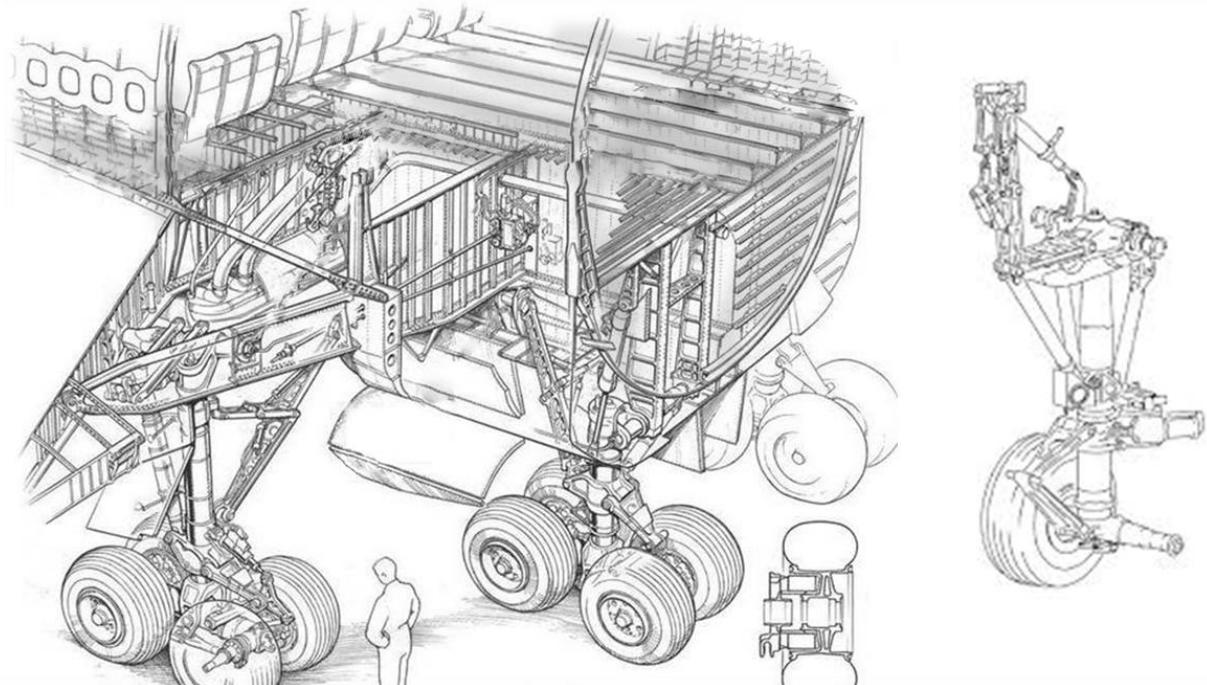


# LANDING GEAR

BOEING  
747-400

## TECHNICAL ANALYSIS: PART B



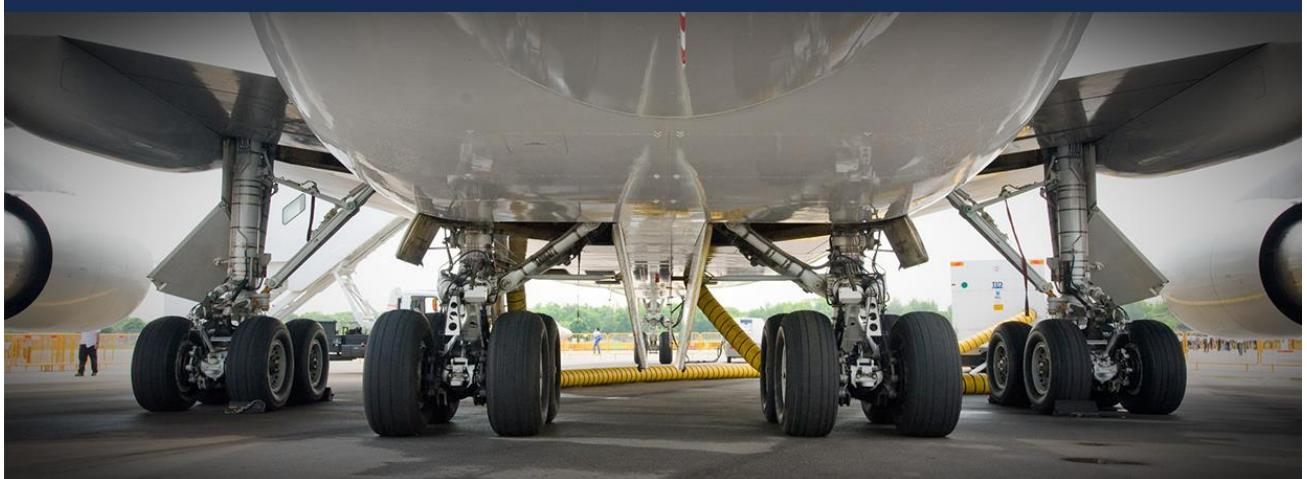
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# Index

|   |    |
|---|----|
| Summary .....   | 1  |
| Introduction.....   | 2  |
| 1 Legislation.....  | 3  |
| 1.1 Certifications specifications - 25.....               | 3  |
| 1.2 Critical situations .....                             | 4  |
| 2 Calculation preparations .....                          | 4  |
| 2.1 Weight and balance manual.....                        | 5  |
| 2.1.1 Centre of Gravity from datum .....                  | 5  |
| 2.1.2 Main Aerodynamic Chord.....                         | 5  |
| 2.1.3 Centre of Gravity in % from MAC .....               | 6  |
| 2.1.4 Balance system .....                                | 7  |
| 2.2 Dimensions .....                                      | 7  |
| 2.2.1 Dimensions of the Boeing 747-400 .....              | 7  |
| 2.2.2 Dimensions of the nose gear .....                   | 8  |
| 2.2.3 Dimensions of the main gear .....                   | 9  |
| 2.3 Mechanical situations.....                            | 10 |
| 2.3.1 Static situation.....                               | 10 |
| 2.3.2 Critical situation rejected take-off at $v_1$ ..... | 11 |
| 2.3.3 Critical situation touchdown .....                  | 12 |
| 2.4 Formulas .....  | 14 |
| 2.4.1 Gravitational force.....                            | 14 |
| 2.4.2 Kinetic energy .....                                | 14 |
| 2.4.3 Energy absorption .....                             | 15 |
| 2.4.4 Brake forces.....                                   | 15 |
| 2.4.5 The sum of forces .....                             | 15 |
| 3 Calculations .....                                      | 16 |
| 3.1 Static situation.....                                 | 16 |
| 3.2 Calculation Rejected take-off .....                   | 18 |
| 3.2.1 Equations .....                                     | 18 |
| 3.2.2 Assumptions rejected take-off .....                 | 19 |
| 3.2.3 Calculating the centre of gravity .....             | 20 |
| 3.2.4 Calculations of the forces and certification.....   | 20 |
| 3.2.5 Critical parts during a rejected take-off .....     | 22 |
| 3.3 Touchdown situation.....                              | 25 |
| 3.3.1 Static force touchdown .....                        | 25 |
| 3.3.2 Dynamic force touchdown .....                       | 25 |

|                     |                           |    |
|---------------------|---------------------------|----|
| 3.3.3               | Total.....                | 27 |
| 3.4                 | Crosswind situation ..... | 27 |
| 3.5                 | Conclusion .....          | 33 |
| Appendix index..... |                           | 34 |

## Summary

Amsterdam Aviation Engineering has assigned group 2F of Aviation Studies to perform an analysis of the certification requirements, part A, and a mechanical analysis, part B, of the critical load situations of the landing gear of a Boeing 747-400. The connection between these two analyses should result into a clear view of the critical loads and the requirements of these certifications in order to ensure that Amsterdam Aviation Engineering can prepare a test program.

Based on the legislation of CS-25, three critical load situations were chosen that should meet specific certification requirements. The requirements of the rejected take-off, the touchdown and the touchdown with crosswind were taken into account to see what kind of critical components these situations have.

Before the calculations were performed a few preparations had to be made like the weight and balance of the aircraft. In this way it became clear what the dimensions are of the aircraft so that the situations could be described based on a free-body diagram. To be able to compare these critical load situations to a normal situation, the static situation of the aircraft was also taken into account with a free-body diagram. Based on all of the situations, the formulas were described in order to eventually perform the calculations.

First off, the static situation of the aircraft was calculated in order to know the size of the forces that work upon and in the landing gear. Thereafter the calculations of the critical load situations were performed and it became clear what the critical components are during these situations.

Altogether the certification requirements and the mechanical calculations of the critical load situations form an explicit analysis which makes it clear what the critical components of the landing gear are in these different kinds of situation. Therefore this report is suited for the preparation of the test program of Amsterdam Aviation Engineering but it must be taken into account that in this report some part, such as the drag and the angle of the strut, are neglected.

## Introduction

Amsterdam Aviation Engineering (AAE) assigned project group 2F to perform a mechanical analysis in addition to the earlier functional analysis. This mechanical analysis forms the second part of Project Landing Gear and is performed by eight students in their second year at the Amsterdam University of Applied Sciences' Aviation Studies. Using skills and the gained knowledge during the first part of the project and the mechanics classes, the forces on a Boeing 747-400's landing gear are described, calculated and analysed.

This report serves as a complement to the first one. Together, they will allow AAE's engineers to understand all important aspects that need to be considered when designing and producing landing gears. This particular report focuses on the structural, mechanical and legal aspects surrounding the certification process of new landing gears. Since it is impossible to predict and account for every possible situation the aircraft could ever encounter, three critical situations (rejected take-off, rough landing without and with crosswind) are used. These situations are critical because in those situations it is expected that the limit loads are going to be exceeded. They therefore serve as benchmarks during certification, as it is unlikely that these forces are ever exceeded in service.

All new aircraft parts need to be certified by the European Aviation Safety Agency (EASA) before being allowed into service. A commercial aircraft's landing gear needs to comply with a number of requirements that are outlined in the Certification Specifications (CS) 25. Including loads the gear needs to withstand during critical situations **(1)**.

During the design process engineers can estimate these loads using calculations. Preparations need to be made to avoid errors and to achieve a greater degree of accuracy **(2)**.

Using Free Body Diagrams (FBDs) force equations, torque equations and all external and internal forces can be determined. This will lead to a conclusion on the compliance of a landing gear with the legal requirements **(3)**.

Various sources were used during the mechanical analysis, including the CS-25 (EASA) and Boeing's technical documentation. The appendices can be found at the end of this report; an overview is available on **page 35**.

## 1 Legislation

For the second report it is important to gain some understanding of the certification specifications (CS) which are made for the safety of the aircraft its landing gear and therefore the aircraft itself. This document is made by the European Aviation Safety Agency (EASA). The different laws and formulas are found in this document and are used for the landing gear (1.1). The calculations which will take place in this report are based on the laws. There are three chosen critical situations (1.2) for the Boeing 747-400 its landing gear which are going to be calculated later on.

### 1.1 Certifications specifications - 25

Since the forces on a landing gear during critical situations will be examined, the laws with regard to ground loads should be investigated. This is because ground loads are considered to be external forces applied to the aircraft structure. Ground loads apply when an aircraft is on the ground. The aircraft will be in the three chosen critical situations on the ground so those ground loads laws provide limits which a landing gear must be able to endure.

The assignment of AAE is to identify whether the Boeing 747-400 satisfies to the certification requirements. Therefore there is worked with the latest certification specifications. The ground loads laws are described by EASA in CS-25 amendment 13; book 1 subpart C –structure from CS 25.471 till CS 25. 519. In all the ground loads laws strength requirements are specified in terms of CS-25 limit loads and ultimate loads. Limit loads are the maximum loads to be expected in service. Ultimate loads are limit loads multiplied by prescribed factors of safety; 1,5. The prescribed loads are limit loads unless otherwise indicated.

The ground loads laws apply when the following conditions are met. Some conditions need to be specified by assumption:

1. Place of external loads
2. Critical centres of gravity
3. Landing condition
4. Lift

#### Ad 1. Place of external loads

The external loads must be balanced with the linear and angular inertia loads in each specified ground load condition.

#### Ad 2. Critical centres of gravity

For each requested certification the critical centres of gravity must be selected so that the maximum design loads are obtained in each landing gear element. This includes fore and aft, vertical and lateral centres of gravity.

If the lateral displacements of the centre of gravity of the aircraft centreline causes main gear loads not greater than 103% of the critical design load for symmetrical loading conditions<sup>1</sup>, the following statement apply: The lateral displacements of the centre of gravity may be selected without considering the effects on the loading on the main gear elements, or on the aircraft structure as long as the lateral displacement of the centre of gravity is maintained within the limits. The lateral displacements will then be due to random passenger or cargo disposition within the fuselage or due to unsymmetrical fuel loading or fuel usage. The appropriate loading instructions for random disposable loads are included in CS 25.2583.

#### Ad 3. Landing condition

For the landing conditions specified in CS 25.479 to 25.485, the aircraft is assumed to contact the ground in the attitudes defined in CS 25.479 and CS 25.481. Further is stated that the limit descent velocity at the design landing weight is 3.05 m/sec (10 fps) and at the design take-off weight is 1.83 m/sec (6 fps). The prescribed descent velocities may be modified if it is shown that the aircraft has design features that make it impossible to develop these velocities.

The design landing weight is the maximum weight for landing conditions at maximum descent velocity and the design take-off weight the maximum weight for landing conditions at a reduced descent velocity.

#### Ad 4. Lift

Assumed is that the lift of an aircraft does not exceed the aircraft's weight. Unless systems or procedures significantly affect the lift.

When analysing an aircraft and landing gear loads the following elements should be taken into account:

- Landing gear dynamic characteristics
- Spin-up and spring back
- Rigid body response
- Structural dynamic response of the airframe, if significant
- The landing gear dynamic characteristics must be validated by tests as defined in CS 5.723(a).
- The coefficient of friction between the tyres and the ground may be investigated. However, this coefficient of friction need not be more than 0,8.

## 1.2 Critical situations

For the critical situations, three different situations are chosen. Looking at the most critical ones, touchdown and rejected take off are seen as one of the situations where the forces are going towards critical. The touchdown is going to be calculated twice, once with crosswind and once without. For the rejected take off the situation takes place in the nose gear and for the touchdown this is mostly the main gear. The laws for these situations are to be found above and in the appendixes (**I** and **II**). Also the static situation is going to be calculated first. The static situation takes place in rest at the platform (no horizontal movement of the aircraft on ground).

