CHAPTER 5

PARACHUTE DECELERATION SYSTEM DESIGN AND TESTING

Notations

μ	Parachute cone angle
ρ	Density of air (kg/m^3)
Φ	Line's conversion angle
η_c	Parachute cluster efficiency
e	Abrasion / cyclic load factor
g	Gravitation constant (9.81 m/s^2)
h	Parachute canopy height (m)
k	Fatigue factor
m	Mass (kg)
n	Filling time index
o	Environment factor
q	Dynamic Pressure (N/m^2)
D	Maximum forebody diameter (m)
M	Mach number
W	Weight of payload (kg_f)
A_p	Allowable strength factor
C_k	Dynamic load factor
V	Velocity (m/s)
$(C_D S)_p$	Drag area of the fully open parachute (m^2)

$(C_D S)_V$	Drag area of forebody (or Vehicle)
C_D	Coefficient of drag
C_x	Opening load factor
D_o	Parachute nominal diameter (m)
D_p	Inflated (projected) parachute diameter (m)
D_r	Reefed parachute diameter (m)
F_c	Steady state descent force (N)
F_D	Drag Force (N)
F'_D	Drag Force (N) with extra 10% due to pyro delay in line cutter
F_s	Snatch force (N)
F_x	Parachute opening peak load (N)
L_e	Suspension-lines length (m)
L_c	Design load for critical components (N)
N_s	Number of suspension-lines
S or S_o	Parachute surface area (m^2)
S_r	Reefed parachute surface area (m^2)
T_c	Time to reach steady state (s)
T_f	Parachute inflation time (s)
V_t	Terminal speed (m/s)
L_{nc}	Design load for non-critical components (N)

Abbreviations

AUW	All Up Weight
CM	Crew Module

DF	Design Factor
FB	Forebody
MoS	Margin of Safety
PDS	Parachute Deceleration System
PRU	Pyro Release Unit
Qty	Quantity
RTRS	Rail Track Rocket-motor Sled
SF	Safety factor
TCS	Top Cover Separation

5.1 Introduction

This chapter presents a novel design for the architecture parachute chosen, besides design and qualification testing, and the philosophy behind it. Parachute system for recovery of aerospace vehicle must be designed to recover crew module under the most critical atmospheric conditions (Alessandro *et al.*, 2017). These recovery systems are designed from sketch keeping in mind the requirements of the specific vehicle. The design process for different types of parachute decelerator system has been described by Knacke (1992). For the design of any decelerator system, particularly for space application, the following basic design criteria are to be considered:

i) Reliability

ii) Stability

iii) Low opening shock and high drag force

iv) Low weight and volume

v) High parachute drag area

vi) Environmental adaptability

vii) Simplicity in design and manufacturing

viii) Simplicity in maintenance and service

ix) Low acquisition cost

The following design rules and criteria are also applied in designing of the deceleration system for the re-entry module:

(i) All mission aborts are operational modes.

(ii) The primary system should consist of a single drogue and a single main parachute with an active redundant drogue and main parachute.

(iii) No single component failure shall cause loss of crew or mission.

(iv) The occurrence of parallel failures such as loss of two drogues or two main parachutes should have almost practically zero probability.

(v) An overall reliability for the PDS must be equal to or better than 0. 999.

(vi) A minimum factor of safety value as 1.6 must be proven for all structural components and parachute load stages by conducting ultimate load tests.

(vii) All parachutes are to be independently deployed while utilizing active deployment means.

5.2 Sequence of Operation

The PDS proposed for the re-entry module is to have two stages (Swadesh *et al*., 2011) parachute system. Because of the high reliability to be maintained, as mentioned earlier, an extra parachute is added at each stage (Table 5.1). In view of this, the architecture of the PDS would be as shown in Figure 5.1. The functioning of the parachutes in sequence is exhibited in Figure 5.2.

Table 5.1: List of functional items in the proposed PDS

S No	Parachute	Type	Qty	Deployment Method
1.	TCS chute	Ringslot	02	Mortar
2.	Pilot Chute	Ringslot	02	Mortar
3.	Drogue Parachute	Ribbon	02	Pilot Chute
4.	Main Parachute	Solid Circular Slotted	02	Drogue Parachute

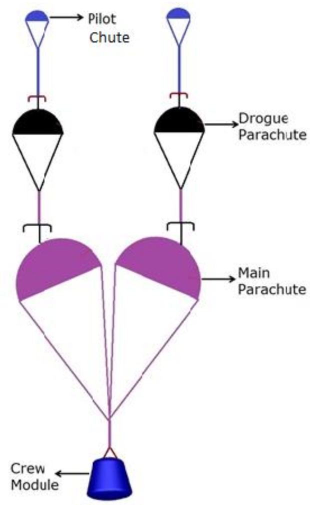


Figure 5.1: Proposed architecture of the PDS

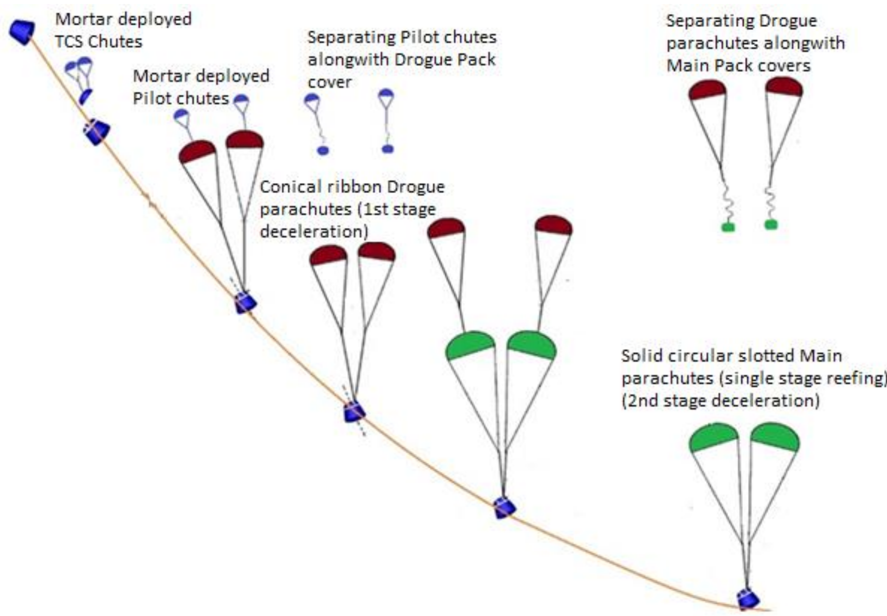


Figure 5.2: Sequence of operations of proposed PDS

The sequence of operations from initiation to touch down for the final landing are as follows.

Step 1: The sequence begins with jettisoning of the forward heat shield at a normal altitude of 7 km. Immediately, after the separation of the forward heat shield from the CM, small ringslot chutes (TCS) are mortar deployed. The chutes exert a force to extract the jettisoned heat shield beyond the wake of CM. The chutes carry the heat shield and start decelerating at a velocity of 40 m/s to avoid the re-contact with CM.

Step 2: On the separation of heat shield, two ring slot pilot chutes are mortar deployed, which, in-turn, extract conical ribbon drogue parachutes attached to it. After deploying drogue parachutes, pilot chutes are separated from the crew module by breaking of weak-ties.

Step 3: Drogue parachutes first stabilize the CM and then decelerate it with a steady terminal speed of 70 m/s upto 3.0 km altitude. McVey (2012) has explained the necessity of drogue parachute for payload stabilization and subsequent retardation.

Step 4: Barometric sensor senses the altitude of 3 km and gives the command for activation of drogue's Pyro Release Unit (PRU) for drogue parachute disconnection.

Step 5: Disconnect of drogue parachute provides the force necessary to pull out solid circular slotted main parachutes through bridle lines from the pack cover. When the lines stretch, drogue parachutes detached from CM snaps off the weak-tie from the main parachute.

Step 6: Main parachute inflates through two reefing stages to a full-open condition. The main parachute decelerates the CM to the safe landing speed.

Step 7: On the touch-down, the impact switch sensor is activated and gives command to the main pyro-release unit. This unit, on activation, disconnects the main parachute from the CM.

The proposed PDS has to function in the both nominal and abort situations.

5.3 General Design Philosophy of Parachute Deceleration System

Prior to World War-II, the design was carried out by trial-and-error method and was relatively less expensive. Such an approach was inadequate for high-altitude, high-speed parachute application. Thus, a reasonable analytical approach was used in designing a new parachute. It was still extremely difficult to predict the behaviour of a new parachute (Warren, 1956; Heinrich et al., 1961). For this reason, the system under study has to be designed based on numerical analysis, primary data validation using software, wind tunnel test, dynamic tests in simulated environment, and flight tests.

