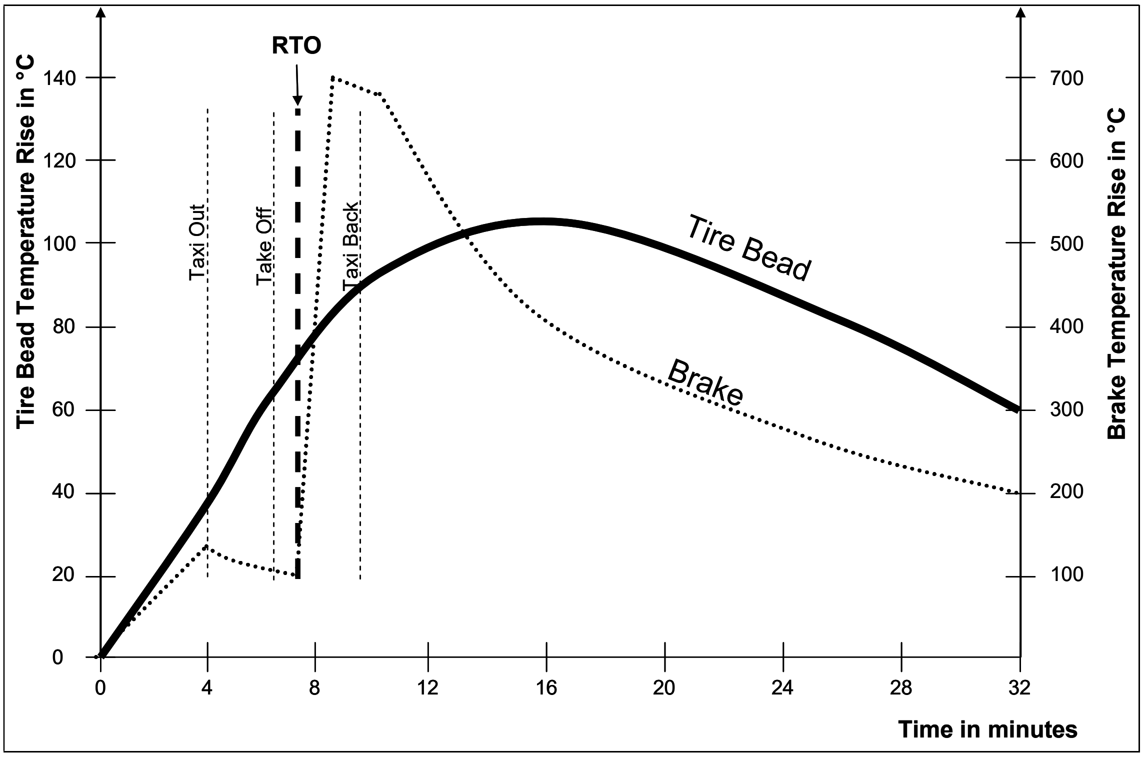


Figure 2-27: Temperature Rise in Tire and Brake during Rejected Take Off [2]

Moreover, several today trends due to traffic congestion – such as shorter landing distances and increase taxiing time – cause severe problems to the tire as they reduce its life.

3. LANDING GEAR LOADS

3.1. Typical Landing Sequence

Let assume a basic 2 point landing case (see §3.3 for more details about aircraft attitude when landing) and let isolate one of the main landing gear. Figure 3-1 illustrates such a case and provide with typical vertical and horizontal reactions on the landing gear.

At about 0,02 sec. after the initial contact, the wheel start to 'spin up' to a rotational velocity. The horizontal force on the landing gear is downward and at its maximum value.

At about 0,05 sec., the spin up is complete, the rotational velocity is equivalent to the aircraft forward speed. At that moment, the 'spring back' effect start and the landing gear is moved forward by a forward horizontal reaction.

At about 0,1 sec., this spring back is at maximum.

At about 0,2 sec., the maximum vertical reaction is reached while the horizontal reaction is still non negligible.

At about 0,3 sec., the deflection is at it maximum and the landing gear goes to its static position.

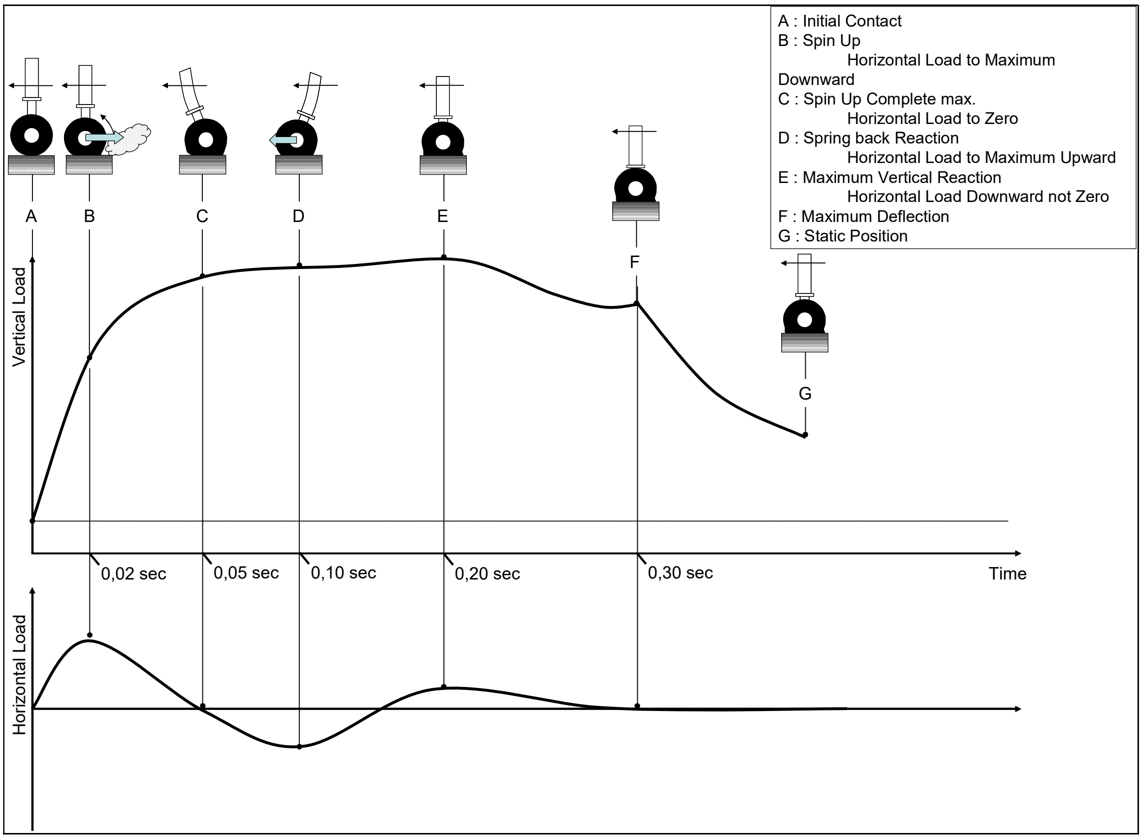


Figure 3-1: Typical landing Sequence; Vertical and Horizontal Load

This landing sequence analysis leads to the following remark: during a basic landing, 3 loading cases must be considered:

1. Spin Up: Maximum Rearward Horizontal Reaction + Vertical Reaction at instant of spin up.

2. Spring Back: Maximum Forward Horizontal Reaction + Vertical Reaction at instant of spring back.

3. Maximum Vertical Reaction: Maximum Vertical reaction + Horizontal Rearward Reaction at that instant.

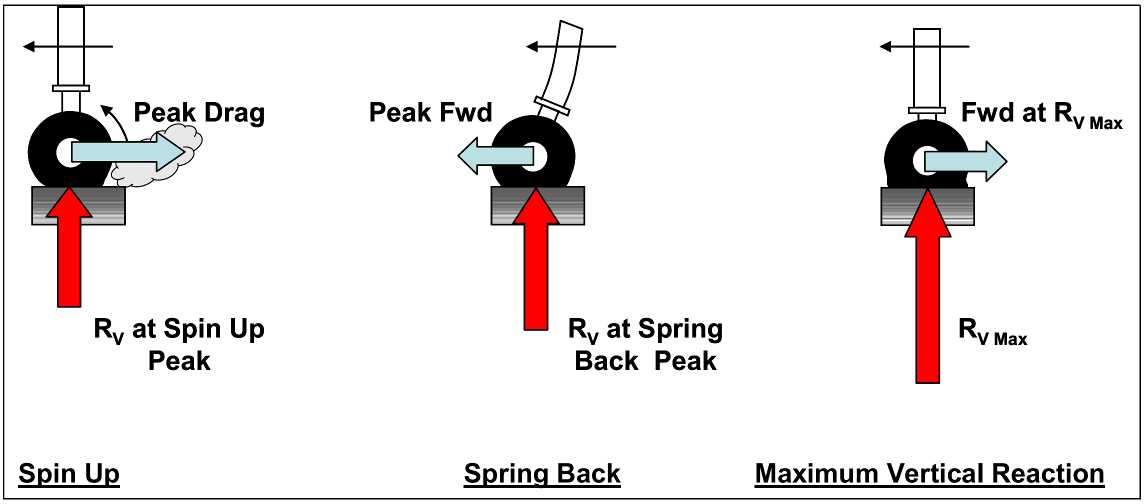


Figure 3-2: Three Load Cases for a Basic Landing

3.2. Aircraft Mass Cases for Landing

The mass of a basic aircraft is usually the highest when it is fully loaded – passengers, cargo and fuel, eventually weapons for fighter – just before the taxi. From its initial parking position to the take off point, a more or less important amount of fuel may have been burnt, leading to a smaller mass just before the take off. Finally, after the flight, just before the landing, the aircraft has burnt an important amount of fuel and has eventually launched its weapon leading again to a smaller mass.

For those reasons, it is required to distinguish 3 different mass conditions for landing gear design:

- Ramp Mass (RM): Maximum mass of the aircraft when fully loaded at parking,

- Maximum Take Off Weight (MTOW): Often equal to RM but sometimes smaller when the amount of fuel burnt to reach take off point is not negligible (long range aircraft),

- Maximum Landing Weight (MLW): Landing mass which allows for the fuel used during the shortest design flight. For long range aircraft and fighter, it is usually significantly less than MTOW.

3.3. Vertical Velocity Requirements and Aircraft Touchdown Attitude at Landing

3.3.1. Vertical Velocity and Aircraft Acceleration at Impact

In the requirements, the energy to be absorbed is defined in term of vertical velocity at impact for a given mass condition. This approach is definitively appropriate as energy is directly proportional to mass and the square of the speed and vertical speed is easier to interpret, measure and pilot than energy itself.

The most conservative approach would be to consider the maximum mass possible and a speed high enough to cover any unlikely situation. But such an approach would lead to a considerable mass penalty.

Figure 3-3 shows the results of a study carried out by FAA in 1994 in JFK airport. The vertical velocities were measured on 1030 landings. One can see that a velocity of 10 ft/s is quite unlikely.