## 2 Calculation preparations

To make the calculations for the critical situations, first some preparing calculations must be made. The preparing calculations are made conform the CS-25 legalisation explained in chapter 1 Legislation. In the Weight and Balance manual (**2.1**) of the Boeing 747-400 the calculations are being made to calculate the centre of gravity. The dimensions (**2.2**) of the Boeing 747-400 are required to calculate the arm and the torque. The described critical situations and the static situation, which is used as a reference situation, are the mechanical situations (**2.3**). Also the formulas (**2.4**) for the calculations in the next chapter are described.



## 2.1 Weight and balance manual

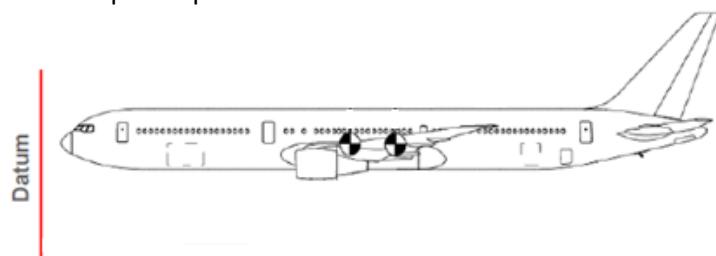
To calculate forces and torques on an aircraft there must be a point of reference from which the center of gravity (CG) can be calculated (**2.1.1**). Each aircraft its CG has limits between which it should be located(**2.1.2**). If the limits are known it is possible to determine where the centre of gravity is located (**2.1.3**). Furthermore there must be a system to indicate whether the aircraft is in balance or not (**2.1.4**).

### 2.1.1 Centre of Gravity from datum

The datum is a reference point that allows accurate, and uniform, measurements to any point on the aircraft (**Figure 1**). The location of the reference datum of a Boeing 747-400 is determined by Boeing on 83.5 feet (25.4508 meters) on the centreline chord from the leading edge. The centreline chord from the leading edge is called the LEMAC.

The Centre of Gravity (CG) is a fictitious point for the calculation of forces and torques which work on the aircraft. The distance of the CG is calculated from the datum. The position of the CG will vary during the flight. This occurs amongst others when the landing gear of the aircraft folds and when the fuel of the aircraft moves.

The direction which way the CG is moving is called the arm of the CG. If the CG is moved too far forward the nose of the aircraft will pitch downwards and if the CG is moved too far backwards the nose will pitch upwards.



*Figure 1: Reference point*

### 2.1.2 Main Aerodynamic Chord

The Mean Aerodynamic Chord (MAC) is the average chord length of a tapered wing. The length of the MAC is the length between the leading and the trailing edge of the wing at the point where two lines cross each other. This is illustrated in (**Figure 2**). The length of the Root Chord will be added on each side of the Tip Chord. The length of the Tip Chord will be added on each side of the Root Chord. Due to these lengths the position of the MAC can be found. The length of the MAC is also possible to calculate with an equation (**equation 1**), if the Root Chord and Tip Chord are known.

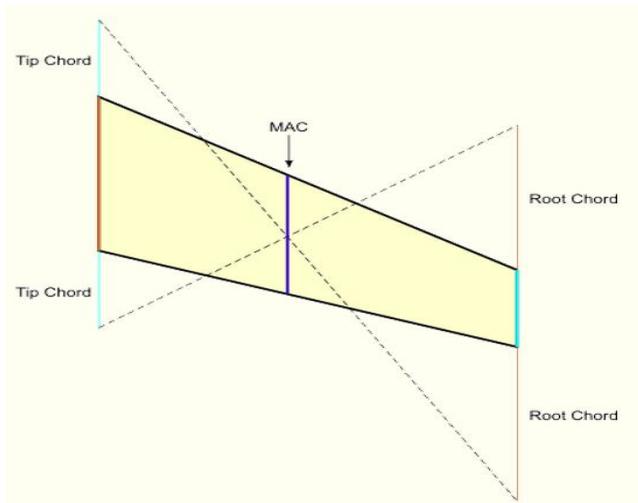


Figure 2: Position MAC

$$MAC = \frac{2}{3} RC \cdot \frac{1 + t + t^2}{1 + t}$$

$RC$  = Root Chord in meters

$t$  = Taper ratio in meters

Taper ratio =  $\frac{\text{Tip Chord}}{\text{Root Chord}}$

Equation 1: Calculation length of MAC

### 2.1.3 Centre of Gravity in % from MAC

The position of the CG can be calculated in percentage of the MAC with a formula. This percentage must be within the allowable range for the aircraft; the CG range (**Figure 3**). During flight the CG of the 747-400 must be between the forward limit 13% and after limit 33% of the MAC. This is adjusted by Boeing.

The CG has several limits which are relative to the MAC. The limits of the CG are divided in MAC Zero Fuel Weight (MACZFW), MAC Landing Weight (MACLW) and the MAC Take-Off Weight (MACTOW). MACZFW is the MAC when there is calculated without the weight of the fuel. MACLW is the calculated MAC with the weight during landing. MACTOW is the calculated MAC with the weight during take-off. The Balance Chart presents the limits and shows in which case it is allowable to take-off or to land (**Appendix III Balance chart**).

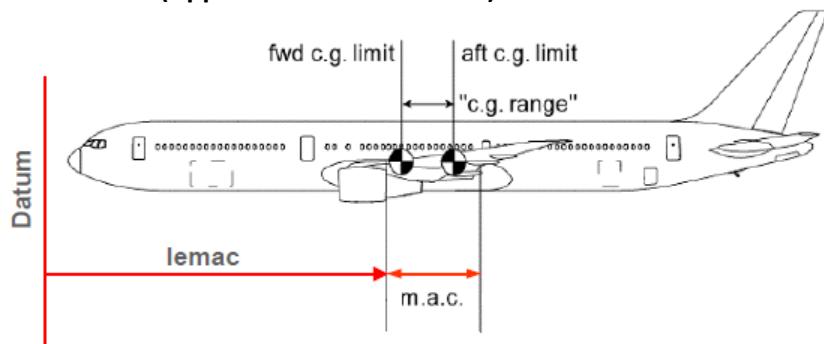


Figure 3: CG Range

When the weight of the aircraft is known the position of CG as percentage of the MAC can be found in the Balance Chart. With this given and when the MAC is calculated it is possible to calculate the distance aft of LEMAC (**Equation 2**). The distance aft of LEMAC is the distance from the leading edge



to the CG. As is described in **(2.1.1)** is LEMAC 25.5 meters long. So to determine the position of the CG the distance aft of LEMAC must be summed up by LEMAC.

$$CG \text{ in \% MAC} = \frac{Distance \text{ aft of LEMAC}}{MAC} \times 100\%$$

$$Distance \text{ aft of LEMAC} = \frac{CG \text{ in \% MAC}}{100} \times MAC$$

*CG in % MAC* = Position CG in % of the MAC (can be found in the Balance Chart)

*MAC* = Mean Aerodynamic Chord in meters

*Equation 2: CG in % of MAC*

#### 2.1.4 Balance system

Loading and offloading should always be controlled to ensure that the CG remains forward of the main gears. The Boeing 747 consist of an On Board Weight and Balance System which monitors the actual percentage of the MAC on the remote indicator panel. This system provides an alarm of sound and lights when the CG is approaching 40% MAC. This applies only during loading and offloading, during flight the limit is 33% again. This means that the sequence of loading and offloading should be such that during the entire operation the MAC will never exceed 40 %.

When 40% is exceeded the aircraft is going to tail tip and the main drive and local drive operation aft of the cargo door and the cargo door area will be disabled. On the master cargo control panel the drive system consist of a reset-switch button and whenever this button is used then the drive system is re-armed. But the Loading/offloading sequence must be changed until the cause of the tipping alarm has been corrected.

## 2.2 Dimensions

The dimensions of the landing gear are necessary to make a proper calculation of the forces which are acting on the landing gear. Those dimensions can be divided into the dimensions of the aircraft **(2.2.1)**, the dimensions of the nose gear **(2.2.2)** and the dimensions of the main gear **(2.2.3)**.

#### 2.2.1 Dimensions of the Boeing 747-400

The dimension of the aircraft are given in Figure 4: Aircraft dimensions just as the location of the reference datum of a Boeing 747-400 is determined by Boeing on 25.4508 meters on the centreline chord from the leading edge. The dimension between the datum and nose gear is 13,28 meters. Between the datum and the main gear is 38,88 meters.

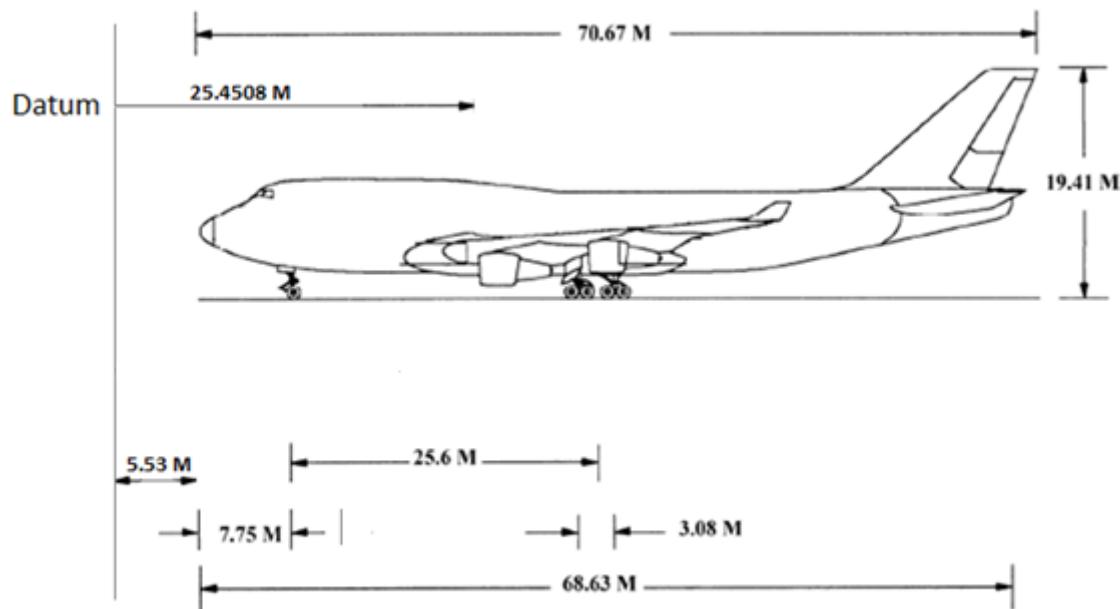


Figure 4: Aircraft dimensions

Landing gear height (HLG) is defined as the distance between the ground and the conjunction between main gear strut and the aircraft structure. The main gear is attached to the nacelle. The nacelle is a housing, separate from the fuselage, that holds engines, fuel or equipment on an aircraft (**Figure 5**) and the wing (**Figure 6**). This connection is made through variety of ways including strut, solid spring, solid axle or oleo. Therefore the landing gear height could be shorter when the aircraft is on the ground due to the spring deflection or oleo compression because of the aircraft weight. In order to have a uniform definition the landing gear height is measured when the aircraft is on the ground and the fuselage is horizontal. The HLG of a Boeing 747-400 is 3,9347 meters.

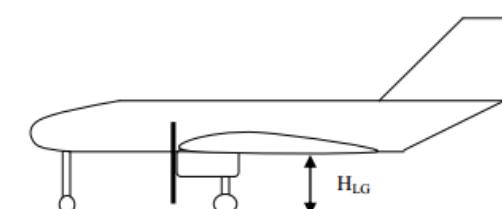


Figure 5: Main gear is attached to the nacelle

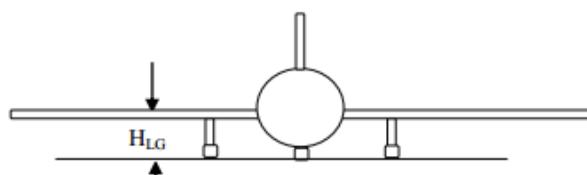


Figure 6: Main gear attached to the wing

## 2.2.2 Dimensions of the nose gear

The dimensions of the nose gear construction are shown in Figure 7. These dimensions are not given in manual so they are based on the tire size, which can be found in the maintenance manual. The tire size of the nose and main gear tires are (49 inch) which amounts 124,26 centimeters. The dimensions of the other components can be determined by inferring a scale from the figure.

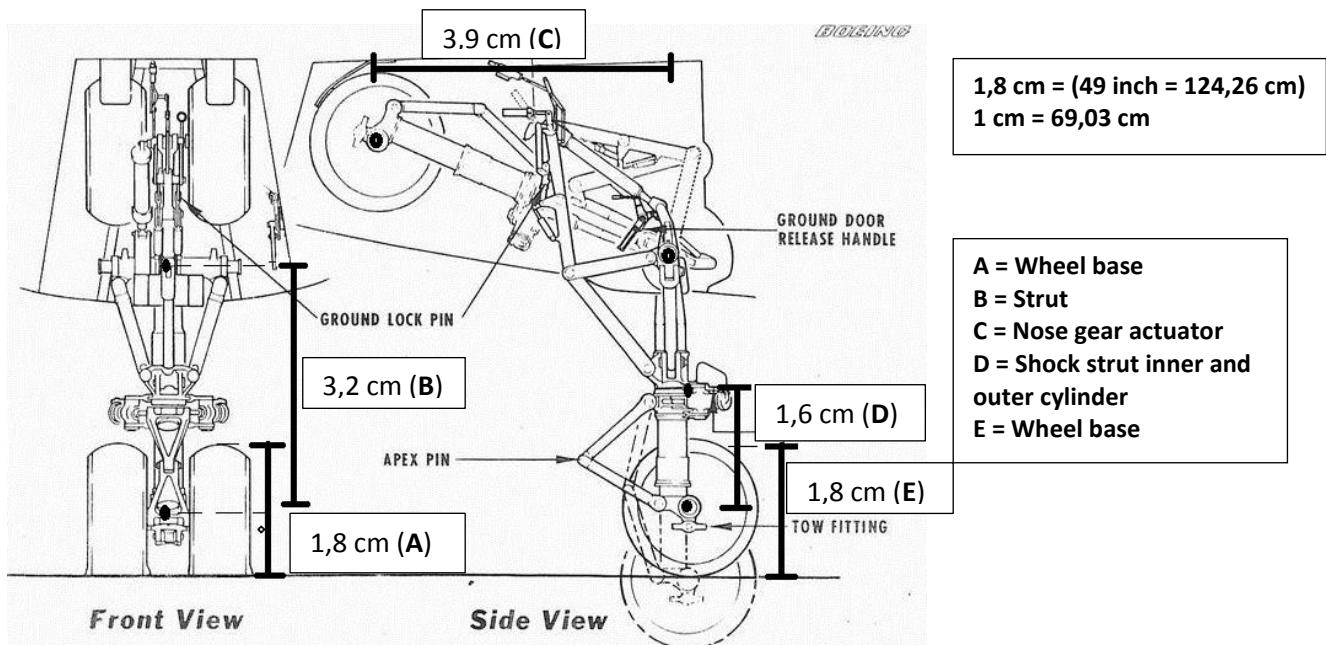


Figure 7: Front and side view nose gear

### 2.2.3 Dimensions of the main gear

The dimensions of the main gear construction are shown in Figure 8. These dimensions are not given in manual so they are based on the tire size, which can be found in the maintenance manual. The tire size of the main gear tires are (49 inch) which amounts 124,26 centimeters. The dimensions of the other components can be determined by inferring a scale from the figure.