Parachutes are designed for particular flight envelopes (Figure 1.1) based on speed, altitude, and required dynamic characteristics. In addition, payload mass, current atmospheric conditions and desire terminal velocity are also to be taken into consideration. Parachute material requirements are to be specified based on deployment characteristics, or specifically the two separate and distinct forces (F_s & F_D) as shown in Figure 5.3 (Macha, 1993; Wolf, 1974). These two forces are known as the snatch and opening forces (Ludtke, 1986). When parachute is in lines-stretched condition, payload and parachute reach the same velocity. At this stage, the force is transmitted from suspension-lines to the payload. This force is called as snatch force (F_s). After the air enters the mouth of the canopy, the parachute inflates. The peak force transmitted to the payload by the parachute during the opening is known as the opening force (F_D). The snatch force is very small and is to be controlled using deployment bag, sequential opening and lines first deployment. The opening force is very high and is for a very short duration, and thus exerts shock force upon the forebody.

These peak loads are very significant in selection of materials for the parachutes. In general, a parachute fails from the weak joints or tears due to defects. Therefore, proper design factors and testing of materials are necessary for the parachute performance evaluation.

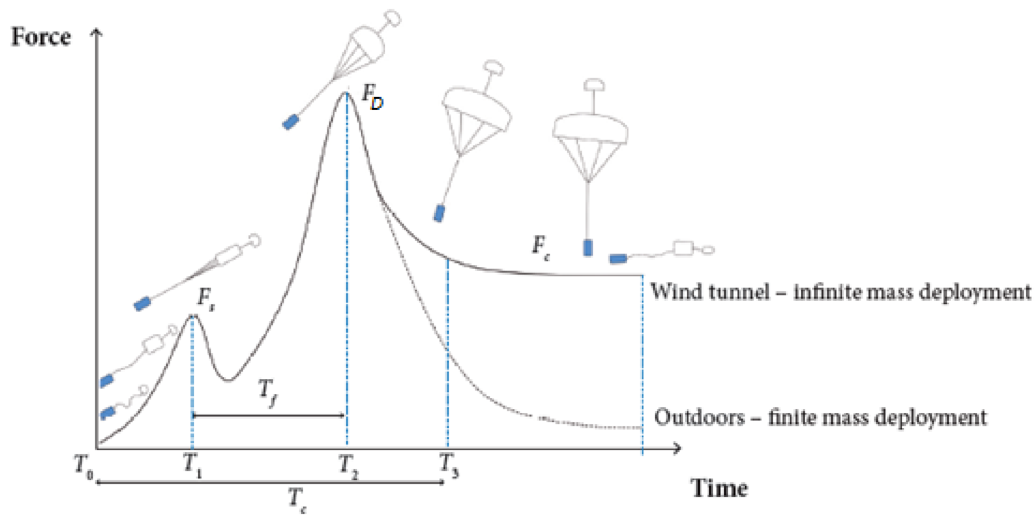


Figure 5.3: Force-time profile of a parachute across its deployment stages

5.3.1 Estimation of Parachute Opening Force

In the steady state condition, when a payload is falling along with the parachute, a gravity force on the parachute-payload mass is balanced by the drag force of the parachute-payload (Figure 5.4). The payload-parachute system falls downward under the gravity at constant velocity called as terminal speed. The size of the parachute is determined by the balancing these forces at terminal speed.

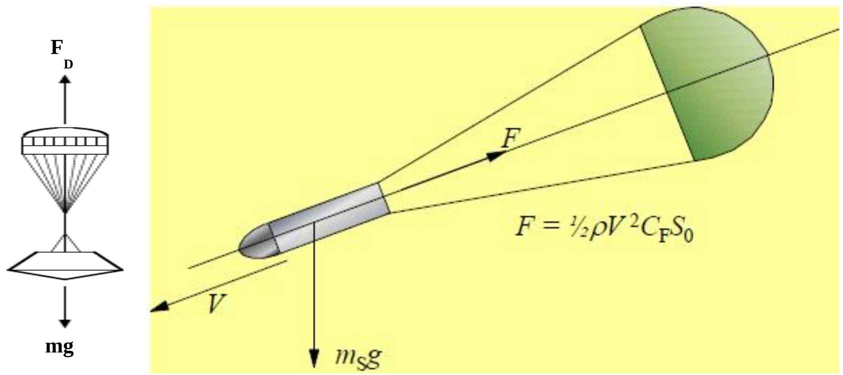


Figure 5.4: Parachute-payload forces in streamlines at terminal speed

There are three main methods to calculate the parachute opening force (Knacke, 1992).

(i) *Canopy loading $(W/C_DS)_p$ method;*

It is a fast method but *should* be used for preliminary calculations only. It is used for small chute/drogue parachutes below 5 km altitude at the infinite mass.

(ii) *Pflanz method*

It is mathematically exact method and provides good results within certain application limits, but no reefed or disreefed inflation cycle is included.

(iii) *Force-trajectory-time method*

This method is a computer approach to evaluate the parachute opening process (reefed and disreefed). A force-trajectory program best meets the requirements for calculating the vehicle trajectory and deceleration as well as parachute forces as a function of time. This program is also used to find the parachute filling-time. It provides good results with no limitations.

From the Newton's second law of motion, at equilibrium, the sum of force is equal to change in momentum of the body (given by equation 5.1), while neglecting the drag force due to forebody in comparison to parachute.

Momentum change of parachute-payload = Parachute drag impulse + Gravitational impulse

Thus,

$$mV_f - mV_i = \int_i^f F_D(t)dt + \int_i^f W\cos\theta(t)dt \qquad (5.1)$$

The parachute drag impulse, F_D, is given by equation (5.2).

$$F_D = ½\, \rho\, V^2[(C_D S)_p\, C_x] \qquad (5.2)$$

Where, C_x is the parachute opening load factor (Table 5.2). C_x will be one at the terminal speed where $V_f = V_i$. Under infinite mass case, the sum of the drag forces due to parachute and forebody will be equal to weight of the payload (Figure 5.4), and the same has been expressed by equation (5.3) for a vertical falling body.

$$½\, \rho\, V^2[(C_D S)_p + (C_D S)_V] = mg \qquad (5.3)$$

where $(C_DS)_p$ is the drag area of the parachute and $(C_DS)_V$ is the drag area of the forebody.

Table 5.2: Parachute design and performance characteristic data (Ewing *et al.*, 1978)

Type	Constructed Shape: Plan	Constructed Shape: Profile	Constructed Shape: $\frac{D_c}{D_o}$	Inflated Shape $\frac{D_p}{D_o}$	Drag Coef. C_{D_o} Range	Opening Load Factor C_X (Inf. Mass)	Average Angle of Oscillation	General Application
Flat Ribbon			1.00	.67	.45 to .50	~1.05	0° to ±3°	Drogue, Descent, Deceleration
Conical Ribbon			.95 to .97	.70	.50 to .55	~1.05	0° to ±3°	Descent, Deceleration
Conical Ribbon (Varied Porosity)			.97	.70	.55 to .65	1.05 to 1.30	0° to ±3°	Drogue, Descent, Deceleration
Ribbon (Hemisflo)			.62	.62	.30* to .46	1.00 to 1.30	±2°	Supersonic Drogue
Ringslot			1.00	.67 to .70	.56 to .65	~1.05	0° to ±5°	Extraction, Deceleration
Ringsail			1.16	.69	.75 to .90	~1.10	±5° to ±10°	Descent
Disc-Gap-Band			.73	.65	.52 to .58	~1.30	±10° to ±15°	Descent

*Supersonic

In the case of finite mass inflation, the change in velocity is considered, which is due to the inflation process. Finite mass inflation occurs when large parachutes are used on small payloads, generating large decelerations while the parachute is still inflating. The force-trajectory method suits the best in this case for calculating the vehicle trajectory and deceleration as well as parachute forces as a function of time taking input from the information provided in Figure 5.5.

5.3.2 Parachute Inflation Time

Parachute inflation time is the time interval from the time the canopy and lines are stretched to the time point when the canopy is fully inflated. The parachute inflation process starts at time T_0 (Figure 5.3) with the pilot chute being extracted from a deployment container. The force exerted from the inflation of the pilot chute at time T_1 initiates the deployment of the main canopy. The suspension-lines get drawn as the canopy inflates due to the airflow accumulating within (between T_1 and T_2). The main canopy continues to inflate until time point T_3 where the payload attains a steady-state descent velocity. The force-time graph is actual experimentation will be as shown in Figure 5.5. However, the inflation time for round canopy parachute is estimated by equation (5.4).

$$t_{fill} = \frac{n_{fill} D_o}{V_{stretch}} \tag{5.4}$$

where 'n_{fill}'is the filling time index and can be obtained from Table 5.3.