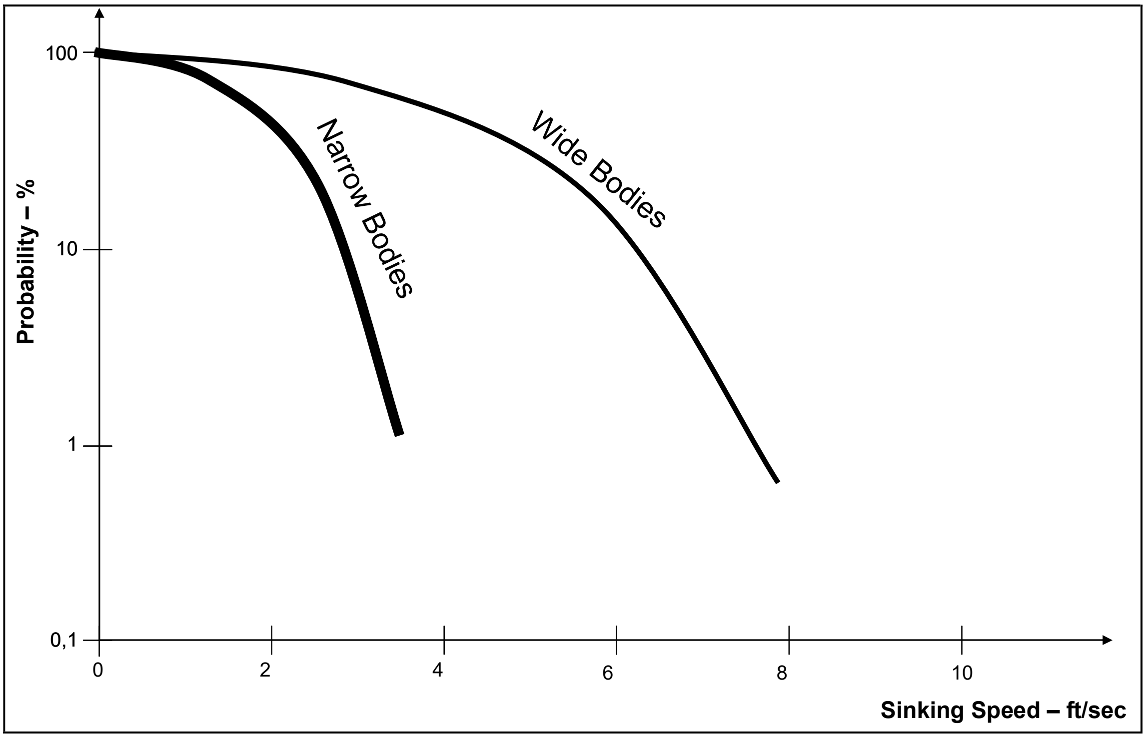


Figure 3-3: Statistic analysis of descent velocity at impact

In practice, 3 cases are identified:

- Landing at MLW: FAR25 and CS25 require the designer to consider a limit descent velocity at impact equal to 10 ft/s. “The maximum weight for landing conditions at the maximum descent velocity” (CS 25-723(a)(1)(ii)).

- Landing at MTOW: This case is an accidental case and by definition unlikely as the aircraft is not supposed to land immediately after take off. Therefore, it would be too conservative to consider the same descent speed at impact as when the aircraft is at MLW. In such a case, the requirements (CS 25-723(a)(1)(iii)) ask for a demonstration at 6 ft/s.

- Ultimate Landing: FAR25 and CS25 (section 25-723) requires that the landing gear must not fail in a test demonstrating its reserve energy absorption capacity, simulating a descent velocity of 12 ft/s at design MLW.

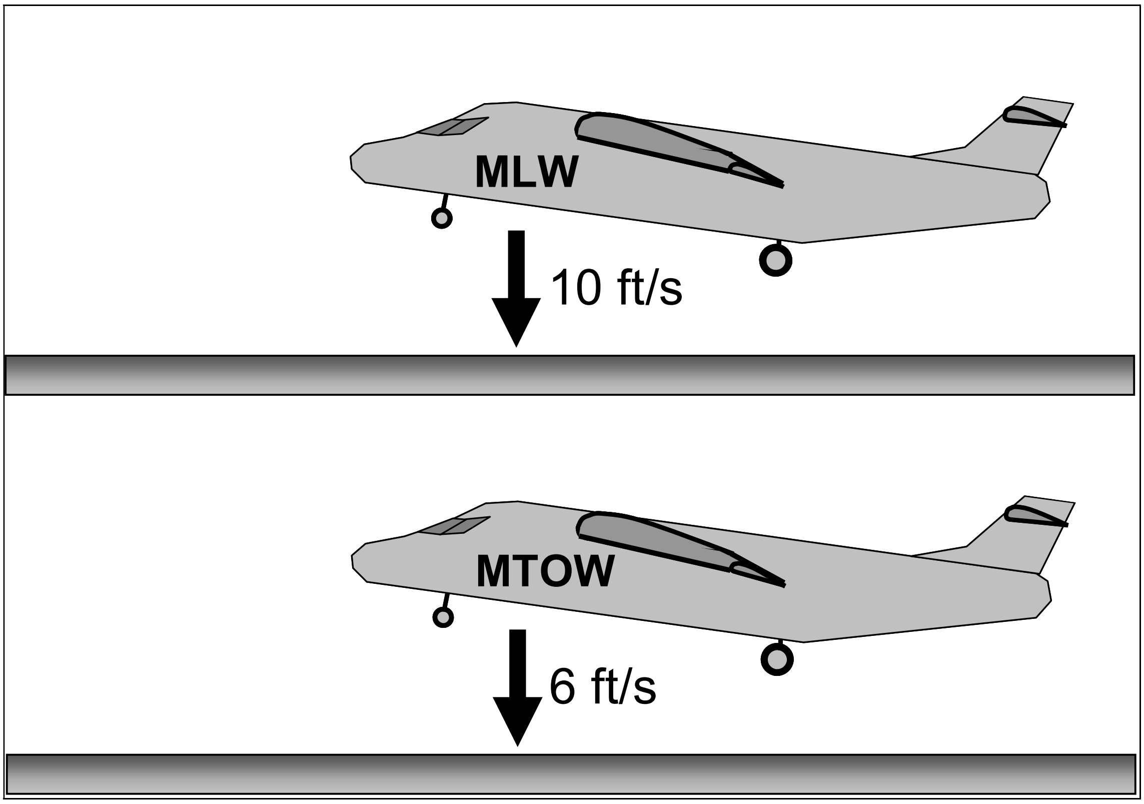


Figure 3-4: Vertical Velocity at Impact Requirements

Concerning the acceleration at impact, most requirements suggest that the aircraft lift at impact does not exceed weight, which lead to no deceleration. In practice, the lift is equal to the weight at impact and the acceleration is zero.

The following copy of CS25 section 25.473 is about the velocities and accelerations requirements.

> ***« Sec. 25.473 Ground load conditions and assumptions.***
>
> *(a) For the landing conditions specified in Secs. 25.479 through 25.485, the following apply:*
>
> *(1) The selected limit vertical inertia load factors at the center of gravity of the airplane may not be less than the values that would be obtained-*
>
> *(i) In the attitude and subject to the drag loads associated with the particular landing condition;*

(ii) With a limit descent velocity of 10 f.p.s. at the design landing weight (the maximum weight for landing conditions at the maximum descent velocity)*; and*

(iii) With a limit descent velocity of 6 f.p.s. at the design takeoff weight (the maximum weight for landing conditions at a reduced descent velocity).

(2) Airplane lift, not exceeding the airplane weight*, may be assumed to exist throughout the landing impact and to act through the center of gravity of the airplane.*

(b) The prescribed descent velocities may be modified if it is shown that the airplane has design features that make it impossible to develop these velocities.

(c) The minimum limit inertia load factors corresponding to the required limit descent velocities must be determined in accordance with Sec. 25.723(a).

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-23, 35 FR 5673, Apr. 8, 1970] »

3.3.2. Aircraft Attitude at TouchDown

The requirements distinguish between a level landing (2 point and 3 point landing) and a tail down 2 point landing.

- **Level Landing :**

During level landing conditions, the lift is supporting the aircraft weight (CS 25-473(a)(2)). Figure 3-5 illustrates both cases.

In the 2 point landing case, vertical loads and horizontal loads are applied at the wheel axles. They are reacted by aircraft inertia loads. The moments created by this combination of loads is placed in equilibrium by the pitching inertia of the aircraft.

In the 3 point landing case, the main and nose gears contact the ground simultaneously.

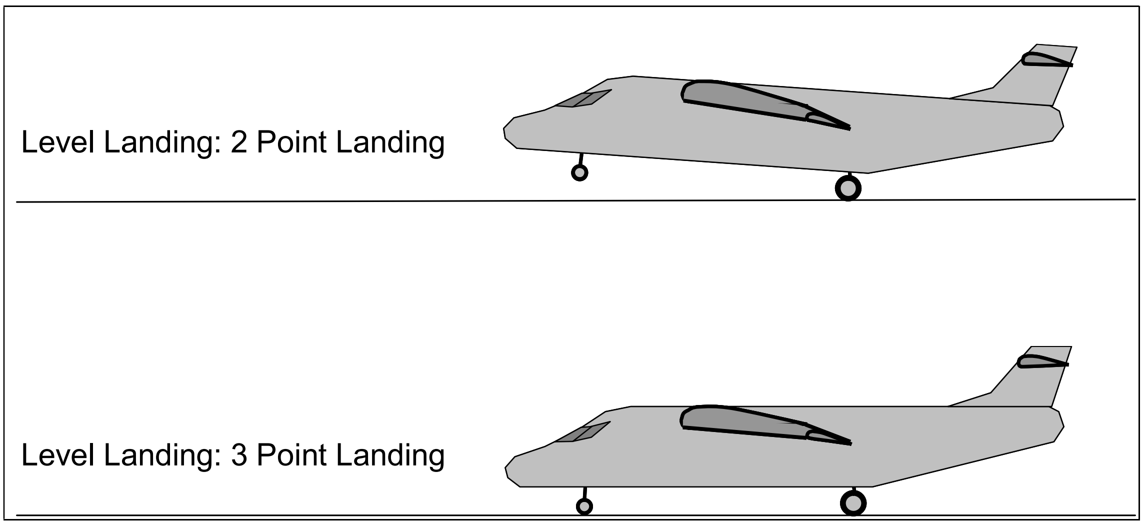


Figure 3-5: Level Landing

The following load cases must be considered for the landing gears:

1. Spin Up: Maximum Downward Horizontal Reaction + Vertical Reaction at instant of spin up (CS 25-479(b)(1)).
2. Spring Back: Maximum Upward Horizontal Reaction + Vertical Reaction at instant of spring back (CS 25-479(b)(3)).
3. Maximum Vertical Reaction: Maximum Vertical reaction + Horizontal Downward Reaction at that instant. The requirements impose this horizontal load to not be less than 25% of the maximum vertical reaction (CS 25-479(b)(2)).

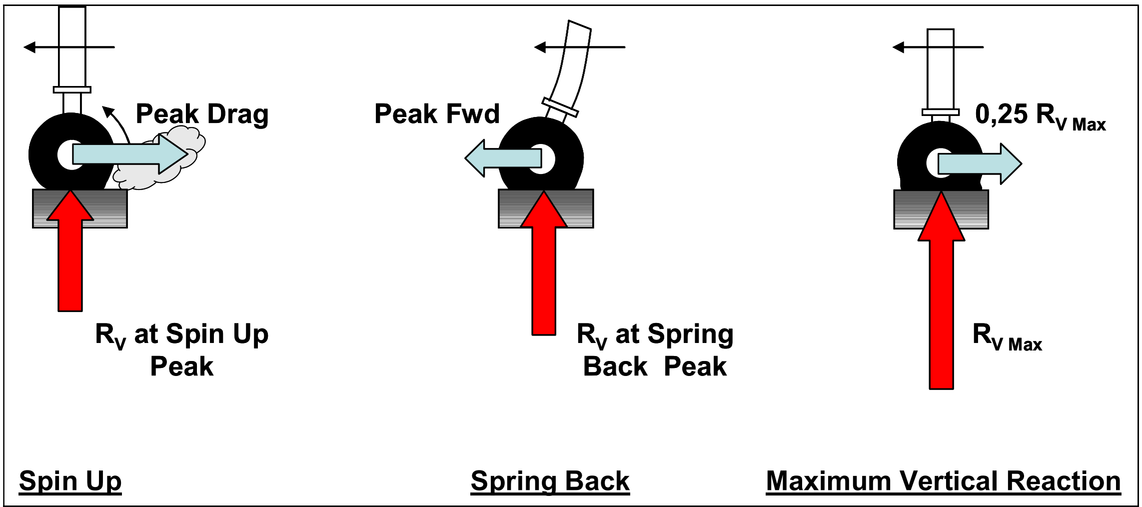


Figure 3-6: The Three Load Cases for the Level Landing

"Sec. 25.479 Level landing conditions.