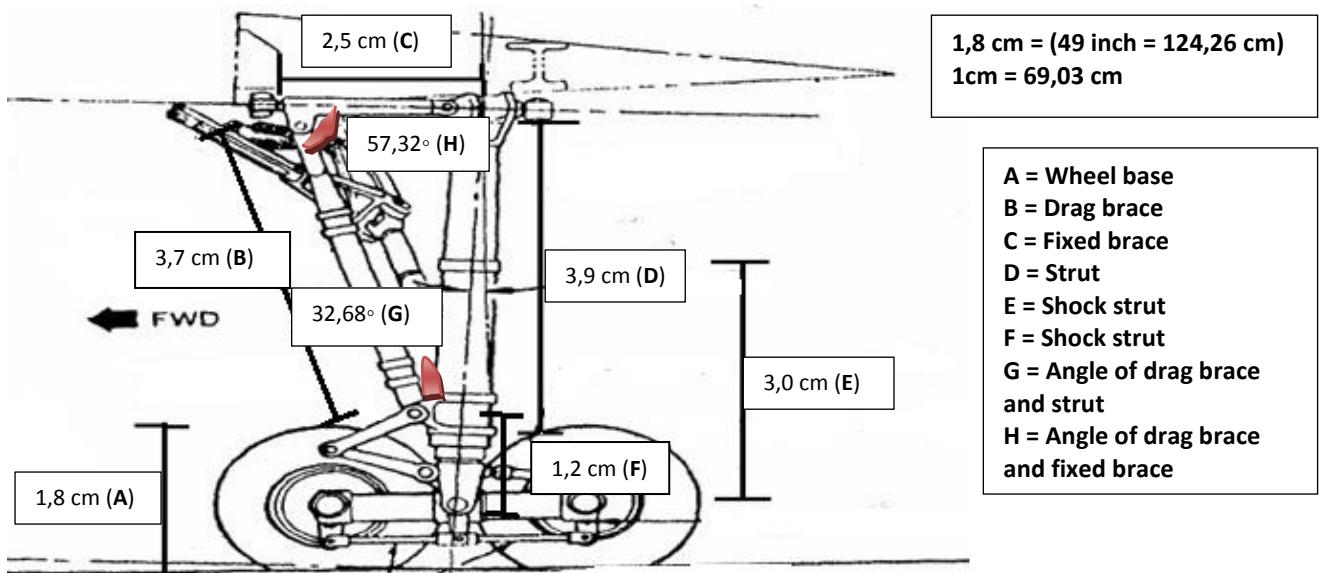


Figure 8: Side view main gear

This angle of the strut with the side brace, is based on the length of the strut and is assumed to be 47,05 degrees. The dimensions of the other components can be determined by inferring a scale from the figure (Figure 9).

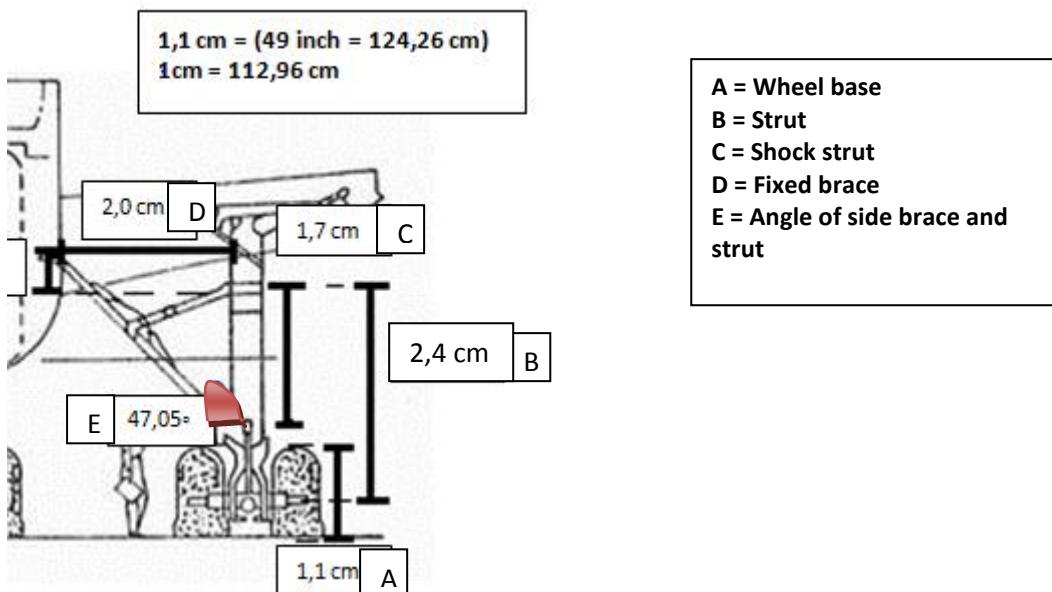


Figure 9: Front view main gear

## 2.3 Mechanical situations

The mechanical situations are divided into four different situations. The first situation is the static situation (**2.3.1**). When an aircraft is in a static situation the aircraft is in rest on the ground and is not moving. Then there will be discussed three kinds of dynamic situations. A dynamic situation is a force relating to motion. The three dynamic situations explained are the situations where the limit loads are expected to be exceeded whereby the situations are critical situations. The first critical situation which is described is the rejected take-off (**2.3.2**). The second and third critical situations that will be explained are the touchdown without and with crosswind (**2.3.3**). In the last situation the landing gear will not land straight on the runway but in a crossed position.

### 2.3.1 Static situation

The static situation of a Boeing 747-400 is shown in Figure 10. At this moment there is no thrust or drag that could influence the aircraft's motional behavior because the aircraft is stationary. Nevertheless there are still three forces present in the construction that must be noticed. The mass of the aircraft provides a downwards force due to gravity (**1**). The downward force is balanced out by the forces that act in the construction of the landing gear (**2**). These components are in contact with the ground's surface which develops normal forces (**3**) upwards to ensure that the aircraft does not sag into the ground. The combination of these three forces allows the aircraft to maintain a steady position.

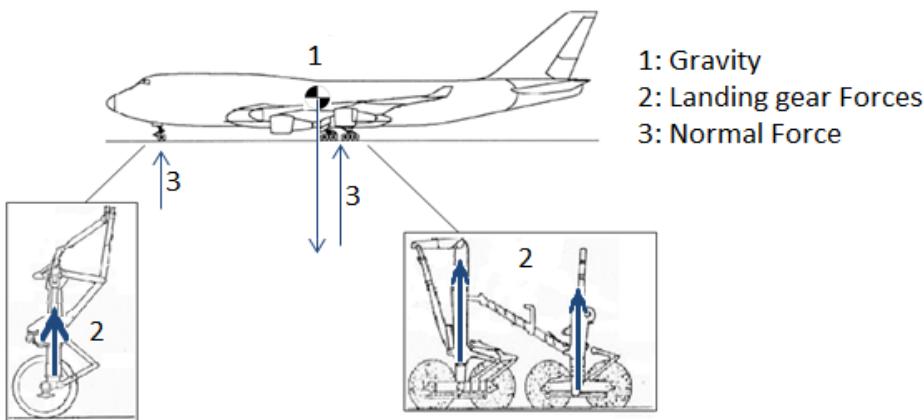


Figure 10: Forces static situation

### 2.3.2 Critical situation rejected take-off at $v_1$

A rejected take-off is the first critical situation which will be discussed. First the definition of a rejected take-off is given to make clear what this situation contains (2.3.2.a). Subsequently the situation which will be investigated is outlined (2.3.2.b).

#### 2.3.2.a Definition of rejected take-off

A rejected take-off (RTO) is a situation in which it is decided that the take-off should be aborted. This kind of occasion will occur when there is a malfunction on the aircraft, such as an engine failure. To safely reject the take-off the decision to reject the take-off must be made before the decision speed ( $V_1$ ). The decision speed varies on the flap configuration and on the weight of the aircraft. Above  $V_1$  the takeoff must be continued unless there is a reason to believe that the aircraft is not capable of flying.

If the decision is made to reject the take-off the aircraft must be brought to a stop within the Accelerate Stop Distance Available (ASDA). If the decision is made to continue the take-off the aircraft must get airborne and achieve or exceed the appropriate screen height within the Take-Off Distance Available (TODA) even with one engine out. If a rejected take-off is initiated at a speed above  $V_1$  a runway excursion is probable.

Experience has shown that tire blow outs and engine malfunctions often cause indecision and rejected take-offs on high speed. According to Boeing, a Boeing 747-400 experiences a RTO situation approximately once in 20 years.

#### 2.3.2.b The RTO situation

According to EASA a rejected take-off on a dry runway must be able to accomplish without reverse thrust. To obtain the most critical RTO situation a rejected take-off precisely at  $V_1$  without reverse thrust with the aircraft at its maximum take-off weight will be investigated.

In Figure 11 is schematically shown which forces influence the aircraft during a RTO. When the aircraft is at  $V_1$  the pilot will set the throttles to idle and the RTO modus of the autobrake will be activated. The autobrake ensures maximum brake pressure for a maximum deceleration (1). To provide extra braking force the pilot will also use the aircraft's spoilers. These decelerate the aircraft also a little because of the friction due to the frontal surface of the spoilers. Also the spoilers ensure the reduction and disposal of lift. Due to the spoilers the aircraft is firmly pressed on the runway making the tires pressed on the runway which provide extra friction (in technical analysis part A more information about this subject is given).

Further gravity will act from the centre of gravity to the ground (2). Due to the gravity a normal force is created by the runway surface acting from the wheels of the nose gear (3) and main gear (4) in upwards direction. Also a drag force is created due to the friction of the aircraft with air particles but



this is negligible because the drag force is equal to the thrust force. Therefore, these two forces are not included in the free-body diagram and in the calculations.

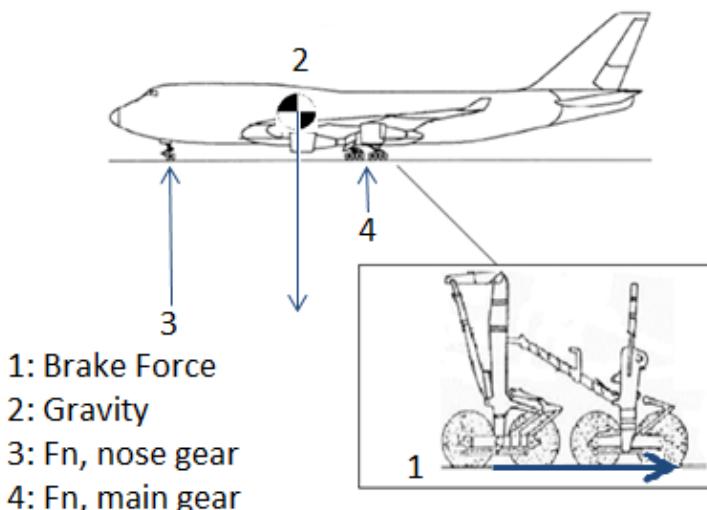


Figure 11: Forces acting on the aircraft during rejected take-off

### 2.3.3 Critical situation touchdown

The second critical situation that is described is the touchdown with the spoilers used exactly when the aircraft touches the ground. Two types of touchdown are considered, without crosswind (**2.3.3.a**) and with crosswind (**2.3.3.b**). A touchdown implies that the aircraft arrive on the runway with a glide slope of three degrees. Due to the spoilers are used exactly at the same time as the aircraft touches the ground there is immediately a normal force that is the same as the weight of the aircraft because the lift disappears and the aircraft will stay firmly on the ground.

#### 2.3.3.a Touchdown without crosswind

In the following situation the touchdown will be investigated without crosswind. Braking operates after the touchdown so the braking force will not be considered in this situation. Assumed is by the hand of CS 25.479 that during a touchdown the main gear absorbs the landing impact while the nose gear is gently lowered towards the ground. Therefore only the forces on the main gear are taken into account. As a reference the Maximum Landing Weight (MLW) is used since this results in the highest forces on the main gear within the limitations.

For a better understanding two schematic figures are used to show the forces that occur during touchdown. First of all when the aircraft approaches there are only two forces which act on the aircraft. Due to gravity, the weight of the aircraft creates a downward force. According of CS-25 is that the load factor is equal to one. Therefore the second force which acts on the aircraft, the lift, is equal to the gravitation force. Before the touchdown the aircraft has only kinetic energy received from the mass and the constant deceleration of the aircraft.

Exactly when the aircraft touches the ground the spoilers are used to dispose the lift. The spoilers are activated by the ground/logic system when the main gear touches the ground. Due to no lift and through contact with the runway surface a normal force will occur. The normal force (**1**) compensates the gravitational force (**2**) and these two forces are equal to each other (**Figure 12**). The tyres will also generate a rearward force upon contact due to friction. This force is neglect because this force is relatively small.

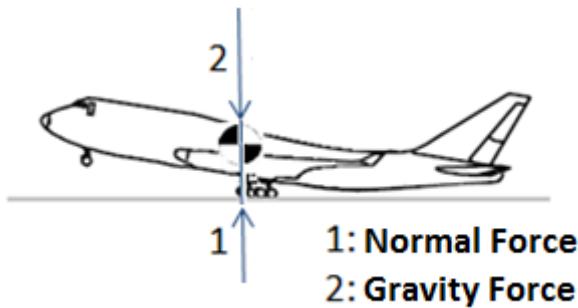


Figure 12: Forces acting on the aircraft during touchdown

### 2.3.3.b Touchdown with crosswind

In the following situation will the same situation be investigated as in (2.3.3.a) only in this situation a crosswind is present. The crosswind situation is shown in Figure 13 . At the side of the incoming wind there is an upwind and on the other side of the aircraft there is a downwind. These terms are based on the effect that the wind has on the aircraft as it tries to roll clockwise.

For a better understanding a schematic figure (Figure 14) is used to show the forces that occur during touchdown. During the touchdown there is often a wind component perpendicular to the runway. This means the aircraft moves slightly sideways during the approach. In some situations, when the pilot fails to execute the touchdown maneuver properly, the aircraft may still move sideways during contact. This will apply a lateral force on the landing gear in addition to the other forces due to the sideways friction of the wheels (1). Further there is a gravity force pointing downwards (2). Due to the spoilers there is no lift anymore but a normal force is created on the main gear (3). Also a friction force in longitudinal axis will occur according to CS-25 (4).