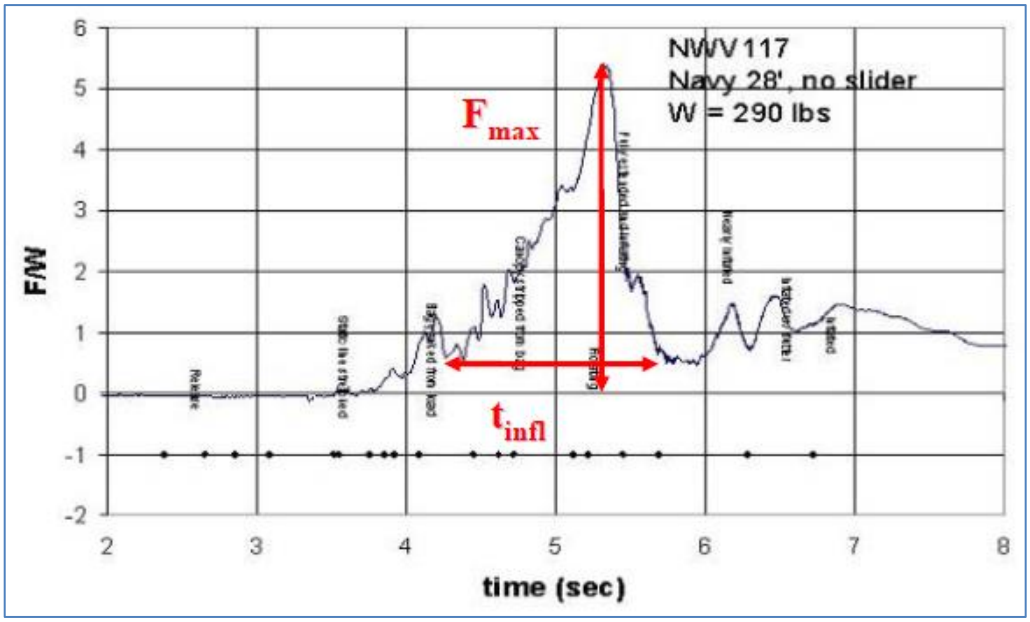


Figure 5.5: Parachute force-time graph (Knacke, 1968)

Table 5.3: Canopy filling time index n_{fill}, for various parachute types (Knacke, 1978)

Parachute type	**Canopy filling time index, n_{fill}**		
	Reefed opening	**Disreefed opening**	**Unreefed opening**
Solid flat circular	-	-	8
Extended skirt, 10%	16 -18	4 - 5	10
Extended skirt, full	16 -18	7	12
Cross	-	-	11.7
Ribbon	10	6	14
Ringslot	-	-	14
Ringsail	7-8	2	7
Ribless guide surface	-	-	4-6

5.3.3 Design Factor

Knacke (1992) recommends a safety factor of 1.6 for all the components of human rated parachute. Michael (2010), however, suggested a higher safety factor of 2 for the following critical elements:

(i) Soft links (Weak-ties)

(ii) Drogue vent band

(iii) Reefing lines

(iv) Risers

The safety factor helps in determining structural design factor (*DF*) defined as the ratio of safety factor (*SF*) and allowable strength factor (A_p), and is given by equation (5.5).

$$DF = (SF / A_p) \tag{5.5}$$

The allowable strength factor is calculated from equation (3.6).

$$A_p = \frac{u.e.o.k}{\cos(\Phi)} \tag{5.6}$$

In the right-hand side of the above equation, the values for various factors are taken from the work of Knacke (1978).

Whenever textiles components are connected to each other or to metals, a loss in joint strength occurs relative to the basic material strength. The resulting joint strength is thus measured by joint efficiency (*u*) and is taken as 0.80 (= 80%) for the PDS to be designed in equation (5.6). One time use parachutes suffer little or no abrasion. While the system designed for regular or repeated use suffer an abrasion and also cyclic loading. Since the proposed PDS is for one-time use, *e* is taken as 1.0 in equation (5.6).

Parachutes are exposed to sunlight, water, vacuum, and the other environmental factors causing loss in the strength of the material. Since the proposed PDS is going to encounter all these adversaries, *o* is taken as 0.95 in equation (5.6).

Fatigue includes strength loss caused by multiple uses. Since the proposed PDS is to be used once, k is taken as 1.0 in equation (5.6).

Loss is due to conversion of suspension-lines, therefore, the lines conversion factor

$$\cos(\Phi) = 0.9524$$

or, $$1/\cos(\Phi) = 1.05$$

Considering above all factors, a combined allowable strength factor can be worked out from equation (5.6) to yield A_p as 0.7238. Using equation (5.5), the design factor will be 2.21 for non-critical components (SF =1.6) and 2.76 for critical components (SF = 2.0).

Most parachute textiles have an additional built-in safety factor. In general, textile specifications are defined at the minimum strength. Manufacturers, to avoid rejections, thus generally weave the material to possess 5 % to 10% extra of the specification strength. This is to provide an additional margin of safety (West, 1973; Carol *et al.*, 2011; Ewing and Hall, 1971).

5.3.4 Estimation of Load on Parachute Components for Material Selection

The drag force is transferred to the different components of parachute as shown in Figure 3.6. The maximum parachute opening load (maximum parachute drag force) is estimated at the speed of parachute deployment stage. Multiplying the design factor with this load will result in the design load. Based on this load, the textile materials for the components will be selected.

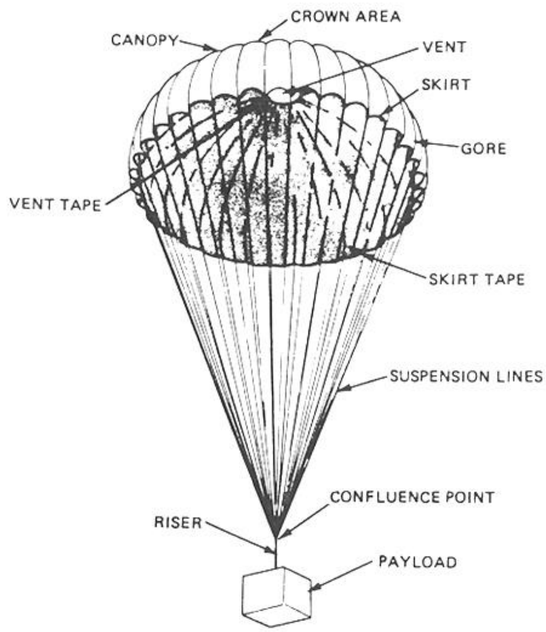


Figure 5.6: Major components of a parachute (Behr and Potvin, 2008)

Taking this maximum parachute drag force (F_D), the requirement on the strength of material for the various components is computed taking the input from the work of Knacke (1992). At each and every stage, chutes and parachutes are to be deployed as a cluster of two parachutes. However, for the design of a parachute at a every stage, it is ensured that even if one of the two chutes/parachute fails, the other should be in a position to bear the complete load and to carry out the intended function safely.

Suspension-lines

Strength of each line = $(F_D / N_S) \times DF$

Canopy fabric

Inflated diameter, D_p = 70 % of D_o

Bulge radius, $r_p = D_p/2$

Dynamic pressure, $q = \frac{1}{2} \rho_{altitude} V^2_{terminal}$

Required strength of the material for canopy = $q\, r_p\, (D.F)$

Radial tapes

Required strength of individual radial tape = Required strength of a suspension-lines

Vent lines

Required strength of a vent lines = Required strength of a suspension-lines

Vent band

Required strength = (10 % of F_D) x DF

Skirt band

Required strength = (5 % of F_D) x DF

Riser

Required strength = (100 % F_D) x DF

5.3.5 Material Selection Criteria

In space application, vacuum will affect the textile material strength due to loss of water from the fabric. This reduces the lubrication between fibres and consequently strength. The material is chosen based on their availability such that they meet the strength required at the minimum mass. An extra 5 % mass is to be added for small size chute and 10 % for the large size parachutes considering the additional materials required for stitching, folding and overlapping.

5.3.6 Parachute Testing and Evaluation

Historically, testing has always been an important part of parachute design. Tests are carried out to evaluate the functionality and performance of the system in simulated environment.

(a) Wind tunnel test

On the scale-down model of the parachutes, wind tunnel test is conducted to study the parachute behavior and performance.