(a) In the level attitude, the airplane is assumed to contact the ground at forward velocity components, ranging from VL1 to 1.25 VL2 parallel to the ground, and to be subjected to the load factors prescribed in Sec. 25.473(a)(1) *with--*

(1) VL1 equal to VS0 (TAS) at the appropriate landing weight and in standard sea level conditions; and

(2) VL2 equal to VS0 (TAS) at the appropriate landing weight and altitudes in a hot day temperature of 41 degrees F. above standard.

(b) The effects of increased contact speeds must be investigated if approval of downwind landings exceeding 10 knots is desired.

(c) Assuming that the following combinations of vertical and drag components act at the axle centerline, the following apply:

(1) For the condition of maximum wheel spin-up load, drag components simulating the forces required to accelerate the wheel rolling assembly up to the specified ground speed must be combined with the vertical ground

reactions existing at the instant of peak drag loads. The coefficient of friction between the tires and the ground may be established by considering the effects of skidding velocity and tire pressure. However, this coefficient of friction need not be more than 0.8. *This condition must be applied to the landing gear, directly affected attaching structure, and large mass items such as external fuel tanks and nacelles.*

(2) For the condition of maximum wheel vertical load, an aft acting drag component of not less than 25 percent of the maximum vertical ground reaction must be combined with the maximum ground reaction of Sec. 25.473.

(3) For the condition of maximum springback load, forward-acting horizontal loads resulting from a rapid reduction of the spin-up drag loads must be combined with the vertical ground reactions at the instant of the peak forward load. *This condition must be applied to the landing gear, directly affected attaching structure, and large mass items such as external fuel tanks and nacelles.*

(d) For the level landing attitude for airplanes with tail wheels, the conditions specified in paragraphs (a) through (c) of this section must be investigated with the airplane horizontal reference line horizontal in accordance with figure 2 of Appendix A.

(e) For the level landing attitude for airplanes with nose wheels, shown in figure 2 of Appendix A, the conditions specified in paragraphs (a) through (c) of this section must be investigated, assuming the following attitudes:

(1) An attitude in which the main wheels are assumed to contact the ground with the nose wheel just clear of the ground.

(2) If reasonably attainable at the specified descent and forward velocities, an attitude in which the nose and main wheels are assumed to contact the ground simultaneously. *For this attitude--*

(i) The nose and main gear may be separately investigated under the conditions in paragraph (c) (1) and (3) of this section; and

(ii) The pitching moment is assumed, under the condition in paragraph (c)(2) of this section, to be resisted by the nose gear

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-23, 35 FR 5673, Apr. 8, 1970]"

- **Tail-Down Landing :**

The tail-down landing is made at an extreme angle of attack. For airplanes with nose wheels, the airplane is assumed to be at an attitude corresponding to either the stalling angle or the maximum angle allowing clearance with the ground by each part of the airplane other than the main wheels, whichever is less (See Figure 3-7). Loading requirements are identical to those of level landing except that the condition of maximum wheel vertical load combined with drag is not considered. This load case introduces severe forward bending in the landing gear (landing gear not perpendicular to the ground).

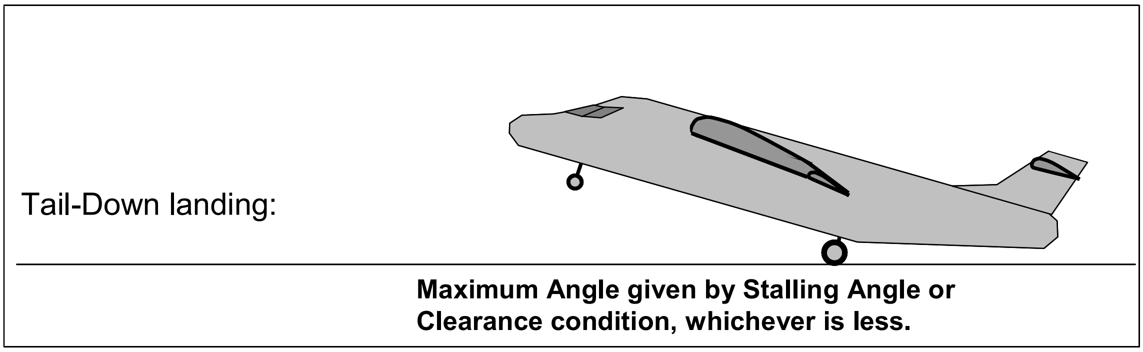


Figure 3-7: Tail-Down Landing

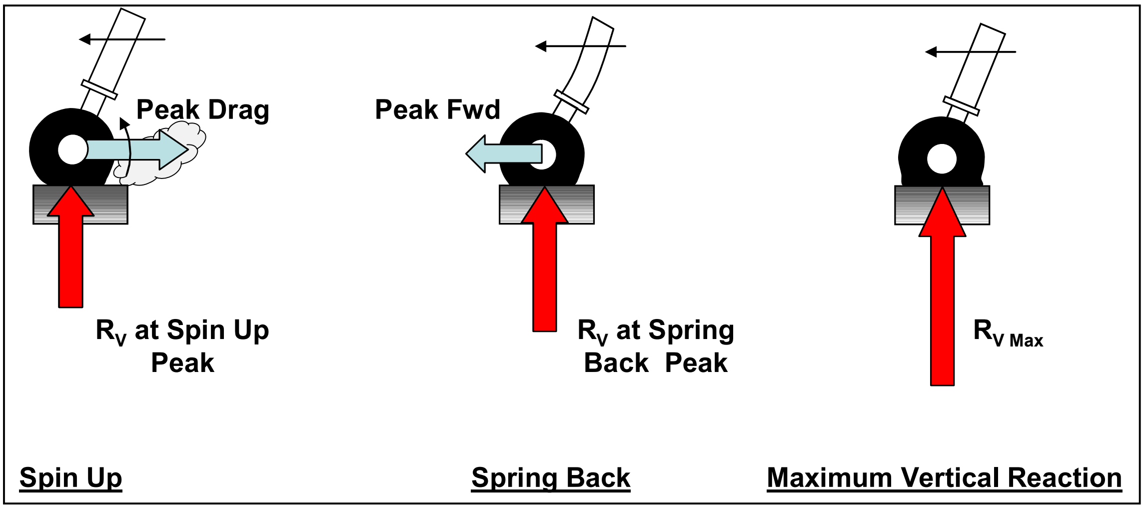


Figure 3-8: The Three Load Cases for the Tail-Down Landing

"Sec. 25.481 Tail-down landing conditions.

(a) In the tail-down attitude, the airplane is assumed to contact the ground at forward velocity components, ranging from VL1 to VL2, parallel to the ground, and is subjected to the load factors prescribed in Sec. 25.473(a)(1) *with--*

(1) VL1 equal to VS0 (TAS) at the appropriate landing weight and in standard sea level conditions; and

(2) VL2 equal to VS0 (TAS) at the appropriate landing weight and altitudes in a hot day temperature of 41 degrees F. above standard.

The combination of vertical and drag components specified in Sec. 25.479(c) (1) and (3) is considered to be acting at the main wheel axle centerline.

(b) For the tail-down landing condition for airplanes with tail wheels, the main and tail wheels are assumed to contact the ground simultaneously, in accordance with figure 3 of Appendix A. Ground reaction conditions on the tail wheel are assumed to act--

(1) Vertically; and

(2) Up and aft through the axle at 45 degrees to the ground line.

> ***(c) For the tail-down landing condition for airplanes with nose wheels, the airplane is assumed to be at an attitude corresponding to either the stalling angle or the maximum angle allowing clearance with the ground by each part of the airplane other than the main wheels, in accordance with figure 3 of Appendix A, whichever is less.”***

3.4. Energetic Aspect for Symmetrical Level Landing

3.4.1. Energy to Absorb at Landing

Let assume an aircraft with a mass M descending at a constant speed V_Z, V_X being the constant horizontal speed. Let assume that when the landing impact occurs, the vertical speed becomes zero so that before any braking, the aircraft speed is V_X.

When designing the landing gear for static cases, M should be MTOW when associated with V_Z=6ft/s and it should be MLW when associated with V_Z=10ft/s.

Let W_0 – respectively W_F – be the kinetic energy just before impact – respectively the kinetic energy just after impact:

$$W_0 = \frac{1}{2} M\left(V_X{}^2 + V_Z{}^2\right) \qquad ; \qquad W_F = \frac{1}{2} M V_X{}^2$$

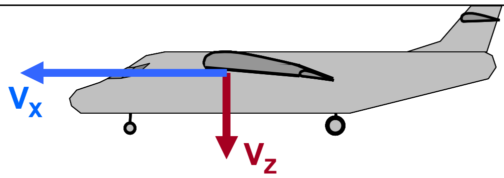
In such a typical landing case, the variation of kinetic energy is given by the following formula:

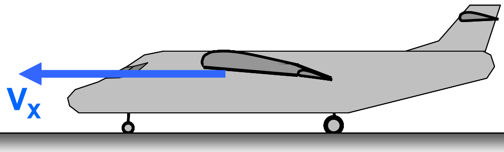
$$\boxed{W_{Abs} = W_0 - W_F = \frac{1}{2} M V_Z{}^2}$$

This energy must be absorbed by the whole landing gear system.

Figure 3-9 illustrates this case.

$$W_0 = \frac{1}{2} M \left(V_X{}^2 + V_Z{}^2 \right)$$





$$W_F = \frac{1}{2} M V_X{}^2$$

$$W_{Abs} = W_0 - W_F = \frac{1}{2} M V_Z{}^2$$

Figure 3-9: Vertical Energy to Absorb at Landing

3.4.2. Reduced Mass

Let assume a symmetrical 2 point landing. As the centre of gravity is somewhere between the nose and the main gears, the vertical force Z which is applied on the Main Landing Gear (MLG) creates a pitching moment, so that a part of the kinetic energy is converted in rotation kinetic energy.

Let M be the aircraft mass, c the horizontal distance between C.G. and MLG, z the C.G. vertical position, θ the pitch and ρ_y the pitch radius of gyration defined by the following equation: $I_{yy} = M\rho_y{}^2$ where I_{yy} is the pitch inertia of the aircraft.

At time $t=t_0$, the C.G. vertical speed is $-V_Z$ and its rotational speed is zero.

At time $t=t_1$, the C.G. vertical speed is z' and its rotational speed is θ'.