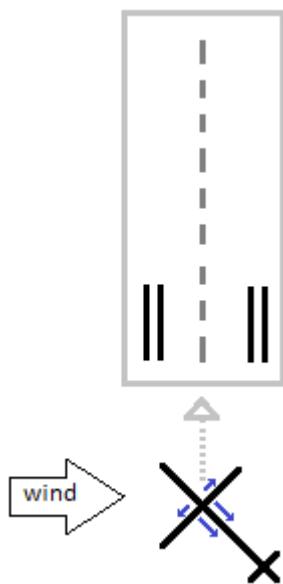


Figure 13: Crosswind situation

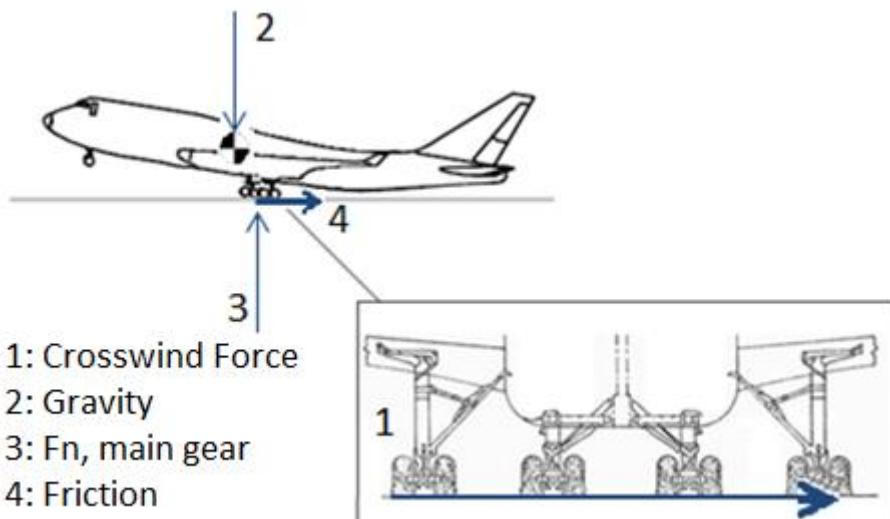


Figure 14: Forces acting on the aircraft during touchdown with crosswind

## 2.4 Formulas

To investigate certain loads at the landing gear in different situations calculations must be made. These calculations can not be made without formulas. The first formula is the gravity constant (**2.4.1**). An aircraft has always a kinetic energy when the aircraft has a speed (**2.4.2**). The landing gear has to absorb this energy mostly during the landing. Most of this absorption is done by the strut (**2.4.3**). Another force which can act on the landing gear is the brake force (**2.4.4**). At last Newtons first law is explained (**2.4.5**).

### 2.4.1 Gravitational force

One of the forces that apply to the aircraft is the gravitational force. This force is created by the aircraft's weight. In a static condition the strut will be compressed by the mass of the aircraft. Also in dynamic condition this force is always pulling on the aircraft. The equation given of the gravitational force is a derivation of Newtons law of gravitation (**Equation 3**).

#### Gravitational force

$$\text{Weight} = F_g = m \cdot g$$

Weight =  $F_g$  = Force of gravity in Newton

$m$  = mass in kg

$g$  = gravitational constant in Newton

*Equation 3: Gravitational force*

### 2.4.2 Kinetic energy

When an aircraft starts to move it has an amount of kinetic energy. The landing gear have to absorb this energy. Eventually this energy have to be converted in thermal energy and other kinds of energy to stop the plane. This will be done by roll friction and braking. The shock absorber also have to absorb the kinetic and potential energy during touchdown and RTO. The equation of kinetic energy is as follows (**Equation 4**).

#### Kinetic energy

$$E_k = \frac{1}{2} \cdot m \cdot v^2$$



$E_k$  = kinetic energy in Joule

$m$  = Mass of the plane in kilograms. (this can be the Maximum Taxi weight, Maximum Landing weight)

$v$  = Speed in meters a second.

*Equation 4: Kinetic energy*

#### 2.4.3 Energy absorption

It is assumed that the energy that is absorbed by the landing gear is equal to the energy of the aircraft during the landing. The absorption is done by the spring of all the struts. The spring stores the kinetic energy at touchdown. The force in the strut can easily be calculated with the spring its stiffness and the stroke (**Equation 5**).

#### Spring energy

$$E_{\text{spring}} = \frac{1}{2} c * \Delta h^2 \quad F = c * \Delta h$$

$E_{\text{spring}}$  = the energy stored in the spring in Joules

$\Delta h$  = Stroke of the strut in meters

$c$  = The spring its stiffness

F= force on the strut

*Equation 5: Spring energy*

#### 2.4.4 Brake forces

The landing gear compete also with horizontal forces. These forces occur due to braking. Due to braking, all the kinetic energy of the aircraft during touchdown or when the aircraft accelerates for a take-off will be converted into thermal energy. The brakes slow down the wheels. Since the wheels have contact with the runway surface friction occurs. This friction converts the kinetic energy into thermal energy. The amount of frictions depends on the type of material and thus on the friction coefficient of the material of the wheel. The equation of the braking force is as follows (**Equation 6**).

#### Brake force

$$\text{Brake force} = F_n * \mu$$

With:

$F_n$

= perpendiculair forces in Newton

$\mu$  = friction coefficient

*Equation 6: Brake force*

#### 2.4.5 The sum of forces

To eventually calculate the forces in the different parts of the landing gear it must be clear which extern loads are forcing in which direction of the construction. According to Newtons first law an object which is at rest or moves in a straight line with a constant velocity has no resultants force. In such situations the following equations apply (**Equation 7**).

$\sum F_x = 0$  The sum of all forces in x-direction

$\sum F_y = 0$  The sum of all forces in y-direction

$\sum F_z = 0$  The sum of all forces in z-direction



$\sum M = 0$  The sum of the torque  
where torque is  $M = F * r$

$F$  = force vector in Newton

$r$  = Displacements vector in meters

$M$  = torque vector in Nm

Equation 7: Newtons first law

### 3 Calculations

The forces working on the landing gear and the centre of gravity should be calculated to find the critical components in the landing gear that cause the critical situations. First off all the forces that work during a static situation will be calculated (3.1). Afterwards the forces acting on the aircraft during the rejected take-off are calculated (3.2). Then there will be looked at the forces acting on the aircraft during a touchdown (3.3). Followed by the calculations of the forces which occur during a touchdown with crosswind (3.4). At last when all the calculations are made the static situation will be compared to the dynamic situations. This will end in a conclusion that explains the difference in forces between the static- and dynamic critical situations (3.5).

#### 3.1 Static situation

The forces which act on the aircraft during the static situation will be calculated by using the maximum take-off weight (MTOW). The MTOW is the maximum weight where the aircraft is still allowed to take-off. The MTOW is taken because it is the maximum number at which the static calculations can be made to determine the centre of gravity. By the hand of the balance chart (**Appendix III**) is assumed that the maximum take-off weight is 390.000kg.

With the CG it is possible to calculate the forces that work on the landing gear. To perform these calculations it is assumed that the forces that act on the main gear work in the centre between the body gear and the wing gear. In Scheme 1 the values that have been used and the calculations of the forces, according to Figure 15, are shown.



*Centre of gravity from the nose=*

$$\begin{aligned} & \text{Reference datum + Distance aft of LEMAC} \\ & - \text{Distance between datum and the nose of the aircraft} \\ & = 25,4508 + \left( \frac{25}{100} * 11,57 \right) - 5,54 = 22,8 \text{ m} \end{aligned}$$

$$\text{Gravity} = 390.000 * 9,81 = 3.825.900 \text{ N}$$

$$\sum^+ M, \text{nose gear} = -(3.825.900 * 15,05) + (25,6 * F_{n, \text{main gear}}) = 0 \\ F_{n, \text{main gear}} = 2.249.252 \text{ N}$$

$$\sum^+ M, \text{main gear} = +(3.825.900 * 10,55) - (F_{n, \text{nose gear}} * 25,6) = 0 \\ F_{n, \text{nose gear}} = 1.576.648 \text{ N}$$

Scheme 1: Calculations static situation

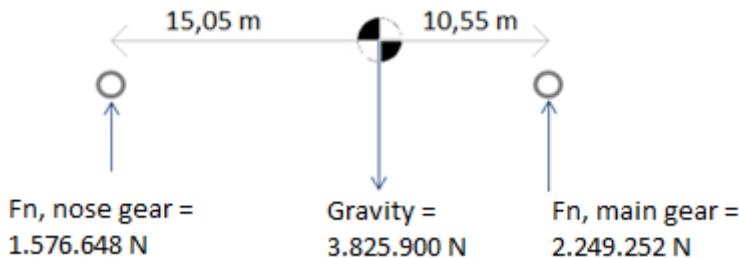


Figure 15: Measurements static situation

Now that the forces that work in the landing gear have been calculated it is possible to calculate the forces that work in the construction of the landing gear. During this situation it is assumed that the shock strut of the main gear is in a perpendicular position from the ground so there are barely external forces that work in the direction of the side brace and the drag brace. Therefore these braces are considered as braces with zero-force and the forces in their attachments are also assumed to be zero. The calculations will be made in one of the four shock struts of the main gear (Figure 16). These calculations are shown in Scheme 2.

$$F_{\text{normal, one main gear}} = \frac{2.249.252}{4} = 562.313 \text{ N}$$

$$\sum^{\uparrow\downarrow} F_z = 0: F_{\text{normal, one gear}} - F_{\text{shock strut}} = 562.313 - F_{\text{shock strut}} = 0 \\ F_{\text{shock strut}} = 562.313 \text{ N in the opposite direction}$$

Scheme 2: Calculations shock strut static situation

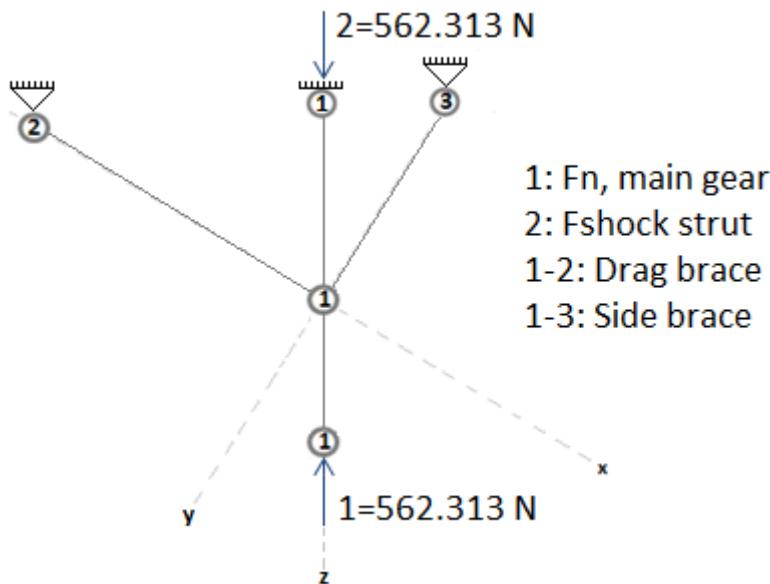


Figure 16: Construction forces

### 3.2 Calculation Rejected take-off

The first critical situation which will be calculated is the rejected take-off. This situation will be viewed in the following manner. First the equations will be formulated (3.2.1). Then some assumptions will be stated (3.2.2). The following step is to calculate the centre of gravity (3.2.3). Next the force on the nose gear can be calculated and compared with the certification requirement (3.2.4). At last the forces in the critical parts of the landing gear will be calculated (3.2.5).

#### 3.2.1 Equations

In (2.3.2) is defined what a rejected take-off is and what happens when the maneuver is performed. Also is given in a schematic figure (Figure 11) which forces act on the aircraft during a rejected take-off. Described is that the rolling drag and the drag because of the friction of the aircraft with the air is neglected.

During a rejected take-off an aircraft decelerates constant. Therefore Newtons first law applies for this situation. The following equations can be made:

In the direction vertical axis acts gravity and since the aircraft is on the ground also a normal force acts in the direction of the vertical axis. This normal force acts on the aircraft where it touches the ground. Therefore the normal force is split into a normal force acting on the nose gear and (as described in 3.1 Static situation ) one normal force acting on the main gear. There is no motion in the vertical direction (Equation 8).

$$\sum_{\text{up}} F_x = F_{\text{normal, main}} + F_{\text{normal, nose}} - F_{\text{gravity}} = 0$$

Where:

$F_{\text{normal, main}}$  = the force acting from the runway on the main gear in Newton

$F_{\text{normal, nose}}$  = the force acting from the runway on the nose gear in Newton

$F_{\text{gravity}}$  = the force acting from the centre of gravity due to the mass of the aircraft in Newton

*Equation 8: Vertical forces rejected take-off*

The equation of gravity is described in (Equation 3).



Since the brake force is the only force on the aircraft which acts in a horizontal position the brake force is the only force which affects the speed of the aircraft (**Equation 9**).

$$\sum F_x = -F_{brake} = m * a_x$$

Where:

$F_{brake}$  = the force created by friction in Newton

$m$  = mass in kilograms

$a_x$  = acceleration in horizontal direction in meters per second

*Equation 9: Horizontal forces rejected take-off*

The brake force is described in (**Equation 3**).

### 3.2.2 Assumptions rejected take-off

To be able to make use of the equations described in 3.2.1 Equations some assumptions need to be made. These assumptions are related to:

1. The mass
2. The acceleration of gravity
3. The deceleration of the aircraft
4. The friction coefficient
5. The centre of gravity
6. The maximum brake energy

#### Ad 1. The mass

Assumed is that the mass of the aircraft during the rejected take-off is equal to the maximum take-off weight to ensure a more critical situation during the rejected take-off.

#### Ad 2. The acceleration of gravity

Assumed is that the runway is at sea level. Therefore the acceleration of gravity is equal to the acceleration of gravity at sea level.

#### Ad 3. The deceleration of the aircraft

In CS 25.735 Brakes and braking systems (**Appendix II Rejected take off**) is described that during an acceleration-stop the deceleration may not be less than  $1,8 \text{ m/s}^2$ . This is the value for which an aircraft will be certified during an acceleration-stop. Therefore the deceleration of the aircraft during the rejected take-off will be  $1,8 \text{ m/s}^2$ .

#### Ad 4. The friction coefficient

In CS 25.471 General (ground loads) is described that the friction coefficient need not be more than 0,8. In practice, it is unlikely that the Boeing 747 has a friction coefficient of 0,8 but a more critical situation will be created when the friction coefficient is on his highest. Therefore the aircraft brakes will have a friction coefficient of 0,8 during a rejected take-off.