(b) Sequence and deployment

The sequence is very important test carried out at bench test to ensure safe working of the parachute during actual operations. This test is performed on prototype parachute.

(c) Dynamic test

Dynamic test is conducted to simulate the actual performance in dynamic condition using Rail Track Rocket Motor Sled (RTRS) system.

(d) **Flight test**

This test is carried out in the last of series of the tests using an aircraft and helicopter to simulate the terminal speed and sequence of operations of parachute system.

5.4 Design of Parachute Deceleration System

5.4.1 TCS Chute

Top heat shield is jettisoned from the CM at an altitude of 7 km through shearing of the pyro-bolts. Mortar deployed TCS chute carries away the heat shield as shown in Figure 5.7. The ringslot chute is selected to carry away the heat shield as it has 10 % to 15 % higher drag strength than the ribbon chute and provides better stability.

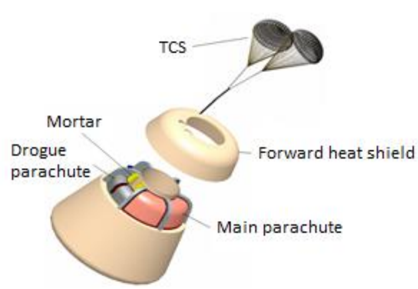


Figure 5.7: Module and forward heat shield separation chutes

Following are the specification parameters (Swadesh *et al.*, 2011) considered for designing of this chute:

i) Type of parachute : Ringslot {20-degree cone angle(μ)}

ii) Nominal drag coefficient (C_D) : 0.56 - 0.65 (Table 5.2)

iii) Initiation altitude : 7.0 km

iv) Density at 7 km (ρ) : 0.5749 kg/m^3

v) Initiation velocity (V) : 155 m/sec

vi) Mass of forward heat shield (m) : 130 kg (including attachments)

vii) Maximum diameter of CM (D) : 3.10 m

viii) Terminal velocity (V_t) : 40 m/s

ix) Inflation time (T_f) : < 2 s

x) The parachute opening load factor (C_x) for ringslot is 1.05 (Table 5.2)

5.4.1.1 Size of Chute

The size of the TCS chute can be obtained using equation (5.3) while neglecting the drag force due to heat shield, i.e.

Weight (payload) = Drag force of chute

or, $$(mg)_{heat\ shield} = ½\, \rho_{altitude} V^2_{terminal}\, C_D S$$

Substituting the values of variables in the above relationship, the following is obtained.

$$130 \text{ x } 9.81 = 0.5 \text{ x } 0.5749 \text{ x } 40^2 \text{ x } 0.56 \text{ x } \pi/4 \text{ x } D_o^2$$

Threfore, the chute nominal diameter, D_0 = 2.50 m

and canopy surface area, (S_o) = ($\pi Do^2/4$)

= 4.91m^2

5.4.1.2 Construction Parameters

Ringslot canopy has high porosity and low opening force. Such a chute is used in high dynamic pressure applications. The size of various components of chute is estimated in terms of canopy diameter as shown in Figure 5.8, and the calculated value given below.

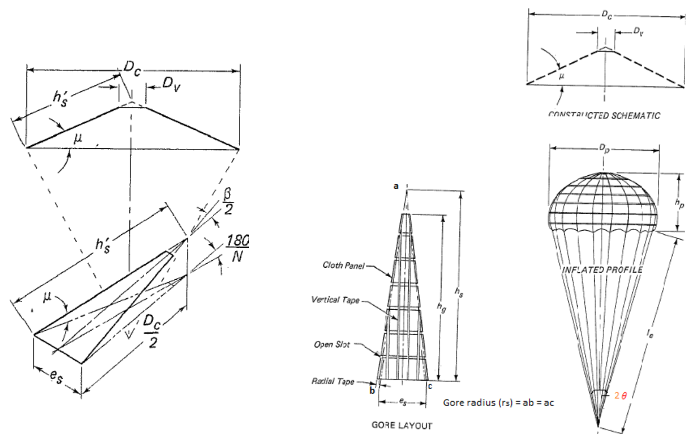


Figure 5.8: Constructional details of ringslot canopy (Knacke, 1992)

i. *Taking number of gores* (N_G) *as 16, Gore area* (S_g)

$$S_g = S_o/16$$

$$= (\pi Do^2/4)/16$$

$$= 4.91/16$$

$$= 0.3068\ \text{m}^2$$

ii. *Gore half angle (β/2)*

Substituting the values

$$\sin(\beta/2) = \cos(\mu)\sin(180/N_G)$$

we get, $\beta/2 = 10.563°$

iii. *Gore radius* (r_s)

Gore area (S_g) = $2[\frac{1}{2} r_s \sin(\beta/2)\, r_s \cos(\beta/2)]$

Substituting the values of variables in the above relationship, we get

$r_s = 1.305$ m

iv. Gore height (h_s)

$$h_s = r_s \cos(\beta/2)$$

$$=1.305 \times \cos 10.563$$

$$= 1.283 \text{ m}$$

v. Gore width (e_s)

$$e_s = 2r_s \sin(\beta/2)$$

Substituting the values of variable fin the above, we get

$$e_s = 2 \times 1.305 \times \sin(10.563)$$

$$= 0.4784 \text{ m}$$

vi. Vent diameter (D_V)

Since it is planned to keep Vent area, S_v, less than 1 % of S_o, then D_v should be less than 10 % of D_o according to Knacke, 1992. Conducting wind tunnel test, a safe Vent diameter was found to be,

D_V = 6.5 % of Do

Substituting the value of parachute nominal diameter in the above relationship,

we get,

$D_v = 0.1625$ m.

vii. Vent width per gore (e_v)

$$e_v = D_v \times \sin(\beta/2)$$

Substituting the value of variables in the above relationship, we get

$e_v = 0.0298$ m

viii. Vent height (h_v)

$$h_v = r_v \cos(\beta/2)$$

Substituting the value of variables in the above relationship, we get

$$h_v = 0.08 \text{ m}$$

ix. Ring grid height (h_g)

$$h_g = h_s - h_v$$

Substituting the value of variables in the above relationship, we get

$$h_g = 1.283 - 0.08$$

$$= 1.203 \text{ m}$$

x. Number of suspension-lines (N_r)

N_r = number of gores

= 16

xi. Length of suspension-lines (L_e)

Taking $L_e/D_O = 1.2$

Thus, $L_e = 3$ m

xii. Length of riser (L_r)

Length of riser = wake length - distance of canopy skirt from confluence of suspension - lines

Taking wake length as five times of the maximum diameter of the forebody (Knacke, 1992)

$$L_r = 5Do - L_e \cos(\theta)$$

$$= 5 \times 3.1 - 3 \cos(16.98)$$

$$= 12.63 \text{ m}$$

where, θ is the angle between the suspension-lines and the vertical axis (Figure 5.8). Therefore,

$$sin(\theta) = ½ D_p/L_e$$

$$= 0.5 \times (2.5 \times 0.7) / 3$$

$$= 16.98^0$$

5.4.1.3 Design Load and Inflation Time

When chute is fully air-filled, it exerts an instant opening shock force. This force, given by equation (5.2), is for an opening load factor (C_x) as 1.05 (Table 5.2), and is

$$F_D = ½ \rho V^2 C_D S C_x$$

$$= 0.5 \times 0.5749 \times 155^2 \times (0.65 \times \pi/4 \times 2.5^2) \times 1.05$$

$$= 23136.53 \text{ N}$$

The canopy starts inflating after the complete stretching of the chute. Mohaghegh and Jahannama (2007) have formulated the canopy filling time as a function of canopy nominal diameter (D_o), velocity after stretch (V) and a filling time index (n) of the chute as given by equation (5.4). Taking n as 14 from Table 5.3 for ribbon parachute with unreefed opening, the filling time will be,

$$T_f = \frac{n D_o}{V}$$

Substituting the values of variables in the above relationship, we get,

$$T_f = 14 \times 2.50/155$$

$$= 0.226 \text{ sec}$$

5.4.1.4 Material Selection and Mass Calculation

Ewing et al. (1978) provide excellent description of the materials used for fabricating all classes of parachutes systems. Pointer (1991) and John (2015) have described the type, nomenclature, strength, and common usage and essentials of modern materials used in today's parachute systems and have also listed most of the specifications that could be used for parachute canopy design. Nylon is the predominant fabric used in the manufacturing of the parachutes. There are many different kinds of nylon and are mainly differentiated based on weave, weight, and finish. The most common uses of suspension-lines materials are nylon or Kevlar cordage because of its inherent strength and relative elasticity. Tapes are used as support and for reinforcing canopies and containers. Since the material used for space mission should be lighter, the material for the tape should be taken as nylon 6 or nylon 66. The webbing is used for load bearing purposes, such as in harness and riser. The materials chosen for the components should have requisite strength to bear the parachute forces. The maximum design force is multiplied by the design factor to determine the maximum design load (L) $= F_D \times DF$

Substituting the values of variables in the above relationship, we get,

$$L_c = 23136.53 \times 2.76 = 63857 \text{ N} \quad \text{for all critical components}$$

$$L_{nc} = 23136.53 \times 2.21 = 51132 \text{ N} \quad \text{for non-critical components}$$

Based on these loads, the loads on the individual components are estimated with the details provided in Section 5.3.4.