The equation of motion becomes: $z' = c.\theta'$

The fundamental dynamics theorems lead to the following equations:

$$\int_{t_0}^{t_1} Z dt = M\left(z' + V_Z\right) \qquad \text{and} \qquad -c.\int_{t_0}^{t_1} Z dt = M\rho_y{}^2\theta'$$

When solving those equations, one obtains the following:

$$z' = -V_Z \frac{c^2}{c^2 + \rho_y{}^2} \qquad \text{and} \qquad \theta' = -V_Z \frac{c}{c^2 + \rho_y{}^2}$$

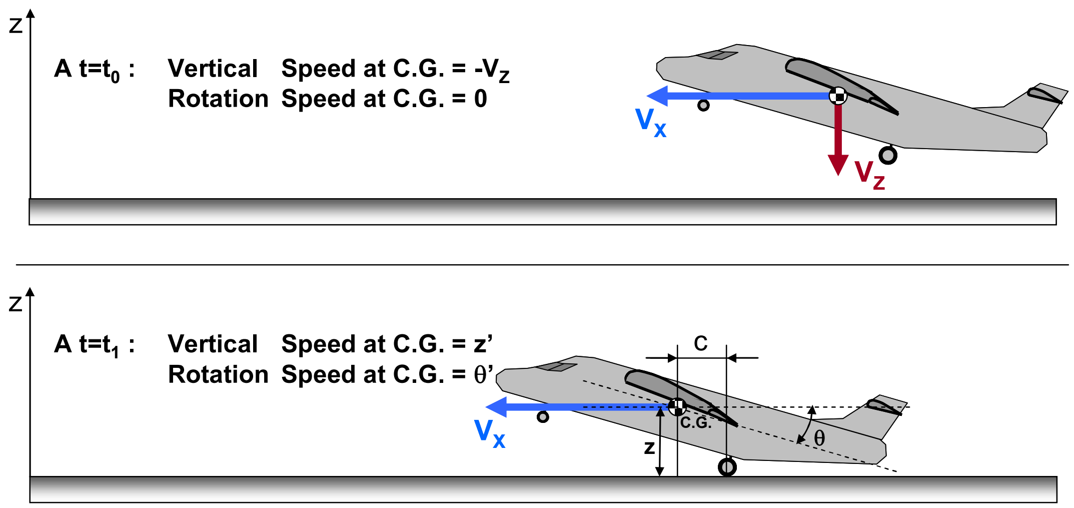
Then the energy to absorb at landing becomes :

$$W_{Abs} = \frac{1}{2} M V_Z{}^2 - \frac{1}{2} M Vz'^2 - \frac{1}{2} M \rho_y{}^2 \theta'^2 = \frac{1}{2} M \left[\frac{1}{1 + c^2 / \rho_y{}^2} \right] V_Z{}^2$$

It is therefore appropriate to define an equivalent mass M_{eq} also called the reduced mass:

$$\boxed{M_{eq} = M \left[\frac{1}{1 + c^2 / \rho_y{}^2} \right]}$$

Figure 3-10 illustrates the demonstration.



Kinematic : $z' = c.\theta'$

Fundamental Dynamic : $\int_{t_0}^{t_1} Z dt = M(z' + V_Z)$ and $-c.\int_{t_0}^{t_1} Z dt = M \rho_y{}^2 \theta'$

Where ρ_y is defined by : $I_{yy} = M \rho_y{}^2$

$$z' = -V_Z \frac{c^2}{c^2 + \rho_y{}^2} \quad \text{and} \quad \theta' = -V_Z \frac{c}{c^2 + \rho_y{}^2}$$

$$W_{Abs} = \frac{1}{2} M V_Z{}^2 - \frac{1}{2} M z'^2 - \frac{1}{2} M \rho_y{}^2 \theta'^2 = \frac{1}{2} \underbrace{M \left[\frac{1}{1 + c^2 / \rho_y{}^2} \right]} V_Z{}^2$$

One can define a reduced mass: $M_{eq} = M \left[\frac{1}{1 + c^2 / \rho_y{}^2} \right]$

Figure 3-10: Reduced Mass at Landing

Note that the same approach can be taken for all landing conditions. It is therefore possible to calculate loads as more accurate as possible, a necessity for fatigue analysis for instance.

3.4.3. Maximum Vertical Load

When the energy W to be absorbed by one landing gear is known ($W=1/2W_{abs}$ for 2 point level landing for example), a mere energetic approach provides with the maximum vertical load Z_{Max}.

Let consider the case of a landing gear equipped with only one tire and one vertical shock absorber. The energy W will be absorbed by the two elements deflected under the same vertical load.

Let η_{SA} – respectively η_T – be the shock absorber efficiency – respectively the tire efficiency.

Let c_{Max} – respectively h_{Max} – be the shock absorber maximum stroke – respetively the tire maximum deflection.

Under those assumptions, one can write the following equation:

$$W = W_{SA} + W_T$$

Where : $W_{SA} = \eta_{SA} Z_{Max} c_{Max}$ and $W_T = \eta_T Z_{Max} h_{Max}$

As the relation between Z and h is quasi-linear for the tire, it is possible to define a constant k so that $h_{Max} = k.Z_{Max}$ (see §2.8.3.).

Therefore: $\boxed{W = \eta_{SA} Z_{Max} c_{Max} + \eta_T k Z_{Max}{}^2}$

Solving this equation gives Z_{Max}.

3.5. Landing Gear Unit Distribution

The attitudes specify in §3.3.2. imply the distributions between the main and the nose landing gear when landing.

Let consider the following distances (see Figure 3-11):

L_M is the horizontal distance between Aircraft c.g. and the main landing gears,

L_N is the horizontal distance between Aircraft c.g. and the nose landing gear,

H is the height of the centre of gravity above axle of the main wheel.

Let μ be the friction coefficient, the horizontal force on each main unit is μR_M. μ should be quoted as 0.25 for transport aircraft (see §3.3.2).

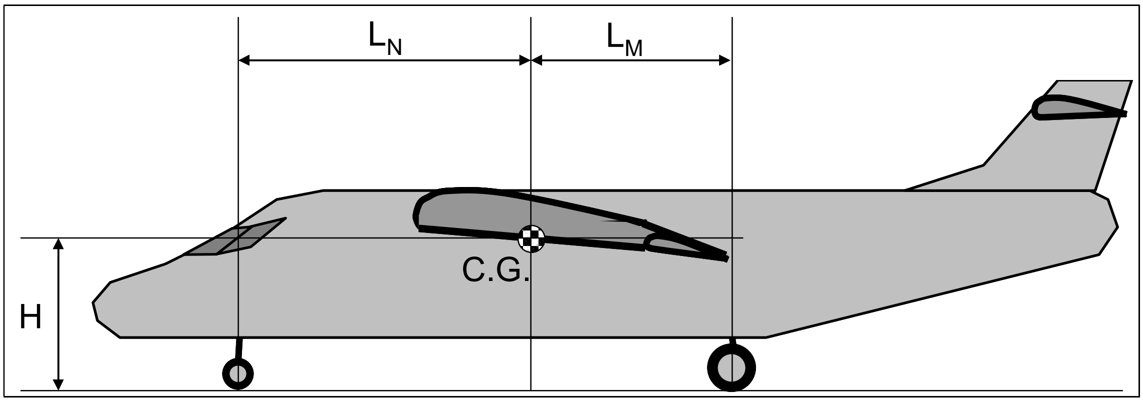


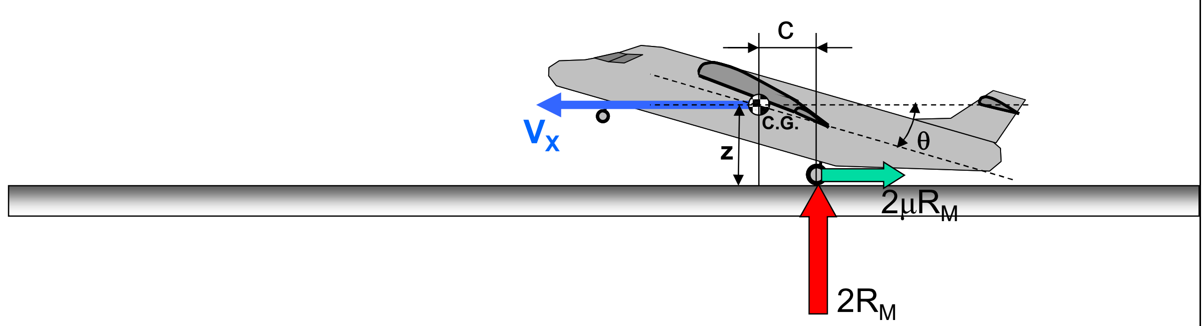
Figure 3-11: Parameters Definitions

3.5.1. Two Point Landing Attitude

Let consider a level two point landing attitude in normal conditions. According to §4.2.3, the maximum vertical load per main landing (R_M) is given by the following formula:

$$R_M \eta_{SA} c_{Max} + \eta_T k R_M^{\ 2} = \frac{1}{2} M_{eqMLG} V^2$$

Figure 3-12 illustrates the load distribution in level two point landing configuration.



Main landing gear:

$$M_{eq\,MLG} = \frac{M}{2}\left[\frac{1}{1+c^2/\rho_y^{\ 2}}\right] \Rightarrow R_M \eta_{SA} c_{Max} + \eta_T k R_M^{\ 2} = \frac{1}{2} M_{eqMLG} V^2 \Rightarrow R_M$$

Figure 3-12: Load on MLG when 2 point landing

3.5.2. Three Point Landing Attitude

Let consider a level three point landing attitude in normal conditions. The equivalent mass for main landing gear (M_{eqMLG}) and nose landing gear (M_{eqNLG}) are given by solving the static equilibrium:

$$M_{eq_{MLG}} = \frac{M}{2}\left[\frac{L_N - H\mu}{L_N + L_M}\right]$$

$$M_{eq_{NLG}} = M\left[\frac{L_M + H\mu}{L_N + L_M}\right]$$

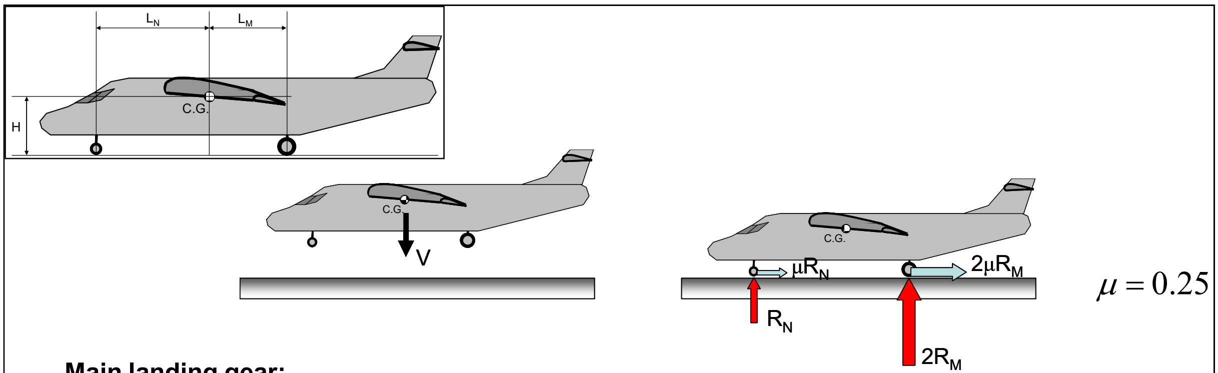
Then, the energetic equations for both units are:

$$R_M \eta_{SA} c_{Max} + \eta_T k R_M{}^2 = \frac{1}{2} M_{eqMLG} V^2$$
$$R_N \eta_{SA}{}^N c_{Max}{}^N + \eta_T{}^N k^N R_N{}^2 = \frac{1}{2} M_{eqNLG} V^2$$

Where the exponent N is for Nose landing gear.

The solving of those equations gives loads per unit.

Figure 3-13 illustrates the load distribution in level three point landing configuration.