#### Ad 5. The centre of gravity

There must be calculated with the most adverse centre of gravity position to ensure a more critical situation during the rejected take-off.

Furthermore is assumed that the centre of gravity position is equal to the height of the cabin floor.

#### Ad 6. The maximum brake energy

When an aircraft reaches its maximum brake energy the brakes will start burning with a possibility of welding the brakes. When the maximum brake energy is reached the aircraft will be able to brake



more than usual because with a higher temperature the brakes are able to absorb more energy (as described in technical analysis part a). This situation is only relevant when a rejected take-off occurs with a maximum take-off weight during a high pressure altitude in combination with a high outside air temperature, tailwind and 2% downslope. Assumed is that the rejected take-off is made during the standard atmosphere conditions and on a zero slope runway. Then the aircraft will not reach its maximum brake energy.

### 3.2.3 Calculating the centre of gravity

As described in (3.2.2) Assumptions rejected take-off, the most adverse centre of gravity position is taken as CG position. This is the most forwarded position during a rejected take-off because then the torque on the centre of gravity is at its greatest. Therefore the greatest force can be created on the nose gear.

As described in 2.1 the position of the centre of gravity can be calculated using a balance chart. This balance chart can be found in **appendix III**. The value of the CG in % of MAC associated with the MTOW is 15% (appendix IV). The value of MAC for the Boeing 747 is also given in (**Appendix V Calculation MAC Boeing 747-400**) and is 11,57293243 meters. The distance aft of LEMAC is then 1,35939864 (**Equation 10**).

$$\text{Distance aft of LEMAC} = \frac{15}{100} \times 11,57293243 = 1,735939864$$

*Equation 10: Calculating the distance aft of LEMAC*

Next to know the position of the CG the distance aft of LEMAC is added to the LEMAC. The LEMAC is 25.4508 meters (as described in (2.1)). Thus the position of the centre of gravity is 27,18672986 meters.

The distance between the nose gear and the reference point and the distance between the main gear and the reference point is given in (2.2.1) Due to that the distance between the CG and respectively the nose gear and the main gear can be calculated. The distance between the nose gear and the centre of gravity is 13,90682986 meters. The distance between the main gear and the centre of gravity is 11,6932704 meters.

### 3.2.4 Calculations of the forces and certification

Now the equations are established, the assumptions are made and the position of the centre of gravity is calculated the calculations of the forces acting on the aircraft can start. First the normal force acting on the nose gear of the aircraft during the rejected take-off will be calculated 3.2.4.a. Next the maximum certified force which may act on the nose gear will be calculated 3.2.4.b. When this force is higher than the force calculated in 3.2.4.a the Boeing 747 will be certified for a rejected take-off under the conditions as described in 3.2.2.

#### 3.2.4.a Calculation normal force on nose gear

Now the position of the centre of gravity is known the forces on the aircraft during the rejected take-off can be calculated. First the brake force will be calculated. As described in 3.2.2 Assumptions rejected take-off, the deceleration of the aircraft is  $1,8 \text{ m/s}^2$  and the mass of the aircraft is equal to the maximum take-off weight. The maximum take-off weight is assumed to be 390.000 kg. Then the equation of the brake force will be as follows (**Equation 11**).

$$F_{\text{brake, total}} = 390000 * 1,8 = 702.000 \text{ N}$$

*Equation 11: Calculation brake force rejected take-off*

Then the normal force in the main gear can be calculated. The friction coefficient is assumed to be 0,8. The equation of the normal force on the main gear will be as follows (**Equation 12**).

$$F_{normal, main\ gear\ total} = \frac{702.000}{0,8} = 877.500N$$

*Equation 12: Calculation normal force on main gear rejected take-off*

The gravitation force can be calculated and because of that the normal force on the nose gear can be calculated. Assumed is the acceleration of gravity is equal to the acceleration of gravity at sea level. The equation of the gravitation force will be as follows (**Equation 13**). The normal force on the nose gear can be calculated when taking the sum of the torques but this is not accurate because the distances of the forces to the CG, and therefore the arms, are assumed. A more accurate calculation will be the sum of the forces in z axis. The equation will be as follows (**Equation 14**).

$$F_{gravity} = 390.000 * 9,81 = 3.825.900N$$

*Equation 13: Calculation gravitation force rejected take-off*

$$F_{normal, nose} = 3.825.900 - 877.500 = 2.948.400N$$

*Equation 14: Calculation normal force on nose gear rejected take-off*

What stands out is the normal force on the nose gear. This force is that large because of a torque which arises when the brakes of the aircraft are applied during the rejected take-off. In order to counteract that torque the normal force on the nose gear increases till the sum of the torques is zero.

### 3.2.4.b Calculation maximum force on nose gear

In CS 25.493 Braked roll conditions is an equation given that can be used to calculate the maximum force which may act on the nose gear. The solution of this is equation (**Equation 15**) must be added to the normal force acting on the nose gear in the 1.0g static situation.

$$V_N = \frac{W_T}{A+B} \left\{ B + \frac{f\mu AE}{A+B+\mu E} \right\}$$

Where:

- $V_N$  = Nose gear vertical reaction
- $W_T$  = Design take-off weight
- $A$  = Horizontal distance between the c.g. of the aeroplane and the nose wheel.
- $B$  = Horizontal distance between the c.g. of the aeroplane and the line joining the centres of the main wheels.
- $E$  = Vertical height of the c.g. of the aeroplane above the ground in the 1·0 g static condition.
- $\mu$  = Coefficient of friction of 0·8.
- $f$  = Dynamic response factor; 2·0 is to be used unless a lower factor is substantiated.

*Equation 15: nose gear vertical reaction*

As described in 3.2.3 Calculating the centre of gravity, the horizontal distance between the centre of gravity of the aircraft and the nose wheel;  $A = 13,90682986$  meters.

The horizontal distance between the centre of gravity of the aircraft and the line joining the centres of the main wheels;  $B = 11,69327014$  meters.

Assumed is that the vertical height of the centre of gravity of the aircraft above the ground; E = 5,18 meters (**Appendix VI Vertical Clearances Boeing 747-400**). The equation of the maximum force which may act on the nose gear will be as follows (**Equation 16**).

$$Vn = \frac{390000}{13,90682986+11,69327014} * (11,69327014 + \frac{2*0,8*13,90682986*E}{13,90682986+11,69327014+0,8*E}) = 237.172,6654\text{N}$$

*Equation 16: Calculation maximum nose gear force*

The maximum force which may act on the nose gear will then be  $237.172,6654 + 1.576.648 = 1.813.820,665$  Newton.

The nose gear force calculated in (**3.2.4.a**) Calculation normal force on nose gear, is much higher than the force calculated in (**3.2.4.b**) Calculation maximum force on nose gear. This is due to the low deceleration. The deceleration of  $1,8 \text{ m/s}^2$  given by CS-25 is a minimum. In reality the Boeing will have a higher deceleration which results in higher force acting on the main gear. Therefore the normal force on the nose gear will be lower. The remaining difference in normal force is created due to the neglecting of the drag.

Due to much unknown elements and because of the neglecting of necessary elements no statement can be made of the certification of Boeing 747-400 for the rejected take off.

### 3.2.5 Critical parts during a rejected take-off

There are some parts in the landing gear during the rejected take-off which will be the first parts to fail. These parts are called critical parts. Assumed is, just as in the static situation, that the shock strut has a perpendicular position of the runway surface. In the upcoming calculations is calculated with the normal force of (**3.2.4.a**) Calculation normal force on nose gear. This is chosen because this normal force of the nose gear is higher than the normal force calculated in (**3.2.4.b**) Calculation maximum force on nose gear, which results into a more critical situation.

Assumed that during a rejected take the critical part in the nose gear will be the strut. This is assumed because as calculated in (**3.2.4.a**) Calculation normal force on nose gear, the normal force of the nose gear is high. This force will be absorbed by the strut. Therefore the force in the strut during the rejected take-off is equal to the normal force on the nose gear which is 2.948.400 Newton.

Assumed is that the critical part in the main gear during the rejected take-off is the drag brace because this part has to absorb a part of the normal force and a part of the brake force. The normal force of the main gear is not as large as in a static situation but the brake force is very high. To know the force which acts on the drag brace a calculation has to be made.

First there must be looked at which forces act on the main gear and how they do seize (**Figure 17**). There is no force that acts in the lateral axis so there will be assumed that there act no force on the side brace.

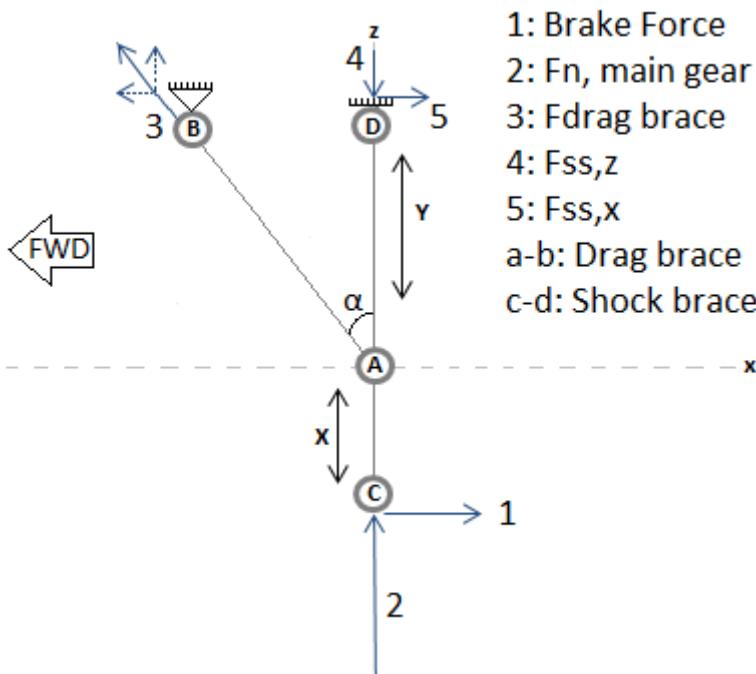


Figure 17: Forces acting on the main gear construction during rejected take-off

Next the torques will be calculated. The sum of the torques has to be zero because the construction of the landing gear is not going to turn. When using the torque of A the (**Equation 17**) can be obtained.

$$\sum_{+G} A = F_{brake} * x - F_{ss,x} * y = 0$$

Where:

$F_{brake}$  = the brake force in Newton

$X$  = the perpendicular distance between  $F_{brake}$  and C in centimeters

$F_{ss,x}$  = the Shock strut force in x direction in Newton

$Y$  = the perpendicular distance between  $F_{ss,x}$  and C in centimeters

Equation 17: Sum of torques of A during rejected take-off

Using (**Equation 17**) and the values of x en y from (**2.2.3**) the shock strut force in x direction can be calculated (**Equation 18**). At first the brake force has to be divided into four because there are four main gear bogies at which the brake force acts;  $\frac{702.000}{4} = 175.500 \text{ Newtons}$ .

$$F_{ss,x} = \frac{175.500 * 82,836}{269,217} = 54.000N$$

Equation 18: Calculating shock strut force in x direction rejected take-off

The force which acts on the drag brace can be divided into a force acting in the x direction and a force acting in the y direction;  $F_{db,x}$  and  $F_{db,y}$ . Then the equation of the forces acting in the x direction can be made (**Equation 19**).

$$\sum_{\leftarrow +} F_{db,x} - F_{brake} - F_{ss,x} = 0$$



Where:

$F_{db,x}$  = the drag brace force in x direction in Newton

*Equation 19: Forces acting in the x direction in the construction of the landing gear*

Using Equation 19 the drag brace force in x direction can be calculated (**Equation 20**).

$$F_{db,x} = 175.500 + 54.000 = 229.500\text{N}$$

*Equation 20: Calculating drag brace force in x direction during rejected take-off*

Since the angle between the drag brace and the shock strut is known the force acting on the drag brace can be calculated (**Equation 21**).

$$F_{db} = \frac{F_{db,x}}{\sin(\alpha)}$$

Where:

$F_{db}$  = the drag brace force in Newtons

$\alpha$  = angle between the drag brace and the shock strut in degrees

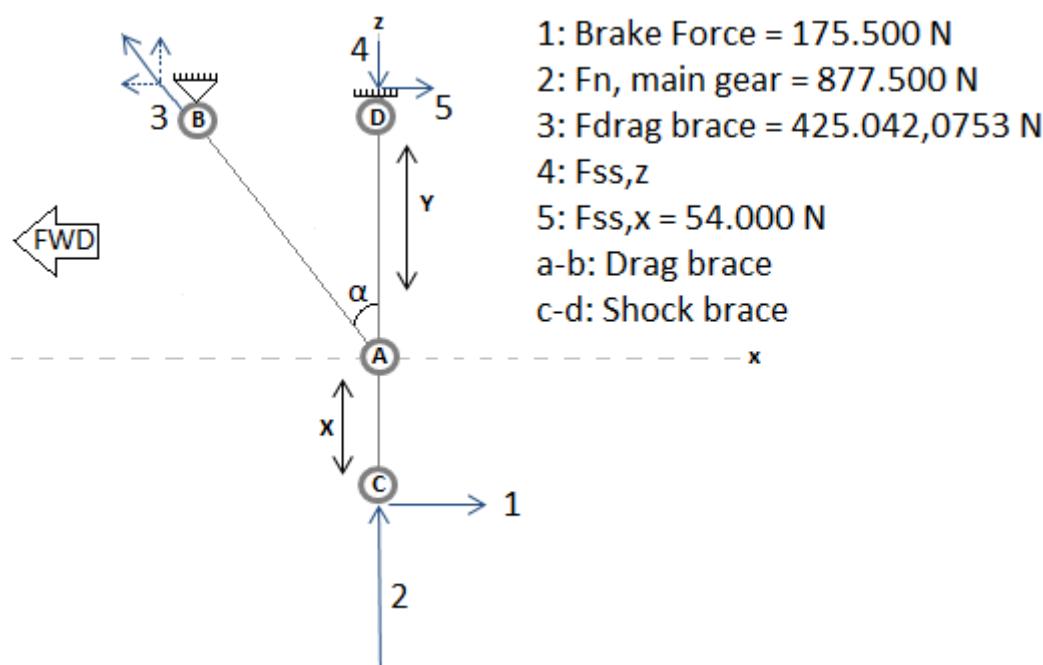
*Equation 21: Drag brace force*

Using (**Equation 21**) and the value of  $\alpha$  described in (**2.2.3**) the drag brace force can be calculated (**Equation 22**).

$$F_{db} = \frac{229.500}{\sin(32,68)} = 425.042,0753$$

*Equation 22: Calculating the drag brace force during rejected take-off*

A drag brace force of 425.042,0753 Newton is found. This is also the force which acts into the pivoting attachment of the drag brace (**Figure 18**).