(i) Canopy fabric

Inflated diameter (D_p) = 70 % of D_o

= 1.75 m

Bulge radius (r_p) = $D_p/2$

= 0.875 m

Dynamic pressure (q) = $\frac{1}{2} \rho V^2$

= 6906 N/m^2

Required strength of canopy = q r_p

= 6043 N/m

= 302 N/5 cm

Design load (L) = 302 x (D.F = 2.21)

= 668 N/5 cm

Based on this design load and the application for, the material isselected as fabric nylon 93 gsm, 1275 N/5cm, Breaking Strength (BS) with material porocity as 16 %.

Mass calculation

Mass of the canopy = S_o (1- percentage porosity) x mass density

= 4.91 x (1- 0.16) x 0.093

= 0.384 kg

Margin of Safety (MoS) = 100 x (1275 - 668)/668

= 91 %

(ii) Suspension-lines

As calculated earlier, the length of suspension-lines is3m and number of lines are 16.

Required strength of each lines = L_{nc}/N_S

= 51132/ 16

= 3196 N

The materials are selected based on the required strength for the suspension-lines. The chosen material for the designed suspension-lines as cordage para-aramid, 3924 N with mass as 4 g/m.

Mass calculation

The total mass of the suspension-lines = 16 x 3 x 0.004

= 0.192 kg

Margin of Safety (MoS) = 100 x (3924 - 3196)/3196

= 23 %

(iii) Radial tapes

Required strength of individual radial tape = Required strength of a suspension-lines

= 3196 N

Based on required strength, the material chosen for the tapes is para-aramid tape of 21 mm width (BS as 2943 N, 2 layers of tapes, and 16 numbers) with mass as 4 g/m.

Mass calculation

Length of the radial tape is $D_o/2$ = 1.25 m.

Total mass of the radial tapes = 1.25 x 16 x (0.004 x 2)

= 0.16 kg

Margin of Safety (MoS) = 100 x (2943 x 2-3196)/3196

= 84 %

(iv) Vent lines

Required strength of vent lines = Strength of suspension-lines

= 3196 N

Margin of safety (MoS) =100 x (3924 - 3196)/3196

= 23 %

The material chosen is cordage para-aramid, 3924 N, 8 lines with mass as 4 g/m. Length is taken as 90 % of Vent diameter (i.e., 0.1625 m) determined already. Including 10 cm of stitching length, the Vent-lines length will be 0.25 m. This information will be used in overall mass calculation.

Mass calculation

Total mass of the vent lines = 8 x 0.25 x 0.004

= 0.008 kg

Margin of safety (MoS) =100 x (3924 -3196)/3196 = 23 %

(iv) Vent band

Required strength = 10 % of L_{nc}

= 0.1 x 51132

= 5113.20 N

Based on the required strength, the material selected s tape para-aramid 26 mm width, with strength as 5886 N and mass as 8 g/m.

Mass calculation

Total mass of the Vend band = Vent band length (л D_v) x mass per unit length

= 0.51 x 0.008

= 0.0041 kg

Margin of Safety (MoS) =100 x (5886-5113.20)/5113.20

= 15 %

(vi) Skirt band

Strength required = 5% of Maximum design load (L_{nc})

= 2557 N

Chosen material as tape para-aramid, 2943 N, 21mm width with mass as 5 g/m.

Margin of safety (MoS) = 100 x (2943 - 2557)/2557

= 15 %

Mass calculation

Total mass of the skirt band = π x D_o x 0.005

= 0.04 kg

(vii) Riser

Required strength of the material to be used same as that for canopy to be bear the designed load of 63857 N. Therefore, material chosen for the riser is as webbing para-aramid, 88290 N, 44 mm width with mass as 84 g/m. Thus,

Margin of Safety (MoS) =100 x (88290-63857)/63857

= 38 %

Mass calculation

Total mass of the riser = Length of riser (12.63m) x mass per unit length

= 12.63 x 0.084 = 1.1 kg

The summary of the selected materials is provided in Table 5.4.

Table 5.4: List of materials selected for the TCS chute

Component	**Sub-component**	**Required strength**	**Material**	**Material strength**	**MoS (%)**	**Mass (kg)**
Canopy	Canopy fabric	668 N/5cm	Fabric nylon 93 gsm	1275 N	91 %	0.384
	Suspension-lines	3196 N	Cordage para-aramid	3924 N	23 %	0.192
	Radial tape	3196 N	Tape para-aramid 21 mm, 2 layers	2943 N	84 %	0.160
	Vent lines	3196 N	Cordage para-aramid	3924 N	23 %	0.008
	Vent band	5113.20 N	Tape para-aramid 26 mm	5886 N	15 %	0.004

	Skirt band	2557 N	Tape para-aramid 21 mm, 2 layers	2943 N	15 %	0.040
Riser	-	63857 N	Webbing Kevlar 44 mm	88290 N	38 %	1.100
						Total mass = 1.888 kg

Adding extra 5% mass considering overlap, threads and folding, etc. Total mass = 2 kg

5.4.2 Pilot Chute

The pilot chutes are used to deploy the large parachute. The pilot chute is initiated immediately after the forward heat shield is separated from the CM. The triggering of the pilot chutes will take place due to the activation of the mortar, which will deploy the pilot chutes in different directions to avoid the entanglement of canopies. The inflated pilot chutes pull pack-cover bag of the drogue parachute. The ringslot type chute is chosen for such an application that allows the deployment at high dynamic pressure. The following design inputs are considered for the design of the pilot chutes.

Density at 7 km (ρ) = 0.5749 kg/m^3, off-nominal initiation altitude

Mass of drogue parachutes (m) = 18 kg (maximum, given)

C_D of the pilot chute = 0.56 - 0.65 (Table 5.2)

Using the present philosophy, the pilot chute is supposed to generate an extraction force that must be at least equal to ten times of the weight of the drogue parachute assembly to be extracted. Having 10% margin and taking deployment velocity as 75 m/s for the pad abort, the size of the pilot chute can be determined from the following:

$$\rho_{7km} V^2 C_D S = 1.1 \text{ x } 10\ m_{drogue}\, g$$

Substituting the values of variables in the above relationship, we get,

$$\frac{1}{2} \times 0.5749 \times 75^2 \times 0.56 \times \pi/4 \times D_o^2 \geq 10 \times 18 \times 1.1 \times 9.81$$

Thus, $D_o \geq 1.65$ m

The above calculation shows that the pilot chute diameter can be taken as 1.65 m. Thus, it will be at variance from the TCS chute diameter value as 2.50 m. Choosing higher diameter for the pilot chute, upto that for the TCS chute, will have the following advantages:

i) Reduction in qualification tests and better performance

ii) Reduction in additional inventories

iii) Overall cost saving

Therefore, the diameter of pilot chute is taken as 2.50 m, being the same as that for the TCS chute. Naturally, pilot chute becomes identical to TCS chute.

5.4.2.1 Dynamic Test

The dynamic test on either of TCS and pilot chutes (chosen to be the same) are carried out under simulated dynamic pressure. The chutes are designed for infinite mass case, but the test is to be carried out on ground track for finite mass case. Therefore, the chute deployment velocity has to be converted from the infinite case to the finite case.

Dynamic load at 7 km altitude = Dynamic load at ground track

or, $$\frac{1}{2}\rho\, v^2 \text{ (ground)} = \frac{1}{2}\, \rho\, v^2 \text{ (7 km)}$$

Substituting the values of variables in the above relationship, we can determine the velocity for the finite case.

$$\frac{1}{2} \times 1.2256 \times V^2 = \frac{1}{2} \times 0.5749 \times 155^2$$

or, $V = 106$ m/s

Therefore, the equivalent lines stretch velocity (*V*) of chute at the ground is taken as 106 m/s for performing the ground test.