Main landing gear:

$$M_{eq\,MLG} = \frac{M}{2}\left[\frac{L_N - H\mu}{L_N + L_M}\right] \Rightarrow R_M \eta_{SA} c_{Max} + \eta_T k R_M{}^2 = \frac{1}{2} M_{eqMLG} V^2 \Rightarrow R_M$$

Nose landing gear:

$$M_{eq\,NLG} = M\left[\frac{L_M + H\mu}{L_N + L_M}\right] \Rightarrow R_N \eta_{SA}{}^N c_{Max}{}^N + \eta_T{}^N k^N R_N{}^2 = \frac{1}{2} M_{eqNLG} V^2 \Rightarrow R_N$$

Figure 3-13: Distribution when 3 point landing

3.6. *Other Landing Loading Cases*

3.6.1. Drift Landing

The requirements specify the assumptions to make when an aircraft is drift-landed (CS 25-485): It can be assumed that the vertical load is half of that of the aircraft in the level landing attitude with only the main wheel on the ground. No drag needs to be assumed (no horizontal down force on landing gears). Side loads of 0,8 of the vertical ground load on one side acting inward and 0,6 of the vertical ground load on the other side outward at the ground contact point. These loads are resisted by aircraft inertia.

Figure 3-14 illustrates this landing case.

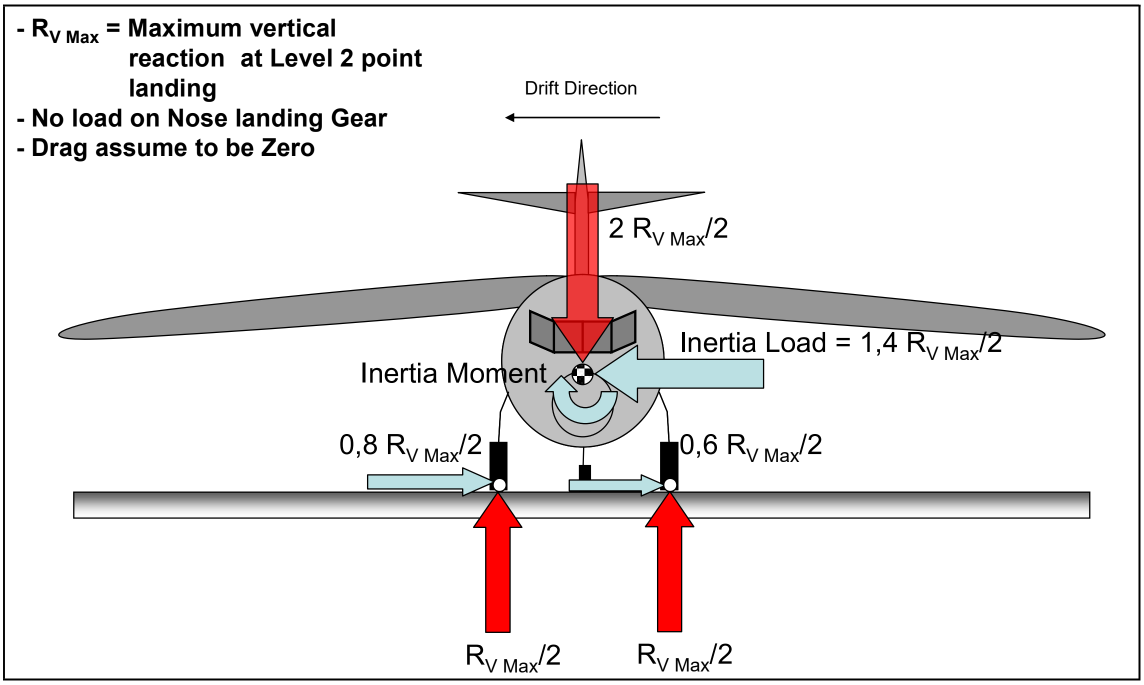


Figure 3-14: Lateral Drift landing

> ***« Sec. 25.485 Side load conditions.***
>
> *(a) For the side load condition, the airplane is assumed to be in the level attitude with only the main wheels contacting the ground, in accordance with figure 5 of Appendix A.*
>
> ***(b) Side loads of 0.8 of the vertical reaction (on one side) acting inward and 0.6 of the vertical reaction (on the other side) acting outward must be combined with one-half of the maximum vertical ground reactions obtained in the level landing conditions. These loads are assumed to be applied at the ground contact point and to be resisted by the inertia of the airplane. The drag loads may be assumed to be zero. »***

3.6.2. Landing with Deflated Tire

As tire may fail during take-off run – due to foreign objects on runway in situation of high load, high speed– the situation of deflated tire at landing must be considered.

The requirements specify that the deflation of one tire – for multiple wheel landing gear unit using less than 4 wheels – or two critical tires – for multiple wheel landing gears unit using more than 4 wheels – must be considered (CS 25-511(c)(1)).

The ground reactions must be applied to the wheels with inflated tires except for multiple-wheel gear units with more than one shock strut (CS 25-511(c)(2)).

For one and for two deflated tires, the applied load to each gear unit is assumed to be 60 percent and 50 percent, respectively, of the limit load applied to each gear for each of the prescribed landing conditions. However, for the drift landing condition of Sec. 25.485, 100 percent of the vertical load must be applied (CS 25-511(d)).

"Sec. 25.511 Ground load: unsymmetrical loads on multiple-wheel units.

...

(c) Deflated tires. The effect of deflated tires on the structure must be considered with respect to the loading conditions specified in paragraphs (d) through (f) of this section, taking into account the physical arrangement of the gear components. In addition--

(1) The deflation of any one tire for each multiple wheel landing gear unit, and the deflation of any two critical tires for each landing gear unit using four or more wheels per unit, must be considered*; and*

(2) The ground reactions must be applied to the wheels with inflated tires except that, for multiple-wheel gear units with more than one shock strut, a rational distribution of the ground reactions between the deflated and inflated tires, accounting for the differences in shock strut extensions resulting from a deflated tire, may be used.

(d) Landing conditions. For one and for two deflated tires, the applied load to each gear unit is assumed to be 60 percent and 50 percent, respectively, of the limit load applied to each gear for each of the prescribed landing conditions. However, for the drift landing condition of Sec. 25.485, 100 percent of the vertical load must be applied.

3.6.3. One Wheel Landing

The requirements specify the assumptions to make when an aircraft is landed on one wheel (CS 25-483): It can be assumed that the aircraft is in the level landing attitude with only one main wheel on the ground. The ground vertical and drag reactions are equal to those on one side for 2 point level landing. These loads are resisted by aircraft inertia.

Figure 3-15 illustrates this landing case.

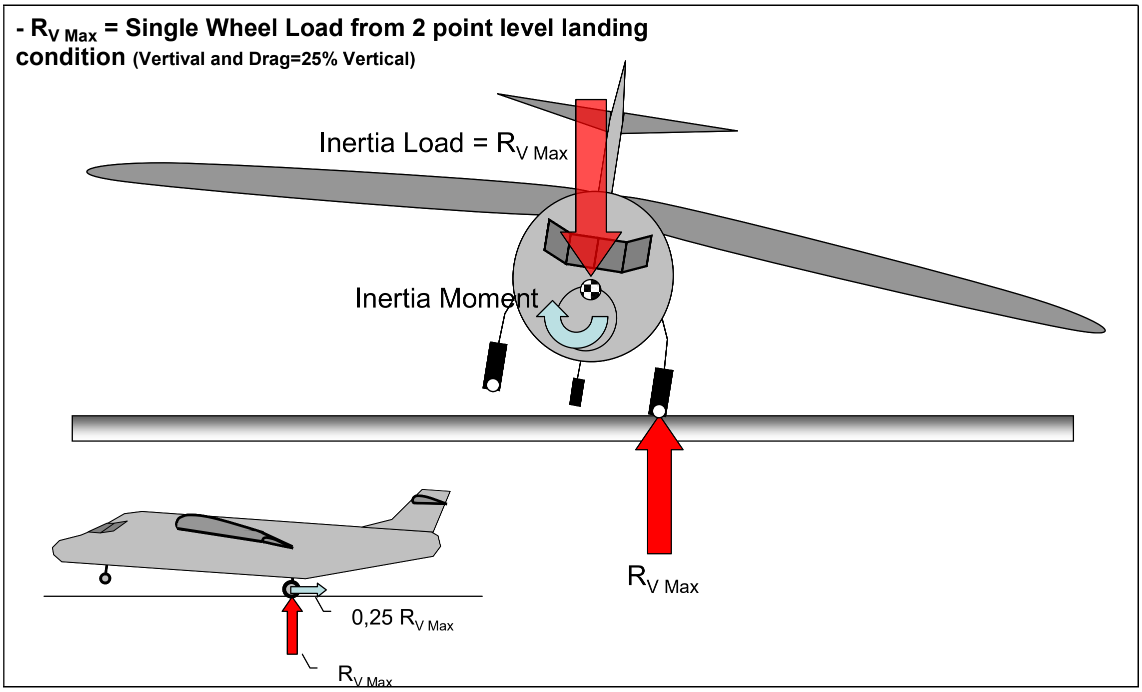


Figure 3-15: One Wheel Landing

> ***"Sec. 25.483 One-wheel landing conditions.***
>
> *For the one-wheel landing condition, the airplane is assumed to be in the level attitude and to contact the ground on one side of the main landing gear, in accordance with Figure 4 of Appendix A. In this attitude--*
>
> *(a) The ground reactions must be the same as those obtained on that side under Sec. 25.479(c)(2); and*
>
> *(b) Each unbalanced external load must be reacted by airplane inertia in a rational or conservative manner."*

3.6.4. Rebound of Unsprung Parts

Since an aircraft may rebound into the air after a hard landing, the gear and its supporting structure must be checked out for this condition. With the landing gear fully extended and not in contact with the ground, a load factor of 20 must be applied to the unsprung weights of the gear. The load factor must act in the direction of the oleo movement (CS 25-487).

> *« **Sec. 25.487 Rebound landing condition.***
>
> *(a) The landing gear and its supporting structure must be investigated for the loads occurring during rebound of the airplane from the landing surface.*
>
> ***(b) With the landing gear fully extended and not in contact with the ground, a load factor of 20.0 must act on the unsprung weights of the landing gear**. This load factor must act in the direction of motion of the unsprung weights as they reach their limiting positions in extending with relation to the sprung parts of the landing gear."*

3.7. Cases Associated with Ground Manoeuvring

> ***"Sec. 25.489 Ground handling conditions.***
>
> *Unless otherwise prescribed, the landing gear and airplane structure must be investigated for the conditions in Secs. 25.491 through 25.509* ***with the airplane at the design ramp weight (the maximum weight for ground handling conditions). No wing lift may be considered. The shock absorbers and tires may be assumed to be in their static position**."*

3.7.1. Braking Cases

- **<u>Braked roll conditions :</u>** The aircraft is taxiing in a level attitude at either 1,2 times the aircraft maximum landing weight, or at 1,0 the design ramp weight – for abort take-off condition –, without using thrust reversal power. The brakes are applied and a friction drag reaction – μ = 0,8 – is applied at the ground contact point of each wheel with brakes. The drag reaction is equal to 0,8 times the vertical reaction load unless it can be shown that lesser loads cannot be exceeded because of brake capacity (CS 25-493). Two attitudes must be considered: The main wheels only are contacting the ground and main and nose wheels are contacting the ground. Figure 3-16 illustrates this case.