*Figure 18: Forces acting on the main gear Construction during rejected take-off*

### 3.3 Touchdown situation

During a touchdown there is a force over the z-axis of the aircraft. When the Boeing 747-400 touches the runway, energy will be released. The Boeing 747-400 has a nose and main gear. The nose gear forces will be neglected but the main gear forces will be calculated. The forces that occur at touchdown can be divided in two situations. A static force touchdown (3.3.1) and a dynamic force touchdown (3.3.2). The dynamic force touchdown is the force that occurs at the moment where the aircraft meets the ground. In this situation the aircraft has a certain vertical speed and mass. So it has an amount of kinetic energy which the strut has to absorb at that moment. The static force touchdown is the force that acts on the aircraft when it is fully on ground and the kinetic energy is absorbed. Gravity is pulling on the mass (maximum landing weight) of the aircraft. At last the total force can be calculated by adding the static and dynamic situation together (3.3.3).

#### 3.3.1 Static force touchdown

The forces working during the static situation will be calculated by using the maximum landing weight (MLW). The MLW is the maximum weight where the aircraft is still allowed to take-off. Only the mass pulled by the gravity force works on the aircraft landing gear when an aircraft is in a static situation. The combination of these forces allows the aircraft to maintain at a steady position (**Equation 23**: Static force in main gear touchdown

). It can be assumed that in all situations the strut is perpendicular on the runway (**Figure 19**).

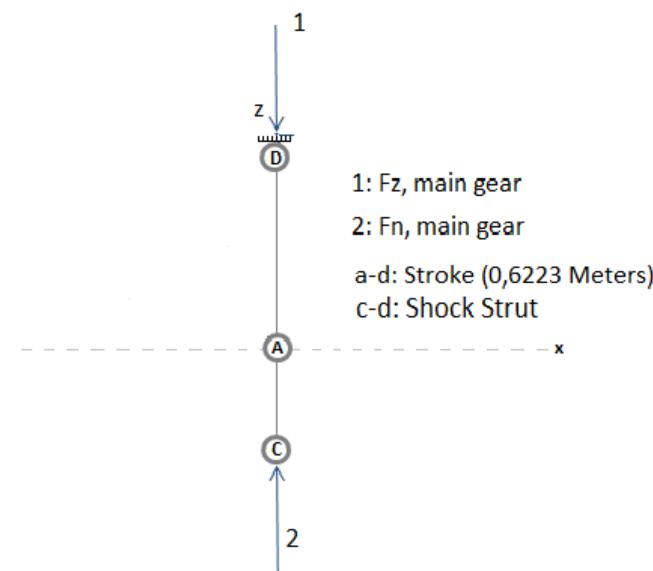
$$F_n = m * g$$

$$m = 295.743 \text{ kg}$$

$$g = 9,81 \text{ m/s}^2$$

$$F_n = 295.743 * 9,81 = 2.901.238,83 \text{ N}$$

*Equation 23: Static force in main gear touchdown*



*Figure 19: Free-body-diagram static force touchdown*

#### 3.3.2 Dynamic force touchdown

With the dynamic force interval it can be assumed that the weight of the aircraft can be neglected due to the presence of lift, because according to CS-25 the load factor is one (**Figure 20**). The b747-400 has a maximum landing weight of 295.743 kilograms and a vertical velocity of 3,05 m/s. This is the



limit descent velocity described in CS-25 (**Appendix 7**) With this information the kinetic energy can be calculated (**Equation 24**: Kinetic energy in main gear touchdown ).

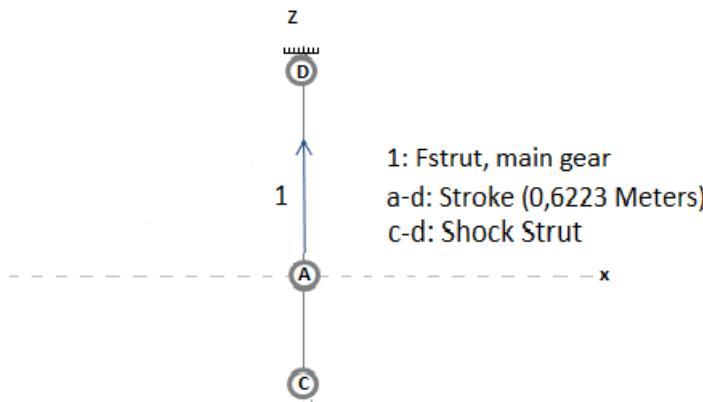
$$Ek = \frac{1}{2} * m * v^2$$

$$m = 295.743\text{kg}$$

$$v = 3,05\text{m/s}$$

$$Ek = \frac{1}{2} * 295.743 * 3,05^2 = 1.375.574,620 \text{ Joule}$$

*Equation 24: Kinetic energy in main gear touchdown*



*Figure 20: Free-body-diagram dynamic force touchdown*

Assumed is that the strut is the only part that handles the force because the forces which act into the drag and side braces, and therefore also in their pivoting attachments, are neglected. The strut exists among others of a spring. It can be assumed that the spring saves all the kinetic energy. The spring energy is dependable of the spring stiffness and length of the stroke (**Equation 25**: Spring energy touchdown). With the value of the spring stiffness and the length of the stroke the force in the strut can be calculated (**Equation 26**: Total force per strut touchdown ).

Other things that have to be mentioned is that 75% of the total strut stroke will be covered at the touchdown. This is because never the whole stroke can be used, because the still higher pressure of the nitrogen under the increasing compression. The assumption is that with maximum touchdown 75% of the stroke will be used. The other is that the main gear takes up all the forces. The b747-400 its main gear exists of four struts. This means the force is divided over the four struts. We can assume that the force is equally divided.

$$E_{\text{spring}} = \frac{1}{2} c * \Delta h^2 \rightarrow c = \frac{E_{\text{spring}} * 2}{\Delta h^2}$$

$$E_{\text{spring}} = 1.375.574,620 \text{ Joule}$$

$$h(* 75\%) = 24,5 \text{ inch} = 0,6223\text{m}$$

$$c = \frac{1.375.574,620 * 2}{(0,6223 * 0,75)^2} = 12.629.670,53\text{N/m}$$

*Equation 25: Spring energy touchdown*



$$F = c * \Delta h$$

$$F = 12.629.670,53 * (0,6223 * 0,75) = 5.894.582,73N$$

$$F_{strut} = \frac{5984582,73}{4(struts)}$$

*Equation 26: Total force per strut touchdown*

### 3.3.3 Total

Now the static and dynamic forces with landing gear are calculated they can be added together. The sum of these forces is the total force the strut handles in the interval of the touchdown.

$$F_{total} = F_n(static) + F_{strut}(dynamic)$$

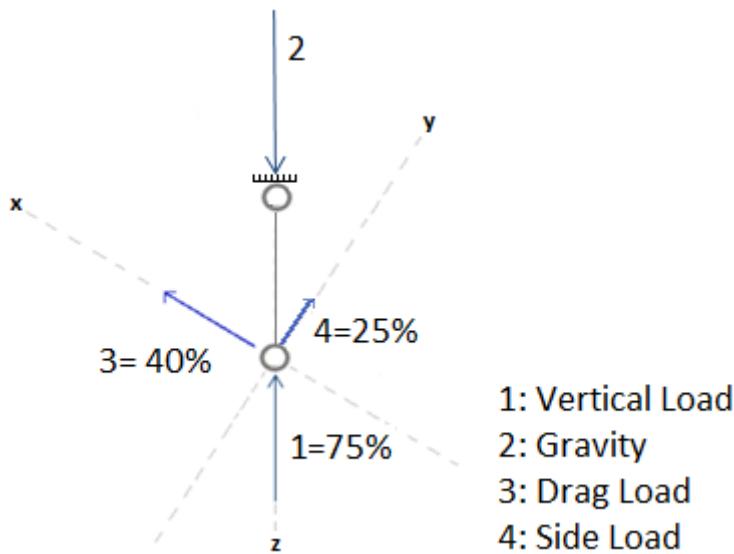
$$F_n = 2.901.238,83 N$$

$$F_{strut} = 1.473.645,683 N$$

$$F_{total} = 2.901.238,83 + 1473645,683 = 4.374.884,513 N$$

## 3.4 Crosswind situation

The landing of the aircraft with crosswind creates a different situation in the main gear compared to a landing without crosswind (**Figure 21**). CS-25 states that without any further information of the Aircraft Flight Manual the following assumption can be made: "A vertical load equal to 75% of the maximum ground reaction must be considered in combination with a drag and side load of 40% and 25%, respectively, of that vertical load". The vertical load is calculated in 273.3.3 Total (1). The other forces which act on the aircraft are the gravity (2), a drag load (3) and a side load (4).



*Figure 21: Crosswind situation*

With this information it is possible to calculate the forces that work in one bogie construction of the landing gear during crosswind landing. These calculations are shown in Scheme 3.



Maximum ground reaction = 4.374.884,513 N

$$\text{Vertical load} = \frac{75\% * \text{Maximum ground reaction}}{4} = 820.290,8462 \text{ N}$$

$$\text{Drag load} = 40\% * 820.290,8462 = 328.116,3385 \text{ N}$$

$$\text{Side load} = 25\% * 820.290,8462 = 205.072,7115 \text{ N}$$

Scheme 3: Calculations crosswind situation

The force acting on the drag brace can also be calculated. First there must be looked at which forces act on the main gear and how they do seize (**Figure 22**).

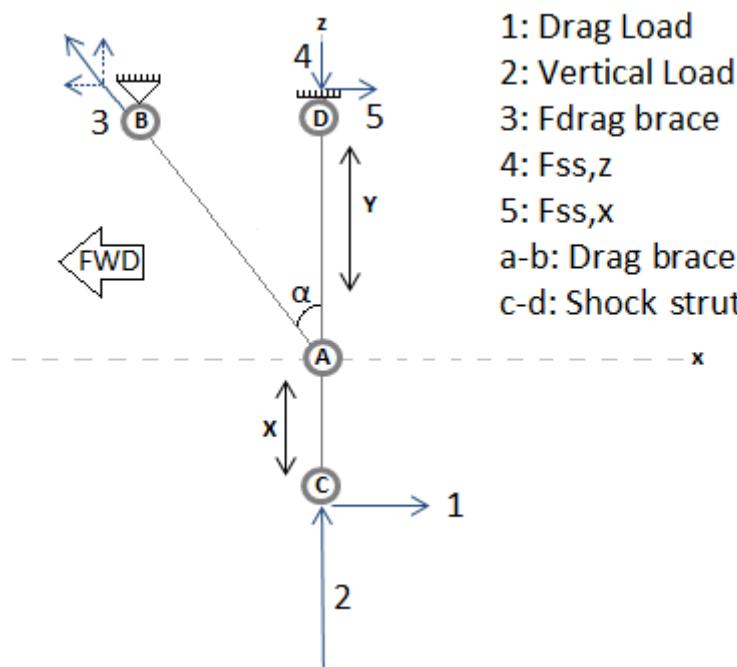


Figure 22: Forces in construction landing gear touchdown with crosswind

Next the torques will be calculated because the sum of the torques has to be zero. This is because the construction of the landing gear is not going to turn. When using the torque of A the (**Equation 27**: Sum of torques of A touchdown with crosswind) can be obtained.

$$\sum_{+o}^{+o} A = \text{Drag load} * x - F_{ss,x} * y = 0$$

Where:

Drag load = the force acting in the x direction in Newton

X = the perpendicular distance between Fbrake and C in centimeters

Fss,x = the Shock strut force in x direction in Newton

Y = the perpendicular distance between Fssx and C in centimeters

Equation 27: Sum of torques of A touchdown with crosswind

Using (**Equation 27**) and the values of x en y from (**2.2.3**) the shock strut force in x direction can be calculated (**Equation 28**).



$$F_{ss,x} = \frac{328.116,3385 * 82,836}{269,217} = 100.958,8734N$$

*Equation 28: Calculating shock strut force in x direction*

The force which acts on the drag brace can be divided into a force acting in the x direction and a force acting in the z direction;  $F_{db,x}$  and  $F_{db,z}$ . Then the equation of the forces acting in the x direction can be made (**Equation 29**).

$$\sum^+ F_{db,x} - \text{Drag load} - F_{ss,x} = 0$$

Where:

$F_{db,x}$  = the drag brace force in x direction in Newton

*Equation 29: Forces acting in the x direction in the construction of the landing gear touchdown with crosswind*

Using Equation 29 the drag brace force in x direction can be calculated (**Equation 30**).

$$F_{db,x} = 328.116,3385 + 100.958,8734 = 429.075,2119N$$

*Equation 30: Calculating drag brace force in x direction*

Since the angle between the drag brace and the shock strut is known, the force acting on the drag brace can be calculated (**Equation 31**).

$$F_{db} = \frac{F_{db,x}}{\sin(\alpha)}$$

Where:

$F_{db}$  = the drag brace force in Newton

$\alpha$  = angle between the drag brace and the shock strut in degrees

*Equation 31: Drag brace force during touchdown with crosswind*

Using (**Equation 31**) and the value of  $\alpha$  described in (**2.2.3**) the drag brace force is 794.662,3901 Newton (**Equation 32**).

$$F_{db} = \frac{429.075,2119}{\sin(32,68)} = 794.662,3901$$

*Equation 32: Calculating the drag brace force touchdown with crosswind*

The force calculated in Equation 32 is equal to the force acting in the pivoting attachment of the drag brace (**Figure 23**).