The observed load profiles from the dynamic test are shown in Figure 5.9 and Figure 5.10.

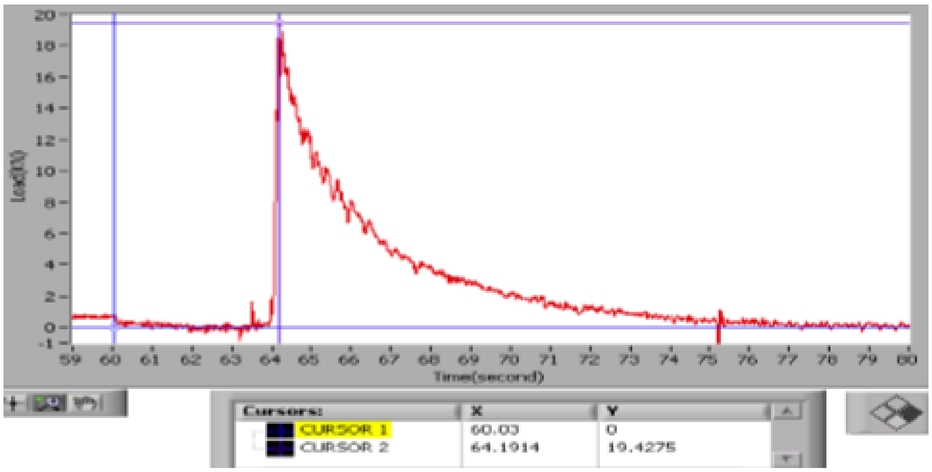


Figure 5.9: Load profile of single chute at a speed of 106 m/s

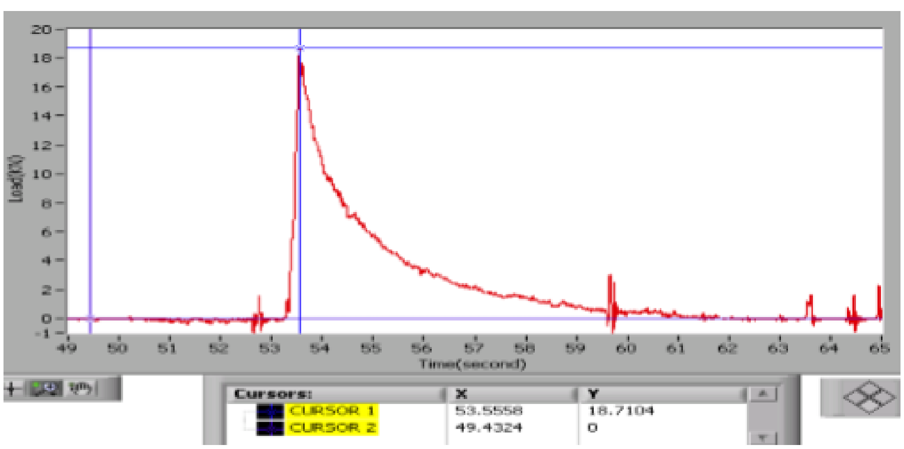


Figure 5.10: Load profile of cluster of two chutes at a speed of 106 m/s

The other test results are presented in Table 5.5. This table shows that the designed parameters for the TCS and pilot chutes are good enough and have more than sufficient margin either to bear additional load or towards deceleration for safe landing.

Table 5.5: Summary of dynamic test results

Number of chutes	**Design value *L*, (kN)**	**Deceleration at chute deployment (*g*)**	**Expected load in application F_D, (kN)**	**Achieved value F_D, (kN)**	**Achieved deceleration (*g*)**
Single	63.857	< 6	23.14	19.43	2.91
Cluster of two	63.857	< 6	23.14	18.71 & 21.86	3.09 & 3.89

5.4.3 Drogue Parachute: First Stage Decelerator

The first phase deceleration in the form of controlled descent is facilitated by drogue parachute(s). The selection and design of the canopy of the drogue parachute is important for payload stabilization and deceleration. A parafoil type canopy is suggested by Alessandro *et al.* (2017) for such an application. But it is ruled out due to error in landing accuracy. A single reefed drogue parachute or a cluster of two drogue parachutes can be chosen for payload stabilization as well as deceleration in space recovery payload. But later is preferred due to better stabilization characteristics and lower terminal speed. Conical ribbon parachute was used in SRE-I and performed very well in subsonic conditions (Mach 0.36). Therefore, 20-degree conical ribbon type parachute was selected for the drogue. The drogue parachute is deployed by the pilot chute (Figure 5.11). The drogue parachute brings the CM from an altitude of 7 km to the 3 km and then gets disconnected from the CM using pyro-release units. Before disconnection, the drogue parachute pulls out the main parachute pack. While pulling out the main parachute, during unfurling of riser-suspension lines length, the payload is supposed to free fall and hence descent rate increases significant. Therefore, design of main parachute is carried out at higher velocity than drogue terminal speed. This enhanced speed is estimated using trajectory analysis.

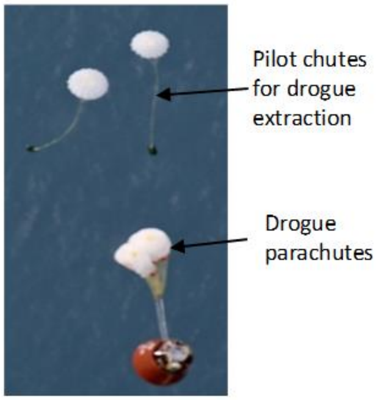


Figure 5.11: Pilot chute and drogue parachute in deployed condition

The following design inputs reconsidered for the design of drogue parachute:

(i) At the initiation of the parachute deployment (7 km)

Air density (ρ)	: 0.5749 kg/m^3
Parachute deployment speed (V_i)	: 155 m/s

(ii) At the termination (3 km)

Air density (ρ)	: 0.873 kg/m^3
Parachute terminal speed (V_f)	: 70 m/s

(iii) Other input

Mass of CM	: 3370 kg (Excluding mass of forward heat shield)
C_D of drogue parachute	: 0.50-055 (Table 5.2)
C_D of CM	: 0.626 (given)
Maximum diameter (D) of CM	: 3.1 m
Inflation time	: < 2 s

5.4.3.1 Checking for the Applicability of Infinite/Finite Mass Inflation

Mass ratio (R_m), as suggested by Knack (1992) is calculated below.

$$R_m = \frac{\rho(C_D S)^{1.5}}{AUW}$$

$$= \frac{0.5749 \, x \, (0.50 \, x \, 0.9 \, x \, 21.57)^{1.5}}{3370}$$

$$= 0.0052$$

If R_m is less than or equal to 0.50, then inflation is considered to be out of infinite mass inflation, and typical finite mass inflation otherwise. Since $R_m < 0.5$, it is a case of infinite mass inflation. Therefore, the opening shock has to be calculated based on infinite mass condition.

5.4.3.2 Size of Parachute

Size of the drogue parachute can be obtained by balancing the forces in vertical direction during the terminal phase using equation (5.6) given below.

$$(m_{CM} - m_{pilot\_chute})g = ½ \, \rho_{3km} \, V_t^2 (C_d S)_{parachute} + ½ \, \rho_{3km} \, V_t^2 (C_d S)_{CM} \qquad (5.6)$$

Substituting the known and / or determined values for the variables in the above relationship, we get,

(3370 - 2) x 9.81= ½ x 0.873 x 70^2 x (0.50 x π/4 x D_o^2) + ½ x 0.873 x 70^2 x (0.626 x π/4 x 3.1^2)

Thus, Parachute nominal diameter, D_0 = 5.24 m

and Canopy surface area,

$$S_o = ¼ \, \pi \, D_o^2$$

$$= 21.57 \text{ m}^2$$

Terminal velocity with cluster of two parachutes

At the terminal speed, the sum of the forces in vertical direction is given by equation (5.7).

$$mg = (F_D)_{\text{parachute}} + (F_D)_{\text{CM}}$$

(Mass of CM - Mass of chutes) $g = (\eta_c\, n_c \frac{1}{2}\, \rho_{3km} V_t^2 C_D S)_{\text{parachute}} + (\frac{1}{2} \rho_{3km} V_t^2 C_D S)_{\text{CM}}$ (5.7)

Considering the parachute cluster efficiency, η_c as 0.90 (Knacke, 1992), and number of parachutes in cluster, n_c as 2.

Substituting the known and/or determined values for the variables in the above relationship, we get,

$(3370 - 2.0) \times 9.81 = (0.9 \times 2 \times \frac{1}{2} \times 0.873 \times V_t^2 \times 0.50 \times \pi/4 \times 5.24^2) + (\frac{1}{2} \times 0.873 \times V_t^2 \times 0.626 \times \pi/4 \times 3.1^2)$

Therefore, the terminal velocity with cluster of two parachutes,

$V_t = 56$ m/s.