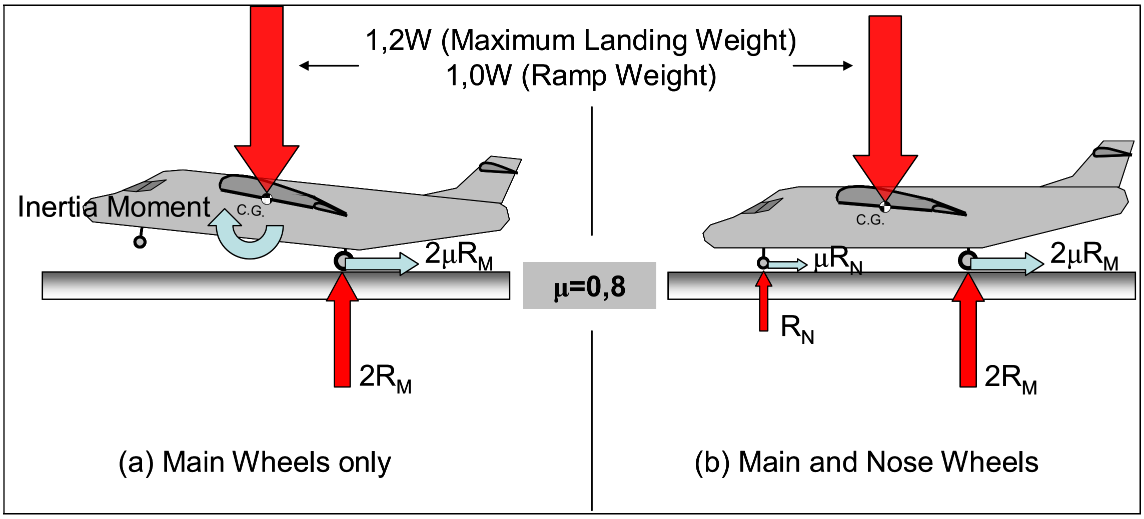


Figure 3-16: Braked Roll Conditions

> ***"Sec. 25.493 Braked roll conditions.***
>
> *(a) An airplane with a tail wheel is assumed to be in the level attitude with the load on the main wheels, in accordance with figure 6 of Appendix A. The limit vertical load factor is 1.2 at the design landing weight and 1.0 at the design ramp weight. A drag reaction equal to the vertical reaction multiplied by a coefficient of friction of 0.8, must be combined with the vertical ground reaction and applied at the ground contact point.*
>
> ***(b) For an airplane with a nose wheel the limit vertical load factor is 1.2 at the design landing weight, and 1.0 at the design ramp weight. A drag reaction equal to the vertical reaction, multiplied by a coefficient of friction of 0.8, must be combined with the vertical reaction and applied at the ground contact point***

of each wheel with brakes. The following two attitudes, in accordance with figure 6 of Appendix A, must be considered:

(1) The level attitude with the wheels contacting the ground and the loads distributed between the main and nose gear. Zero pitching acceleration is assumed.

(2) The level attitude with only the main gear contacting the ground and with the pitching moment resisted by angular acceleration.

(c) A drag reaction lower than that prescribed in paragraphs (a) and (b) of this section may be used if it is substantiated that an effective drag force of 0.8 times the vertical reaction cannot be attained under any likely loading condition."

- **Unsymmetrical Braking:** It is assumed that the brakes are applied to one main gear (CS 25-499 (b)). A drag load is applied to this gear at the ground with a value equal to the maximum brake capacity but limited to 0,8 of the vertical load on the gear. Equilibrium is obtained by balancing side and vertical loads on the nose and main gear. Any moment which would cause a side load on the nose gear greater than 0,8R_N is balancing by aircraft inertia. Figure 3-17 illustrates this case.

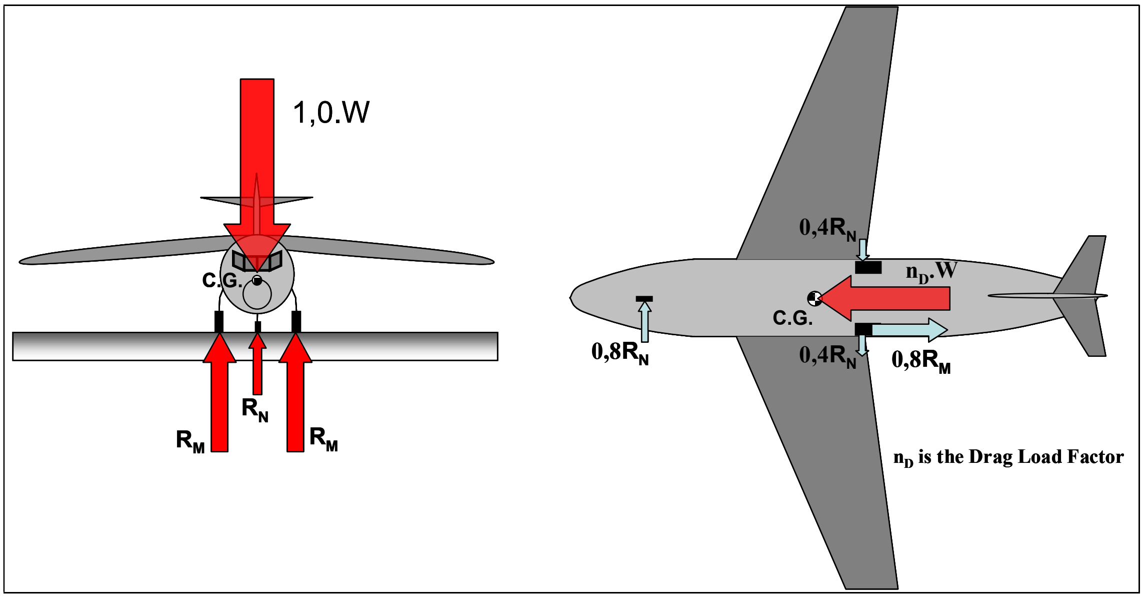


Figure 3-17: Unsymmetrical braking, Nose gear yawing

- **Dynamic Braking :** CS 25-493 requires to study the dynamic pitching motion due to sudden application of maximum braking at MTOW, with a vertical load equal to 1. This case is often the design case for NLG.

- **Reverse Braking :** The airplane must be in a three point static ground attitude. Horizontal reactions parallel to the ground and directed forward must be applied at the ground contact point of each wheel with brakes. The limit loads must be equal to 0.55 times the vertical load at each wheel or to the load developed by 1.2 times the nominal maximum static brake torque, whichever is less. For airplanes with nose wheels, the pitching moment must be balanced by rotational inertia. For airplanes with tail wheels, the resultant of the ground reactions must pass through the center of gravity of the airplane (CS 25-507).

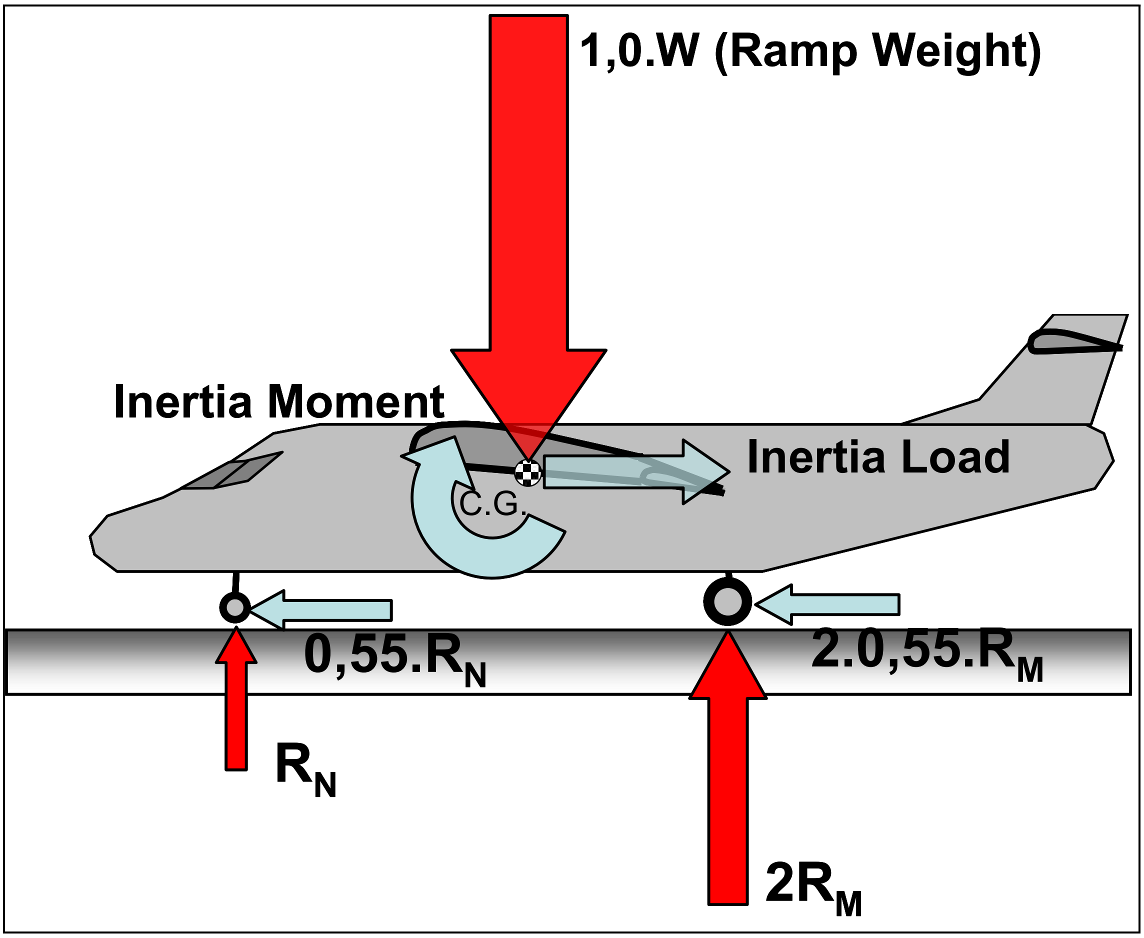


Figure 3-18: Reverse Braking

3.7.2. Turning

The aircraft is assumed to be in a steady turn – in accordance with Figure 3-19 – so that so that the limit load factors applied at the centre of gravity are 1.0 vertically and 0.5 laterally. The side ground reaction of each wheel must be 0.5 of the vertical reaction (CS 25-495). If appropriate procedures exist in the flight manual, this coefficient might be reduced (0.25 according to AIR 2004E).