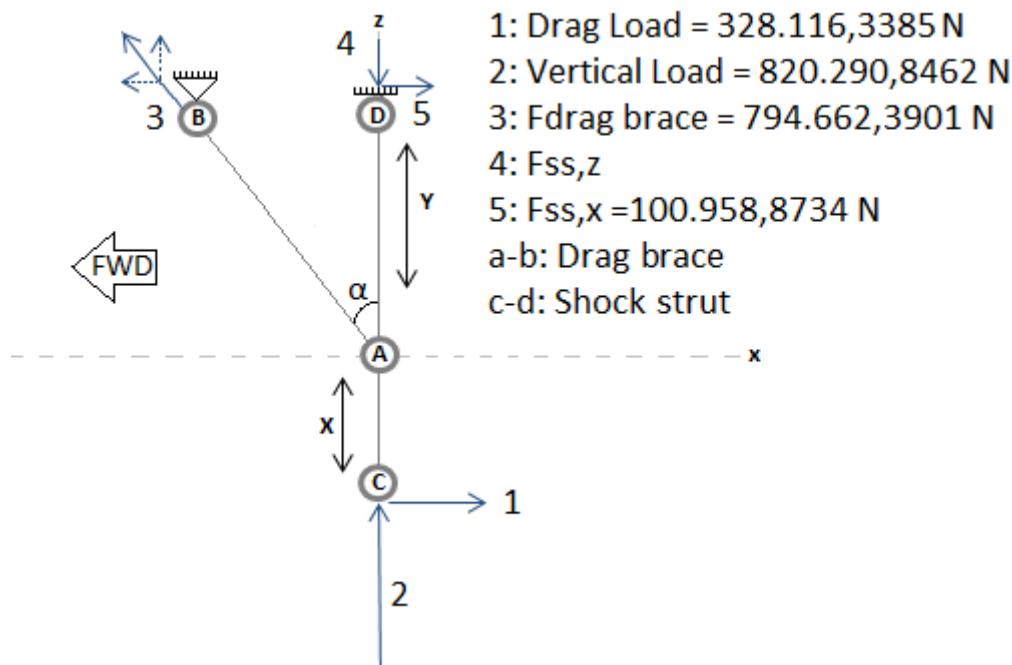


Figure 23: Forces in drag brace and shock strut during touchdown with crosswind

The force acting on the side brace can also be calculated. First there must be looked at which forces act on the main gear and how they do seize (**Figure 24**). Assumed is that the crosswind has a component acting from the left on the aircraft.

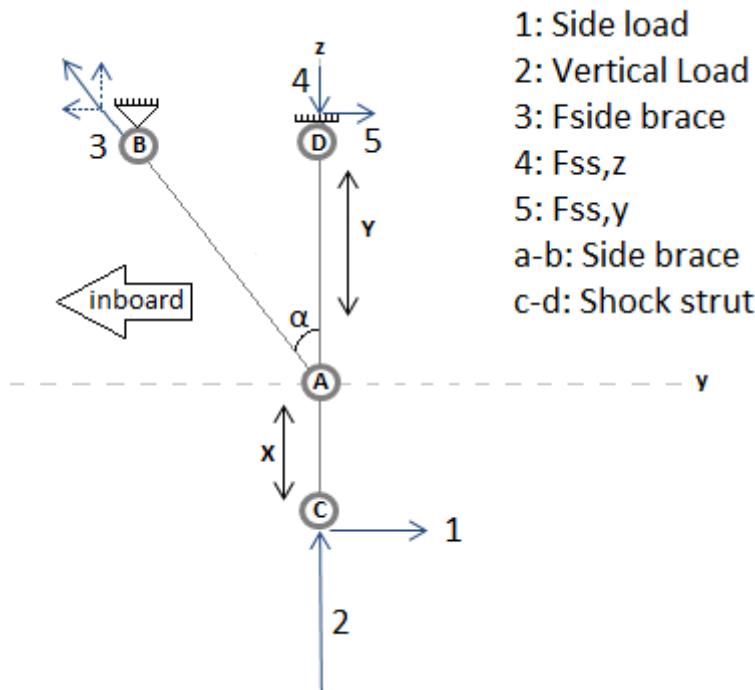


Figure 24: Forces in construction landing gear touchdown with crosswind

Next the torques will be calculated because the sum of the torques has to be zero. This is because the construction of the landing gear is not going to turn. When using the torque of A the (**Equation 33**) can be obtained.



$$\sum_{+o} A = \text{Side load} * x - F_{ss,y} * y = 0$$

Where:

Side load = the force acting in the y direction in Newton

X = the perpendicular distance between Fbrake and C in centimeters

F<sub>ss,y</sub> = the Shock strut force in y direction in Newton

Y = the perpendicular distance between F<sub>ss,y</sub> and C in centimeters

*Equation 33: Sum of torques of A touchdown with crosswind*

Using (**Equation 33**) and the values of x en y from (**2.2.3**) the shock strut force in y direction can be calculated (**Equation 34**).

$$F_{ss,y} = \frac{205.072,7115 * 79,072}{192,032} = 84.441,70474N$$

*Equation 34: Calculating shock strut force in x direction*

The force which acts on the side brace can be divided into a force acting in the x direction and a force acting in the y direction; F<sub>db,y</sub> and F<sub>db,z</sub>. Then the equation of the forces acting in the y direction can be made (**Equation 35**).

$$\sum_{-+} F_{sb,y} - \text{Side load} - F_{ss,y} = 0$$

Where:

F<sub>sb,y</sub> = the side brace force in y direction in Newton

*Equation 35: Forces acting in the y direction in the construction of the landing gear touchdown with crosswind*

Using Equation 35 the side brace force in y direction can be calculated (**Equation 36**).

$$F_{db,x} = 205.072,7115 + 84.441,70474 = 289.514,4162N$$

*Equation 36: Calculating side brace force in y direction*

Since the angle between the side brace and the shock strut is known, the force acting on the side brace can be calculated (**Equation 37**).

$$F_{sb} = \frac{F_{sb,x}}{\sin(\alpha)}$$

Where:

F<sub>sb</sub> = the side brace force in Newton

α = angle between the drag brace and the shock strut in degrees

*Equation 37: Side brace force touchdown with crosswind*

Using (**Equation 37**) and the value of α described in(**2.2.3**) the drag brace force is 483.536,1859 Newton (**Equation 38**).

$$F_{sb} = \frac{289.514,4162}{\sin(36,78)} = 483.536,1859$$

*Equation 38: Calculating the side brace force touchdown with crosswind*



The force calculated in Equation 38 is equal to the force acting in the pivoting attachment of the side brace (**Figure 25**: Forces in side brace and shock strut during touchdown with crosswind).

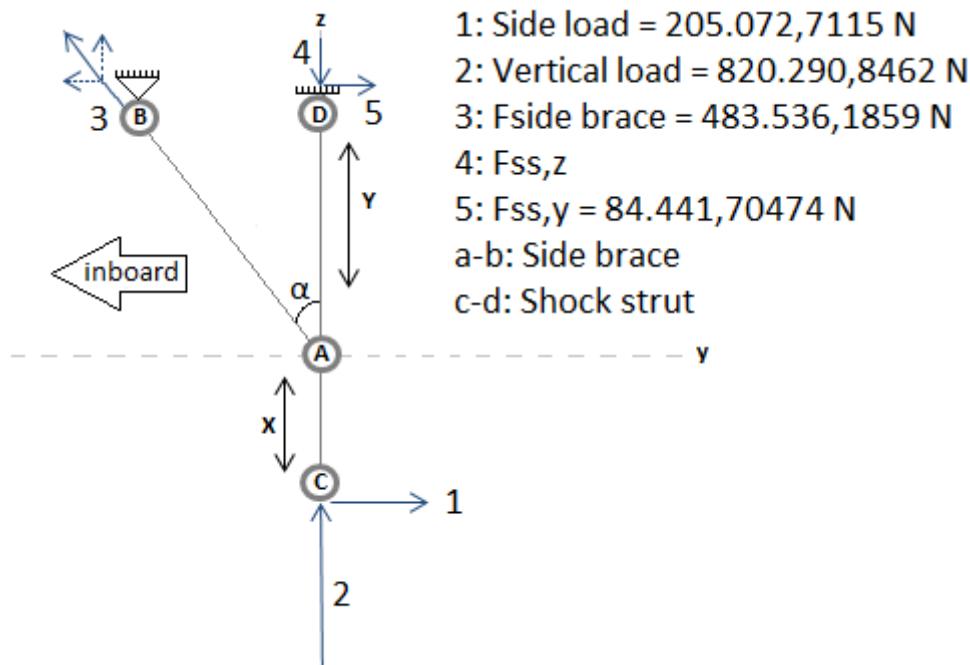


Figure 25: Forces in side brace and shock strut during touchdown with crosswind

In the figure above the situation is shown in case of downwind and in Figure 26 the upwind situation is shown. The difference between these two situations is the force that works in the side brace. In the downwind situation there is a traction force in the side brace and during the upwind situation there is a pressure force in the side brace.

- 1: Side load
- 2: Vertical Load
- 3: Fside brace
- 4: Fss,z
- 5: Fss,y
- a-b: Side brace
- c-d: Shock strut

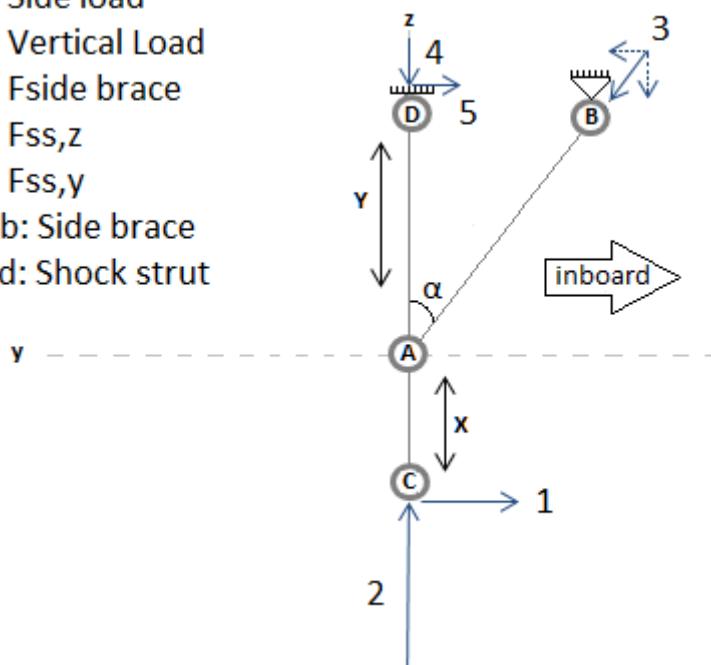


Figure 26: Upwind situation side brace



### 3.5 Conclusion

A few questions should be answered to set a conclusion about, on which parts of the landing gear act the most forces. First off which certification requirements and critical situations could be identified based on the legal requirements was examined. All those information was found in CS-25. A critical situation is a situation in which is expected that the limit loads are going to be exceeded. The part in which is expected the limit loads are going to be exceeded is called a critical part. Although a critical situation occurs the critical part may not forsake. When an aircraft makes a rejected take-off the strut of the nose gear is, and the drag braces in the main gear are critical parts. During touchdown is the strut in every main gear unit the critical part. By landing with crosswind are the side braces of the main gear the critical parts. Because the aircraft is in motion at all those situations we call them dynamic situations.

First there is calculated the forces on the aircraft in rest, called a static situation, to make a reference for the rest of the calculations. In the static situation a force of 2.249.252 Newton acts on the main gear of which 562.313 Newton on each main gear unit. On the nose gear acts a force of 1.576.648 Newton. Assumed is that both forces will be entirely absorbed by the strut. During the RTO in the nose gear act the most dynamic forces because of the torque working around the CG, less dynamic forces work in the main gear during the RTO. In this situation the calculations are made with the MTOW of 390.000 kg. 2.948.400 Newton works during the RTO on the nose gear, compared with the forces that act on the nose gear during the static situation it makes it clear that the strut of the nose gear is a critical part during the RTO. It is clear that the forces working on the main gear are less, because of the torque during the RTO compared with the static situation. 877.500 Newton do work in the main gear. That is almost 1.5 million Newton less than in static situation. Next the landing during touch down is calculated with the MLW of 295.743 kg. The forces which are working on the strut in this situation are 4.374.884 N. This is the static force and the dynamic force. Seen that the force in the strut in a static situation the touch down situation is almost doubled.

The MLW is also used in the crosswind landing situation. The calculated forces in the drag brace are 794.629 N traction force and in the side brace are 447.890 N, which is a critical part, on each side of the gear works a traction force or pressure force. In the static situation there are no forces working on those braces, but with crosswind the forces of the strut are divided in the drag and side brace. So the strut shall be relieved during a crosswind landing.

So the conclusion for this calculations means that during RTO the critical part of the nose gear is the strut. The critical part during touch down is the strut of the main gear. During a crosswind landing the side brace is the critical part, because of the crosswind force that is working on the gear.

## Appendix index

|   |      |
|---|------|
| Appendix I Touch down .....                           | I    |
| Appendix II Rejected take off .....                   | II   |
| Appendix III Balance chart .....                      | IV   |
| Appendix IV Balance chart RTO .....                   | V    |
| Appendix V Calculation MAC Boeing 747-400 .....       | VI   |
| Appendix VI Vertical Claearances Boeing 747-400 ..... | VII  |
| Appendix VII Landing load .....                       | VIII |



## Appendix I Touch down

### CS 25.473 Landing load conditions and assumptions

(a) For the landing conditions specified in CS 25.479 to 25.485, the aeroplane is assumed to contact the ground:

(1) In the attitudes defined in CS 25.479 and CS 25.481.

(2) With a limit descent velocity of 3.05 m/sec (10 fps) at the design landing weight (the maximum weight for landing conditions at maximum descent velocity); and

(3) With a limit descent velocity of 1.83 m/sec (6 fps) at the design take-off weight (the maximum weight for landing conditions at a reduced descent velocity).

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

(b) Aeroplane lift, not exceeding aeroplane weight, may be assumed, unless the presence of systems or procedures significantly affects the lift.

(c) The method of analysis of aeroplane and landing gear loads must take into account at least the following elements:

(1) Landing gear dynamic characteristics.

(2) Spin-up and spring back.

(3) Rigid body response.

(4) Structural dynamic response of the airframe, if significant.

(d) The landing gear dynamic characteristics must be validated by tests as defined in CS 25.723(a).

(e) The coefficient of friction between the tyres and the ground may be established by considering the effects of skidding velocity and tyre pressure. However, this coefficient of friction need not be more than 0.8.

### CS 25.479 Level landing conditions

(a) In the level attitude, the aeroplane is assumed to contact the ground at forward velocity components, ranging from  $V_{L_1}$  to 1.25  $V_{L_2}$  parallel to the ground under the conditions prescribed in CS 25.473 with:

(1)  $V_{L_1}$  equal to  $V_{S_0}(\text{TAS})$  at the appropriate landing weight and in standard sea-level conditions; and

(2)  $V_{L_2}$ , equal to  $V_{S_0}(\text{TAS})$  at the appropriate landing weight and altitudes in a hot day temperature of 22.8°C (41°F) above standard.

(3) The effects of increased contact speed must be investigated if approval of downwind landings exceeding 19 km/h (10 knots) is requested.

(b) For the level landing attitude for aeroplanes with tail wheels, the conditions specified in this paragraph must be investigated with the aeroplane horizontal reference line horizontal in accordance with Figure 2 of Appendix A of CS -25.

(c) For the level landing attitude for aeroplanes with nose wheels, shown in Figure 2 of Appendix A of CS -25, the conditions specified in this paragraph 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;



## Appendix II Rejected take off

### CS 25.493 Braked roll conditions

(b) For an aeroplane 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 this paragraph 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.