5.4.3.3 Constructional Details of Parachute

The constructional details of a 20-degree conical ribbon parachute (Figure 5.12) are estimated using the following relationship.

$h_g = [S_o/(N \tan(\beta/2))]^{1/2}$

$e_s = 2\, h_g \tan(\beta/2)$

$\beta = 2 \sin^{-1}[(\sin 180/N) \cos(\mu)$

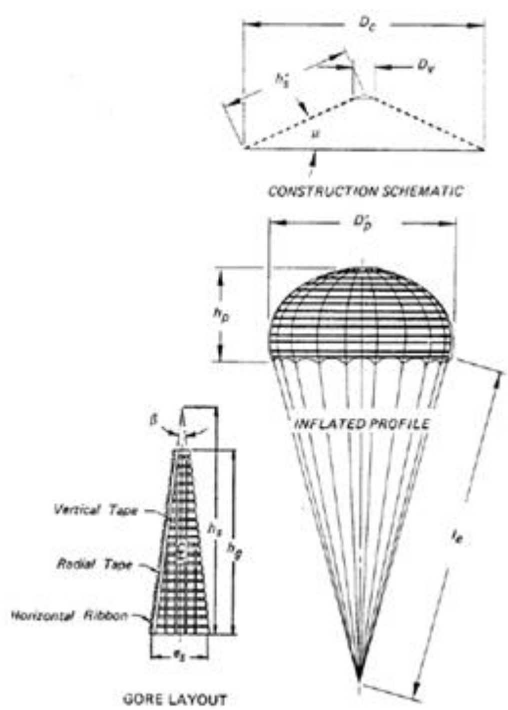


Figure 5.12: Constructional details of conical ribbon drogue parachute

According to Knacke (1992), S_v < 0.001 S_o and L_e/D_o = 1.00 to 2.0. Based on these considerations, the constructional details of the parachute have been worked out. The various constructional are worked out and are as given below.

(i) Number of gores (N_G) is taken as 24.

(ii) Gore area (S_g)

$$S_g = S_o/N_G$$

Thus, $S_g = 21.57 /24$

$= 0.899 \text{ m}^2$

(iii) Gore half angle ($\beta/2$)

It is determined using the following relationship

$$\sin(\beta/2) = \cos(\mu)\sin(180/N_G)$$

Thus, $\beta/2 = 6.794^{o}$

(iv) Gore radius (r_s)

$$S_g = 2[\tfrac{1}{2} r_s \sin(\beta/2)\, r_s \cos(\beta/2)]$$

Substituting the values of variables in the above relationship, we get

$$r_s = 2.766 \text{ m}$$

(v) Gore height (h_s) = $r_s \cos(\beta/2)$

$= 2.747$ m

(vi) Gore width (e_s)

$$e_s = 2\, r_s \sin(\beta/2)$$
$$= 2 \times 2.766 \sin(6.794)$$
$$= 0.654 \text{ m}$$

(vii) Vent diameter (D_v)

Based on wind tunnel test, D_v is taken as 6.5 % of D_o, which gives vent diameter as

$D_v = 0.065 \times 5.24$

$= 0.34$ m

Taking Vent lines length as 90% of the vent diameter (D_v)

Vent lines length = 0.9 x Vent diameter

= 0.306 m

(viii) Vent width per gore (e_s)

$e_v = 2\, r_v \sin(\beta/2)$

$= 0.654$ m

(ix)Vent height (h_v)

$h_V = r_v \cos(\beta/2)$

$= 0.169$ m

(x) Ring- grid height (h_g)

$h_g = h_s - h_v$

$= 2.747 - 0.169$

$= 2.58$ m

(xi) Number of suspension-lines (N_r)

N_r = Number of gores

= 24

(xii) Length of suspension-lines (L_e)

Since, $L_e/D_O = 1.2$

thus, $L_e = 1.2 \times 5.24$

$= 6.288$ m

(xiii) Length of riser (L_r)

The angle between the suspension-lines and the vertical axis is θ (Figure 5.8). It can be calculated as,

$$\sin(\theta) = 0.5 \times 5.24 \times 0.7/6.288$$

Thus, $\theta = 16.96^0$

Length of riser = Wake length - distance of canopy skirt from the confluence of suspension-lines

Taking wake length as five times of the diameter of CM (3.1 m),

$$L_r = 5 \times 3.1 - L_e \cos(\theta),$$

or $$L_r = 5 \times 3.1 - 6.288 \cos(16.96)$$

$$= 9.50 \text{ m}$$

5.4.3.4 Design Force and Inflation Time

The drogue parachute is deployed after the pilot chute. Therefore, the opening speed of the drogue parachutes would be less than 155 m/s. However, for a better safety, the worst case is considered. Hence the speed is taken to be the same as at the time of pilot chute deployment. Thus, the opening force (infinite mass case) on a single drogue parachute for equation (5.2) will be

$$F_D = ½ \rho V^2 (C_D S)_p C_x$$

$$= ½ \times 0.5749 \times 155^2 \text{x}(0.55 \times \pi/4 \times 5.24^2) \times (1.05)$$

$$= 86006 \text{ N}$$

Canopy inflation time

The canopy starts inflating after the complete stretching of the parachute. Therefore, the canopy filling time is a function of canopy nominal diameter (D_o), velocity after stretch (V) and a filling time index (n_{fill}) of the parachute. From equation (5.4),

$$T_f = 14 \times 5.24/155 = 0.473 \text{ sec}$$

5.4.3.5 Peak Deceleration

The peak deceleration of the parachute is limited to 6g according to the payload structural requirements. The drogue parachute is designed while considering single parachute operation so that it can decelerate the CM to the required terminal speed. The CM will experience maximum peak deceleration when both the parachutes are inflated simultaneously. The peak deceleration is estimated using force-time-trajectory method and is found to be 4.82g (< 6g) with a cluster of two parachutes opening. The complete profile is shown in Figure 5.13.

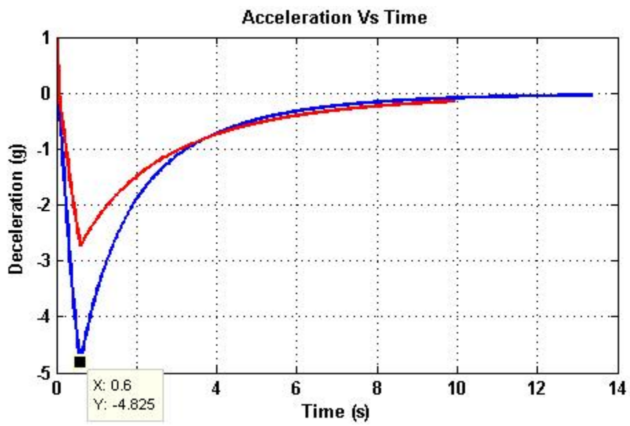


Figure 5.13: Peak deceleration of drogue parachute

5.4.3.6 Material Selection for Components

The materials for the various components of the drogue parachute are to be selected based on the design load given as

$$L_c = F_D \times DF$$

$= 86006 \times 2.76$ for critical components

$= 237377$ N

and $L_{nc} = 86006 \times 2.21$ for non-critical components

$= 190074$ N

The loads on the components are determined using the methodology of Section 5.3.4. Based on the loads on the components, the materials are selected with details as given below.

(a) Canopy

(i) Horizontal ribbon

Taking inflated diameter (D_p) of parachute as 70 % of D_o.

` Thus, $D_p = 3.668$ m

Bulge radius (r_p) = $D_p/2$

= 1.834 m

Dynamic Pressure $q = ½ \rho V^2$

= 6906 N/m^2

Required strength of canopy material = $q\ r_p$

= 12666 N/m

or, = 634 N/5 cm

Design Load (L) = 634 x (DF = 2.21)

= 1400 N/5 cm

Selecting the material for the horizontal ribbon is nylon 1962 N/5cm, webbing 50 mm width with mass as 15 g/m.

The effective length of the horizontal tape is as given below.

Since conical ribbon parachute is made of slotted ribbons, hence the solid surface area of the canopy is 84 % (Knacke, 1992) of the nominal surface (S_o).