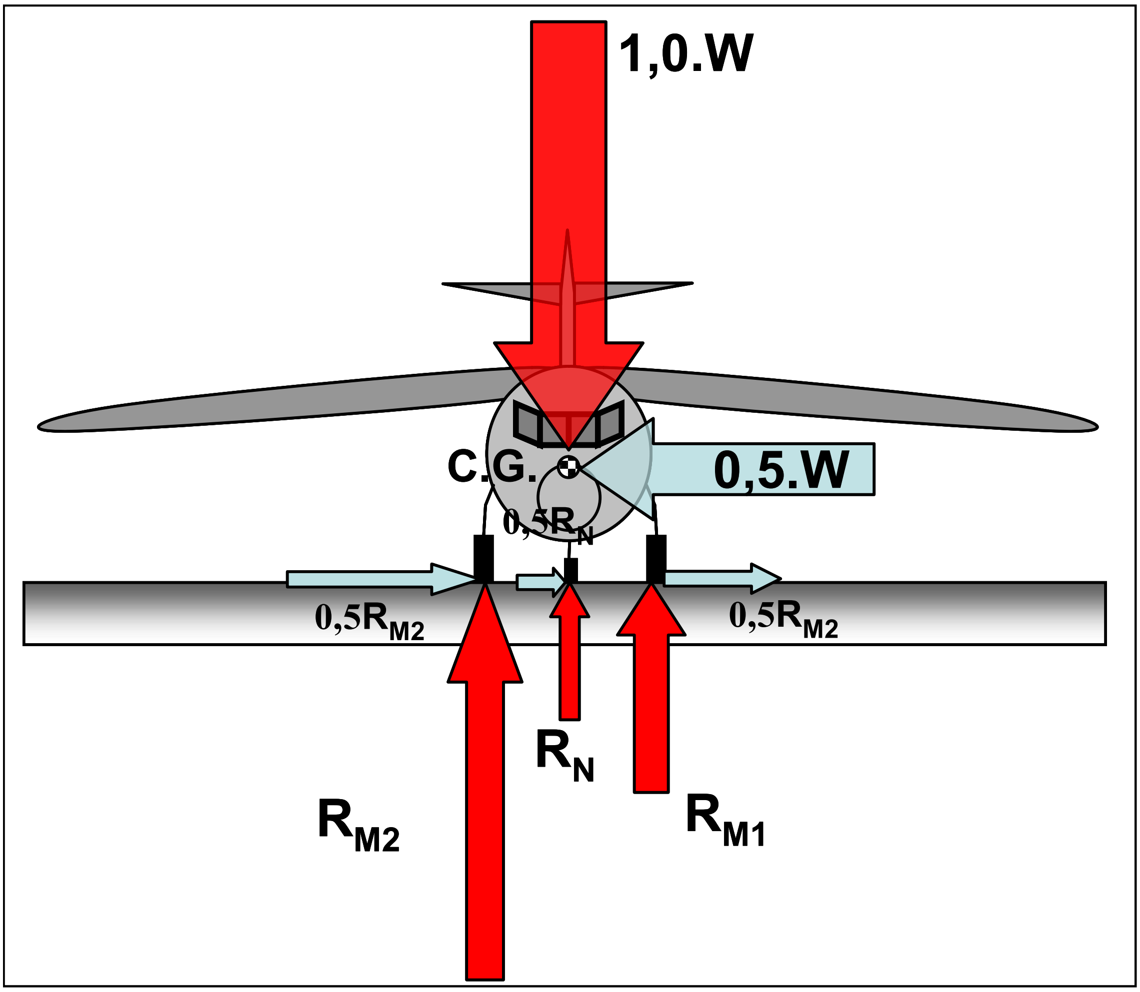


Figure 3-19: Turning

> *« Sec. 25.495 Turning.*
>
> ***In the static position, in accordance with figure 7 of Appendix A, the airplane is assumed to execute a steady turn by nose gear steering, or by application of sufficient differential power, so that the limit load factors applied at the center of gravity are 1.0 vertically and 0.5 laterally. The side ground reaction of each wheel must be 0.5 of the vertical reaction."***

3.7.3. Pivoting

The aircraft is assumed to pivot about one main landing gear which has its brakes locked as shown in Figure 3-20. The aircraft is placed in static equilibrium by loads at the ground contact point. The aircraft is in the three point attitude and pivoting is assumed to take place about one main landing gear unit.

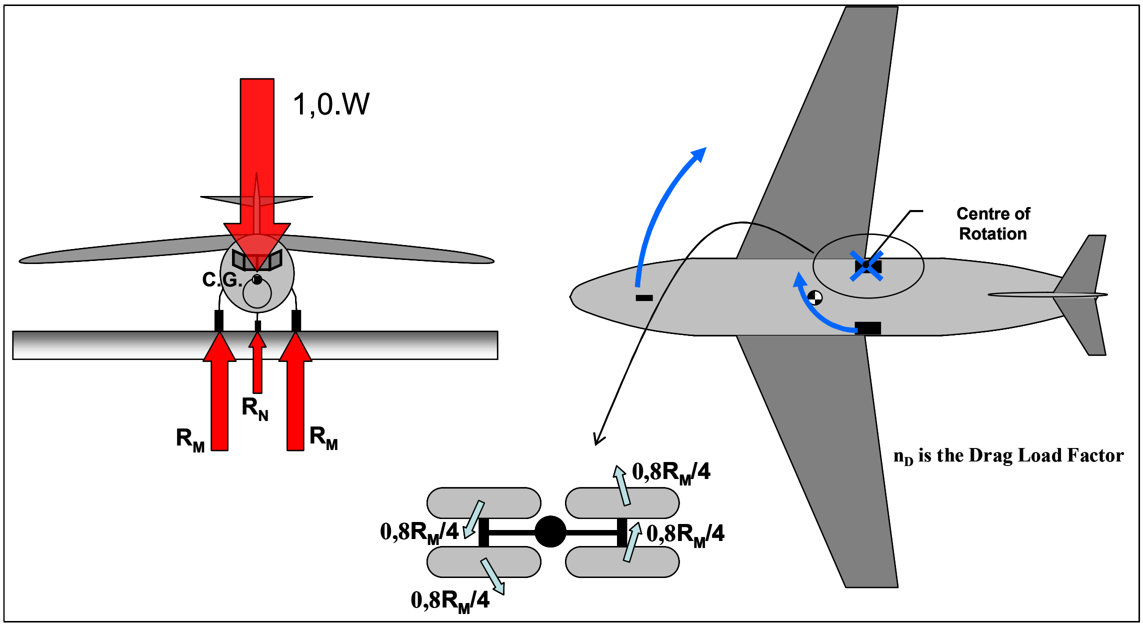


Figure 3-20: Pivoting

> *« Sec. 25.503 Pivoting.*
>
> *(a) The airplane is assumed to pivot about one side of the main gear with the brakes on that side locked.* ***The limit vertical load factor must be 1.0 and the coefficient of friction 0.8.***
>
> *(b) The airplane is assumed to be in static equilibrium, with the loads being applied at the ground contact points, in accordance with figure 8 of Appendix A."*

3.7.4. Towing

Towing requirements (CS 25-509) consist of many separate conditions which provide for loads on nose and main landing gears due to aircraft towing. They are summarized in Figure 3-22 for towing at nose gear.

Figure 3-21: Towing on a Virgin A340

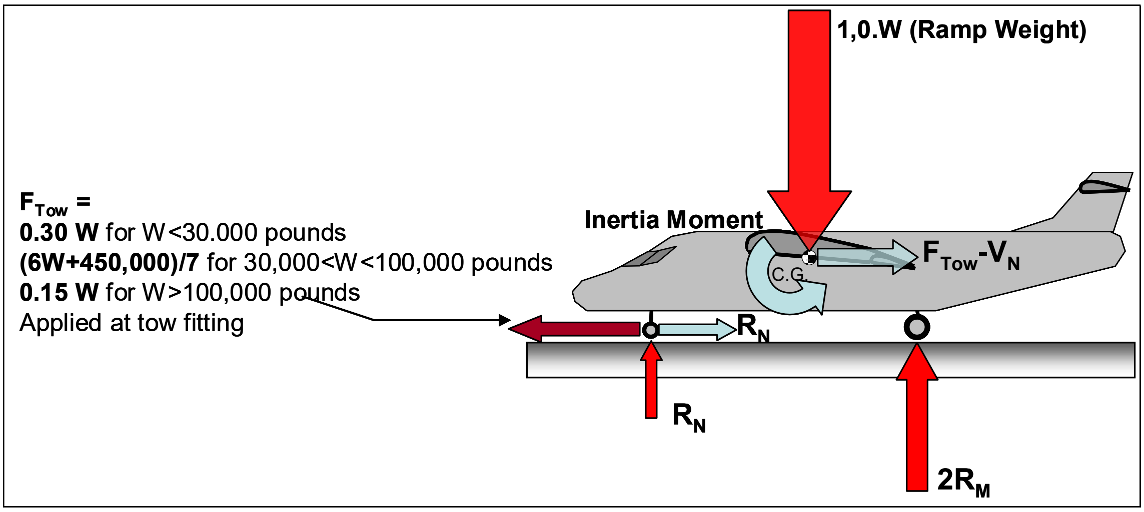


Figure 3-22: Towing at nose landing gear

*« **Sec. 25.509 Towing loads.***

(a) The towing loads specified in paragraph (d) of this section must be considered separately. These loads must be applied at the towing fittings and must act parallel to the ground. In addition--

*(1) **A vertical load factor equal to 1.0 must be considered acting at the center of gravity**;*

*(2) **The shock struts and tires must be in their static positions**; and (3) With WT as the design ramp weight, the towing load, FTOW, is--*

(i) 0.3 WT for WT less than 30,000 pounds;

(ii) (6WT+450,000)/7 for WT between 30,000 and 100,000 pounds; and

(iii) 0.15 WT for WT over 100,000 pounds.

(b) For towing points not on the landing gear but near the plane of symmetry of the airplane, the drag and side tow load components specified for the auxiliary gear apply. For towing points located outboard of the main gear, the drag and side tow load components specified for the main gear apply. Where the specified angle of swivel cannot be reached, the maximum obtainable angle must be used.

(c) The towing loads specified in paragraph (d) of this section must be reacted as follows:

(1) The side component of the towing load at the main gear must be reacted by a side force at the static ground line of the wheel to which the load is applied.

(2) The towing loads at the auxiliary gear and the drag components of the towing loads at the main gear must be reacted as follows:

(i) A reaction with a maximum value equal to the vertical reaction must be

applied at the axle of the wheel to which the load is applied. Enough airplane inertia to achieve equilibrium must be applied.

(ii) The loads must be reacted by airplane inertia. »

3.7.5. Taxi, Take off and Landing run: Bumps on Runway

Even if runways are generally carefully built in accordance with stringent standards, they are not perfect, and it is possible to encounter short discrete bumps or waves variations of height, change of slope etc.

Airfield roughness affects both the landing gear and the airframe. It is receiving increased attention for the following reasons:

- Aircraft are becoming larger and therefore more flexible. Roughness of airfield therefore lead to fatigue of structure,

- Military doctrine envisages operation from bomb damaged or unpaved airfields.

Large load can be generated during taxiing as the landing gear system is not well fitted to deal with profile variation of the runway. The use of double acting shock absorber could be a solution to this problem. In such configuration, bumps and hollows are more comfortable as approximately equal increments of load are obtained for equal increment of stroke in each direction. This is not the case for single-acting shock absorber as shown in Figure 2-18.

Let F be the bump factor – the ration between the load due to bump and the static load. M. NIU [5] recommends the following value for F:

- F=2,00 for single axle gear,

- F=1,67 for truck type gear.

4. WHAT TO DO WITH THAT LOAD?

4.1. Landing Gear Sizing

The first think to do with those loads is of course to size the landing gear itself and its attachments with the aircraft structure. The maximum load will help in size the landing gear in static, but normal loads must also be considered for fatigue point of view.

Concerning fatigue, it is important to notice that, contrary to most aircraft structure parts which are designed with multiple load paths to give fail-safe capability, most landing gear structures satisfy the safe-life concept. This implies that the fatigue life of the landing gear must be well predicted or that the growth of a crack is slow enough to allow detection at normal inspection intervals.

Figure 4-1 is an example of landing gear FEM calculation [6].

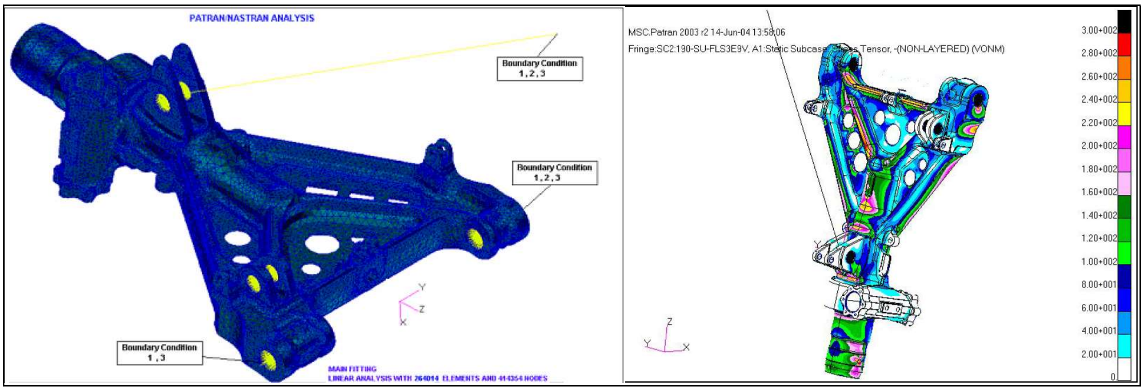


Figure 4-1: Landing Gear FEM model [6]

4.2. Ground Loads Effect on Aircraft Structure

The landing gear loads are the largest local loads on an airplane. Therefore, considerable reinforcement is usually needed to transmit those loads to a wing box or a fuselage. Moreover, as stated in §2.5., the load paths must be kept simple and determinate-structure.