(d) An aeroplane equipped with a nose gear must be designed to withstand the loads arising from the dynamic pitching motion of the aeroplane due to sudden application of maximum braking force. The aeroplane is considered to be at design takeoff weight with the nose and main gears in contact with the ground, and with a steady state vertical load factor of 1·0. The steady state nose gear reaction must be combined with the maximum incremental nose gear vertical reaction caused by sudden application of maximum braking force as described in sub-paragraphs (b) and (c) of this paragraph.

(e) In the absence of a more rational analysis, the nose gear vertical reaction prescribed in sub-paragraph (d) of this paragraph must be calculated in accordance with the following formula:

$$V_N = \frac{W_T}{A + B} \left\{ B + \frac{f\mu AE}{A + B + \mu E} \right\}$$

Where:

- $V_N$  = Nose gear vertical reaction
- $W_T$  = Design take-off weight
- $A$  = Horizontal distance between the c.g. of the aeroplane and the nose wheel.
- $B$  = Horizontal distance between the c.g. of the aeroplane and the line joining the centres of the main wheels.
- $E$  = Vertical height of the c.g. of the aeroplane above the ground in the 1·0 g static condition.
- $\mu$  = Coefficient of friction of 0·8.
- $f$  = Dynamic response factor; 2·0 is to be used unless a lower factor is substantiated.

In the absence of other information, the dynamic response factor  $f$  may be defined by the equation.

$$f = 1 + \exp \left[ \frac{-\pi \xi}{\sqrt{1 - \xi^2}} \right]$$

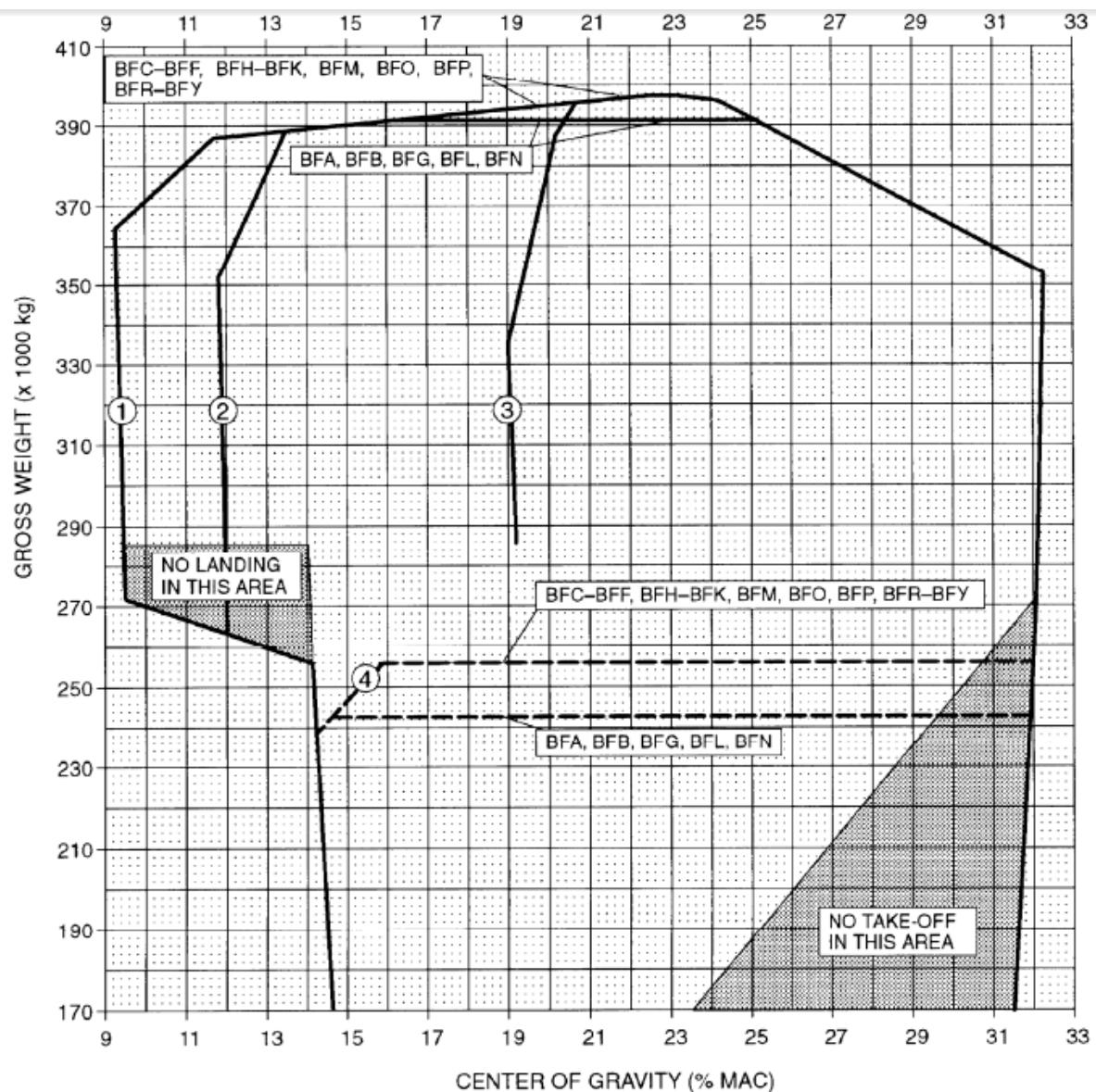
Where:  $\xi$  is the critical damping ratio of the rigid body pitching mode about the main landing gear effective ground contact point.

## CS 25.735 Brakes and braking systems

(2) *Maximum kinetic energy accelerate-stop.* The maximum kinetic energy accelerate-stop is a rejected take-off for the most critical combination of aeroplane take-off weight and speed. The accelerate-stop brake kinetic energy absorption requirement of each wheel, brake, and tyre assembly must be determined. It must be substantiated by dynamometer testing that the wheel brake and tyre assembly is capable of absorbing not less than this level of kinetic energy throughout the defined wear range of the brake. The energy absorption rate derived from the aeroplane's braking requirements must be achieved. The mean deceleration must not be less than  $1.8 \text{ m/s}^2$  ( $6 \text{ fps}^2$ ).

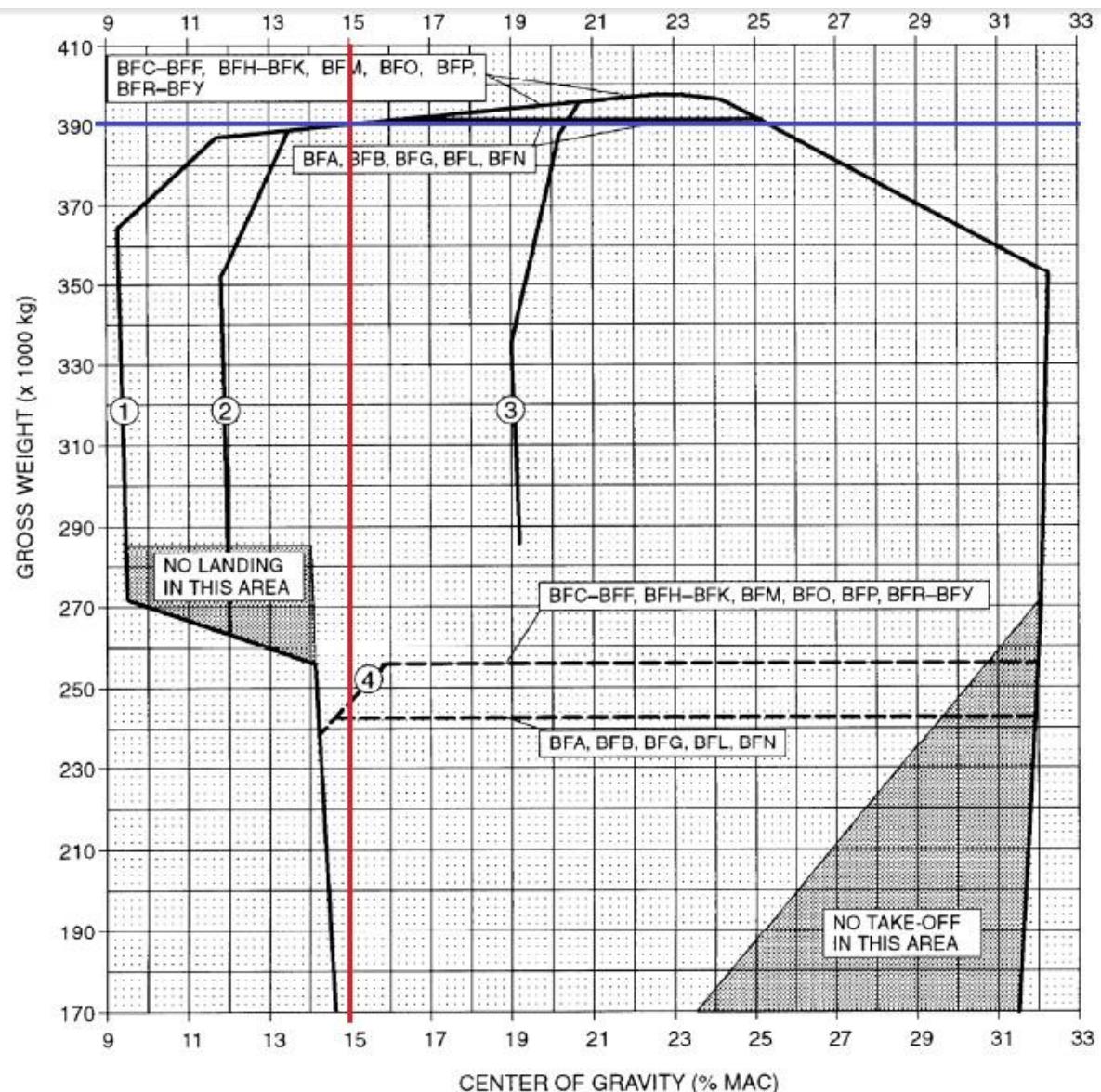


### Appendix III Balance chart





## Appendix IV Balance chart RTO



## Appendix V Calculation MAC Boeing 747-400

The equation which is used to calculate the MAC is as follows (**Equation 39**).

$$MAC = \frac{2}{3} RC \cdot \frac{1 + t + t^2}{1 + t}$$

*RC* = Root Chord in meters

*t* = Taper ratio in meters

Taper ratio =  $\frac{\text{Tip Chord}}{\text{Root Chord}}$

*Equation 39: MAC formula*

The values of the Tip Chord and the Root Chord of the Boeing 747-400 are:

- Tip Chord: 4,06 meters
- Root Chord: 16,56 meters

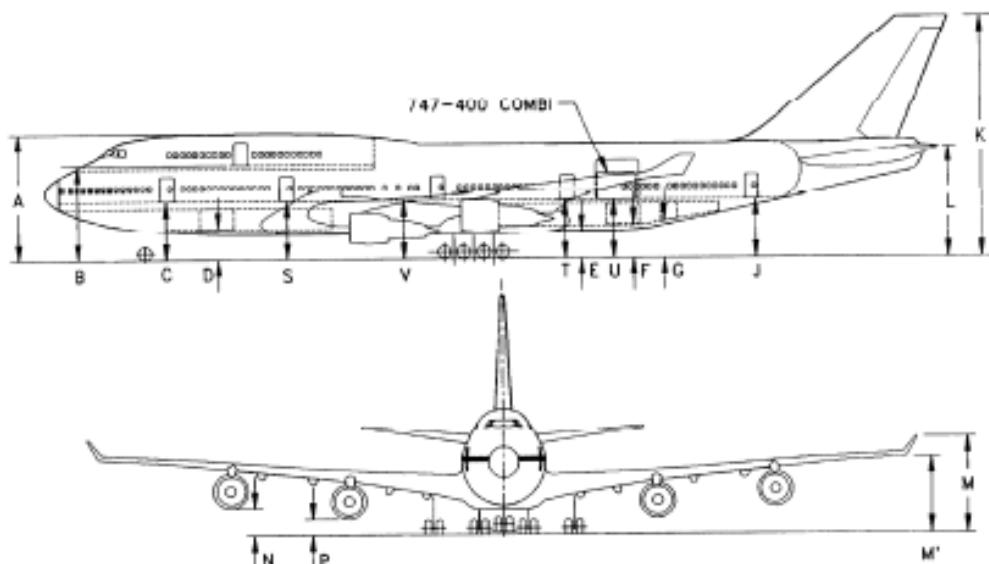
Source: **Boeing 747-400** - Door Peter Gilchrist

$$MAC = \frac{2}{3} * 16,56 * \frac{1 + 0,245 + 0,245^2}{1 + 0,245} = 11,57293243 \text{ meters}$$



## Appendix VI Vertical Clearances Boeing 747-400

### 10.2.1.2 Vertical Clearances



|    | MINIMUM |       | MAXIMUM |       |
|----|---------|-------|---------|-------|
|    | FT - IN | M     | FT - IN | M     |
| A  | 32 - 1  | 9.80  | 33 - 6  | 10.23 |
| B  | 24 - 8  | 7.53  | 25 - 11 | 7.91  |
| C  | 15 - 6  | 4.74  | 16 - 11 | 5.18  |
| D  | 8 - 10  | 2.71  | 10 - 2  | 3.11  |
| E  | 6 - 10  | 2.09  | 7 - 11  | 2.42  |
| F  | 9 - 3   | 2.82  | 10 - 5  | 3.18  |
| G  | 9 - 10  | 3.00  | 11 - 2  | 3.41  |
| H  | 29 - 7  | 9.02  | 31 - 4  | 9.56  |
| J  | 15 - 9  | 4.82  | 17 - 5  | 5.33  |
| K  | 61 - 7  | 18.80 | 64 - 0  | 19.51 |
| L  | 27 - 6  | 8.39  | 29 - 9  | 9.09  |
| M  | 16 - 9  | 5.11  | 18 - 8  | 5.70  |
| M' | 17 - 2  | 5.24  | 19 - 1  | 5.84  |
| N  | 4 - 4   | 1.32  | 5 - 10  | 1.00  |
| P  | 2 - 3   | 0.71  | 3 - 0   | 0.93  |
| S  | 15 - 9  | 4.80  | 16 - 10 | 5.15  |
| T  | 16 - 0  | 4.88  | 17 - 0  | 5.19  |
| U  | 16 - 0  | 4.88  | 17 - 3  | 5.28  |
| V  | 15 - 11 | 4.87  | 16 - 9  | 5.11  |

## Appendix VII Landing load

**CS 25.473      Landing load conditions  
and assumptions**

(2) With a limit descent velocity of 3.05 m/sec (10 fps) at the design landing weight (the maximum weight for landing conditions at maximum descent velocity); and