Usually, landing gear loads do not govern the aircraft structure design, except locally. However, for some aircraft, in some specific situations, a ground case may size an important part of the aircraft structure. This is the case of some aircraft at hard landing (see Figure 4-2). Such a case leads to high compressive stress and high shear stress in the bottom side part of the fuselage.

Ground operations such as taxi, take off and landing, also affect the aircraft structure in fatigue due to airfield roughness. Increase of aircraft weight and flexibility are at the origin of such problems.

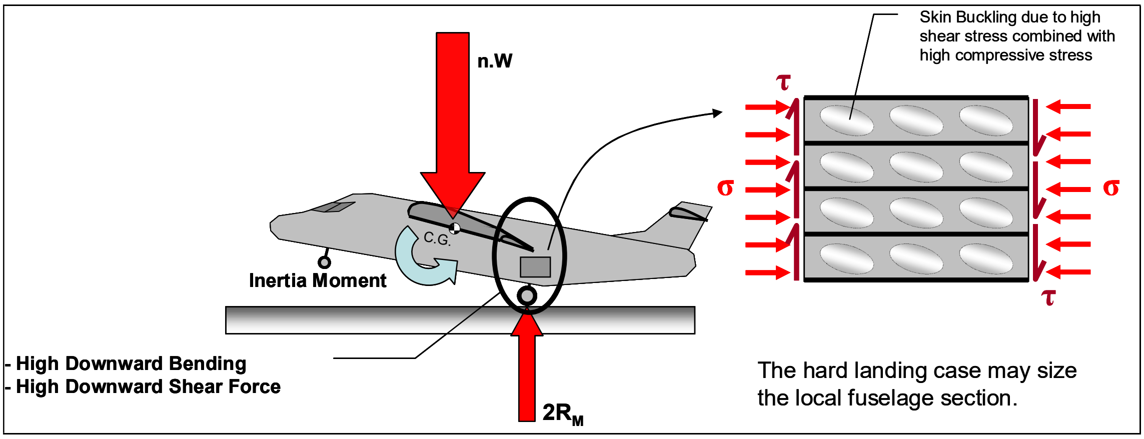


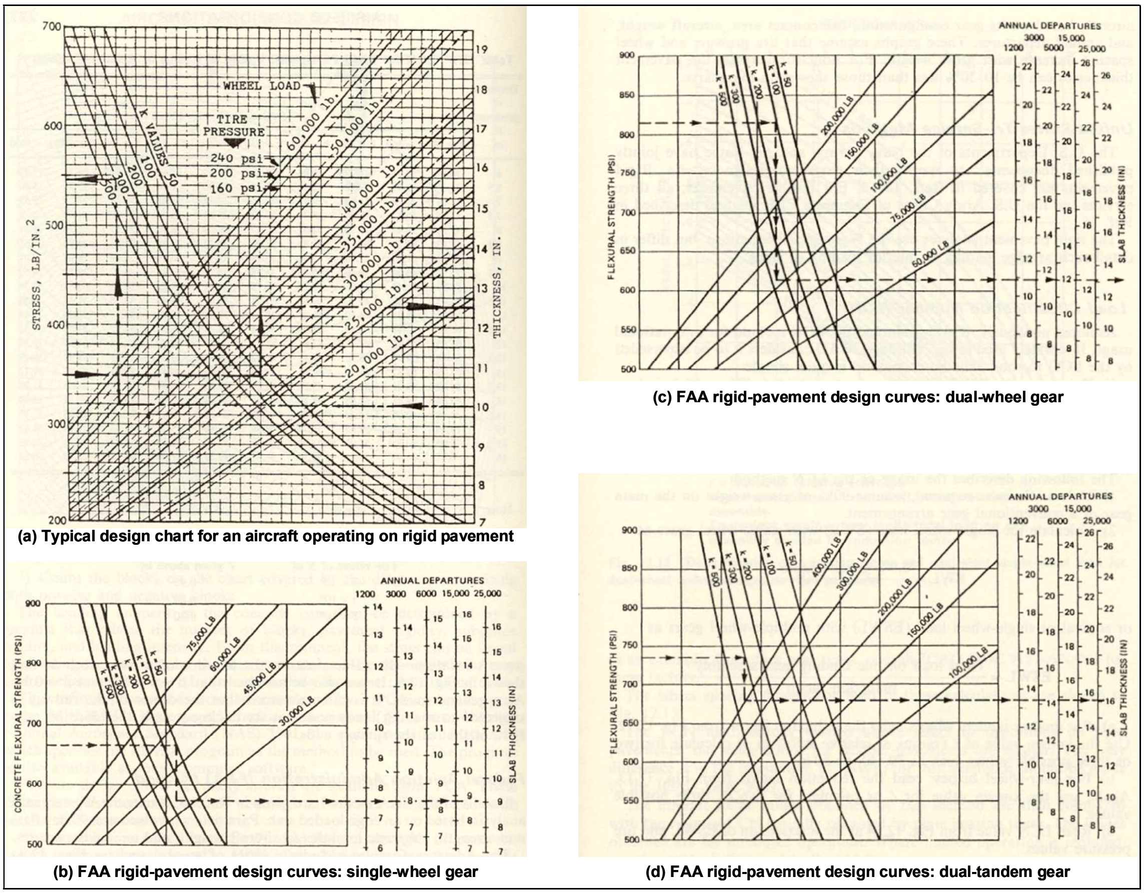
Figure 4-2: Effect of Hard Landing on airframe

4.3. Ground Loads Effect on Runway

The main parameter concerning effect on runway is flotation. Some operations analysts use flotation values in determining the precise number of landings that can be made at a given location before airfield failure. This approach can be criticised as the definition of the airfield failure itself is not well defined. However, flotation analysis is excellent to compare different aircraft and for obtaining approximate capabilities of an aircraft to operate on a specific surface.

Several methods do exist to calculate the pavement thickness required to support a given aircraft. FAA recommends the use of Westergaard analysis, based on edge-loaded stab. Parameters involved are: 90 days flexural strength, subgrade modulus, aircraft weight and annual departure. The advisory circular includes a series of graphs, such as Figures 4-3, to permit simple evaluation of a runway's capability to support an aircraft, based on its gear configuration, tire contact area, aircraft weight and annual departure. For non critical area, the pavement thickness can be 10-30% less than those shown on the charts.

The reader is invited to read [2] for more details.



(a) Typical design chart for an aircraft operating on rigid pavement

(b) FAA rigid-pavement design curves: single-wheel gear

(c) FAA rigid-pavement design curves: dual-wheel gear

(d) FAA rigid-pavement design curves: dual-tandem gear

Figure 4-3: Ground Load Effect on Runway [2]

5. LANDING GEAR TESTING

Landing gear testing is one of the most extensive testing programs in aircraft design. It involves structural tests, system tests, shimmy test and wheel and brake test.

5.1. Structural Tests

5.1.1. Stress and Strain Field Measurements

The first structural test carried out on a landing gear consists in determining stress level and direction in the complex parts. The use of photostress has become standard practice to do it. Strain gauges are also used to complete the test. The aim is to eventually detect design defects and made local changes.

5.1.2. Fatigue Tests

The second type of structural test is the fatigue one. Since landing gear are usually safe-life structures, a fatigue test is required. This test is often associated with a very complex test rig as all the various gear loading conditions must be applied. Figure 5-1 shows a fatigue test rig around a nose landing gear.

5.1.3. Static Tests

Static tests are also carried out but they are usually not critical as high margins of safety are obtained due to safe-life design.

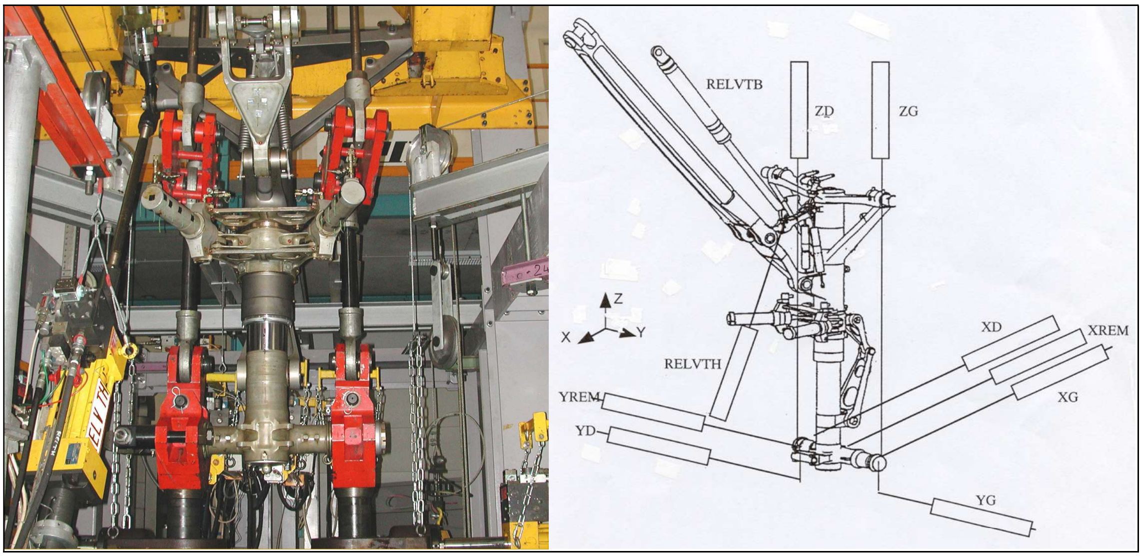


Figure 5-1: Nose landing Gear Fatigue Test *(Courtesy of CEAT)*

5.2. System Tests

The two main systems tests are the drop test and the retraction test.

5.2.1. Drop Tests

The drop test is required to develop and substantiate the energy absorption characteristics of the shock strut. The test variables are typically the landing weight, the sink speed, the level attitude and the wheel speed.

The gear is placed in the jig mounted in a vertical tower. The jig is loaded with weights and hoisted to the height corresponding with the desired sink speed. The effect of spinning up the wheels upon landing is simulated by spinning the wheels to the desired landing speed before the drop.

Figure 5-2 shows a drop test on a A340-600 nose and a main landing gears.

(a) Nose Gear (b) Main Gear

Figure 5-2: A340-600 Landing Gear Drop Tests (Courtesy of CEAT)

5.2.2. Retraction Tests

The landing gears retractions are usually laboratory tested to:

- Adjust the hydraulic and mechanical systems so that the gear operates smoothly without large impact forces and,
- Prove the service life of the moving parts.

5.3. Shimmy Test

Shimmy is an unstable condition caused by the coupling of the torsional mode with side bending mode of the gear. Dynamic tests and simulations must be carried out to demonstrate that shimmy does not appear in normal conditions.

5.4. Wheel and Brake Test

The basic test facility to assess wheels and brakes is the flywheel dynamometer. It consists of a large wheel that is spun up to the desired speed by an electric motor. The desired kinetic energy is obtained by adjusting the mass of the dynamometer wheel.

Wheels are static tested to ultimate and yield load with tires installs, and are usually roll tested several thousand miles to establish fatigue life.

Figure 5-3 illustrates wheel and brake tests.

(a) Tire under Vertical and Horizontal Loading **(b) Tire Burst in an OverLoad Take Off**

***Figure 5-3: Wheel and Brake Test** (Courtesy of CEAT)*

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