Therefore, area of canopy = 0.84 x 21.57

= 18.12 m^2

Since the width of tape is 50 mm therefore, effective length of tape is 18.12/0.005 $\underset{\sim}{}$ 363 m

Component Mass = 363 x 0.015

= 5.445 kg

Margin of safety (MoS) = 100 x (1962-1400)/1400

= 40 %

(ii) Suspension-lines

Required strength on one suspension-lines is calculated by using

L_{nc}/N_S = 190074/ 24 = 7920 N

Material selection

Based on required strength, the material selected as tape para-aramid, 15696 N, 25 mm width with mass as 20 g/m.

Mass calculation

The length of one suspension-line is 6.288 m. Therefore, mass of suspension-lines is calculated as given below.

Mass of suspension-lines = Number of lines x length of lines x mass per unit length

= 24 x 6.288 x 0.02

= 3.02 kg

Thus, Margin of safety (MoS) = 100 x (15696-7920)/7920

= 98 %

(iii) Radial tapes

Required strength = (80 % of suspension-lines load)

= 0.8 x 7920

= 7128 N

Thus, Margin of safety (MoS) = 100 x (15696 -7128)/7128

= 120 %

Material selection

Material selected for tadial tape is tape para-aramid, 15696 N, 25 mm width, 24 numbers with mass as 20 g/m.

Mass calculation

Length of the radial tape (h_g) = 2.58 m

Mass of the radial tapes = 2.58 x 24 x 0.02

= 1.24 kg

(iv) Vent lines

Required strength = strength of suspension-lines

= 7920 N

Thus, Margin of safety (MoS) = 100 x (15696-7920)/7920

= 98 %

Material selection

Material selected as tape para-aramid, 15696 N, 25 mm width, 12 nos. with mass as 20 g/m.

Mass calculation

Vent lines length = 0.306 m

Total mass of the vent lines = 12 x 0.306 x 0.02

= 0.074 kg

(v) Vent band

Required strength of material is to be estimated as

Design load (L) = 237377 N

Load component on Vend band tape (F_{VB}) = $L_c/[2N_r \sin(360/N_r)]$

= 237377/(2 x 24 x sin (360/24))

= 19108 N

Thus, Margin of Safety (with layering factor of 0.8) = 100 x (26487x 0.8 x 2-19108)/19108

= 122 %

Material selection

The selected material is tape para-aramid, 26487 N, 25.4 mm width, in two layers with mass as 35 g/m.

Mass calculation

For Vent diameter (D_V) of 0.34 m, the mass of Vent band can be calculated as,

Total mass of the Vend band = π x D_V x 0.035 x 2

= 0.075 kg

(v) Skirt band

Strength required = 5 % of maximum design load (L_{nc})

= 9504 N

Thus, Margin of safety (MoS) = 100 x (26487- 9504)/9504

= 178 %

Material selection

The material is selected as tape para-aramid,25.4 mm width, 26487 N with mass as 35 g/m.

Mass calculation

Total mass of the skirt band = π x 5.24 x 0.035

= 0.58 kg

(viii) Riser

The drogue riser is a critical element which connects the parachute to the CM. It is to be designed on the maximum load generated by the parachute.

Thus, required strength of material = 237377 N

and,

Margin of Safety (with layering factor of 0.8) = 100 x (88290 x 0.8 x 7-237377)/237377

= 108 %

Material selection

Based on required strength, the material is selected as webbing para-aramid, 44 mm width, 4 mm thickness; Breaking Strength (BS) is 88290 N, in 7 layers with mass as 84 g/m.

Mass calculation

Length of riser = 9.50 m

Mass of the riser = 9.5 x 0.084 x 7

= 5.59 kg

Based on the required strength of the components, the materials are chosen and the summary of the same is presented in Table 5.6.

Table 5.6: Component's mass, materials and MoS for the drogue parachute

Component	**Required strength**	**Material**	**Strength**	**MoS %**	**Mass (kg)**
Horizontal Ribbon	1400 N/5cm	Nylon ribbon 50 mm	1962 N/5 cm	40	5.445
Suspension-lines	7920 N	25mm, tape para-aramid	15696 N	98	3.020
Radial Tape	7128 N	25mm, tape para-aramid	15696 N	120	1.240
Vent lines	7920 N	25 mm, tape para-aramid	15696 N	98	0.074
Vent band	19108 N	25.4mm tape para-aramid (2 layers)	26487 N	122	0.075
Skirt band	9504 N	25.4mm tape para-aramid	26487 N	178	0.580
-	237377 N	Webbing Kevlar 44 mm, 07 layers	88290 N	108	5.590
					Total mass = 16.024 kg

Considering additional 10 % of mass of stitching, folding and overlap of materials, the total mass of the system is 18 kg.

5.4.3.7 *Design Validation*

The design is validated using wind tunnel test and dynamic test. The details are provided below.

(i) Wind tunnel test

Each forebody produces a wake that affects the performance of the parachute. The wake distance depends upon the relationship of the inflated parachute diameter 'D_p' to forebody diameter 'D' and the distance between the end of the forebody and the leading edge of the inflated parachute canopy (Peterson and Jonson, 2012). The detailed analysis on parachute wind tunnel model tests have been carried out by McVey *et al.* (2012) and Macha (2012). They found that the lengths of the riser and the lines have to be five to six times of the maximum diameter of CM for the safe parachute deployment. At the same time, the distance between the leading edge of the parachute and the rear of the CM is kept to a minimum to save weight. Hence, the length of the riser is very important for the safe deployment in free air stream. For this, an investigation has been carried using wind model test (Figure 5.14) to establish the size of riser. It is found to be five times of forebody in the case of cluster of two drogue parachutes.

(a)

(b)

Figure 5.14: Wind tunnel test setup (a) single parachute with and without FB (b) a cluster of two parachutes with and without FB

Wind tunnel test finds the single drogue parachute to have C_D in the range (0.50, 0.55). The cluster of two drogue parachutes results a C_D value in the range of (0.52, 0.56). In both of the case, C_D value is found to be satisfactory as it meets the design criteria on C_D to have value in the range (0.50, 0.55). Rather, the cluster of two parachutes is preferred.

5.4.3.8 Dynamic Test of Drogue Parachute with Pilot Chute and CM

To assess the structural integrity and dynamic loads, the dynamic test was performed with the pilot chute, drogue parachute and CM. The detail of the dynamic test setup is shown in Figure 5.15. The summary of test results is presented in Table 5.7.

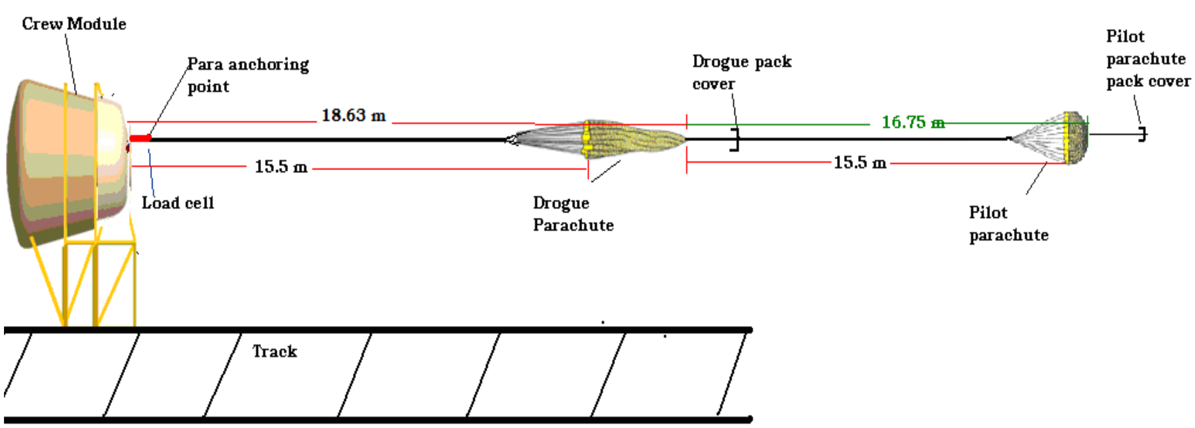


Figure 5.15: Deployment of pilot and drogue parachute behind the CM in track test

Table 5.7: Track test results of pilot chute and drogue parachute with CM

Sl. No.	**Planned speed (m/s)**	**Measured speed (m/s)**	**Estimated Load (kN)**	**Measured Force (kN)**
1.	112	108.70	86.00	89.49
2.	112	119.10	86.00	94.76

Since the measured force is less than the design load even at a speed higher than the planned speed of 112 m/s, the specifications worked out seems to be good for satisfactory operation.

5.4.3.9 Overload Test of Drogue Parachute in Dynamic Condition

The overload test is carried out to check the parachute structural integrity and sequence of operation at a high speed. Test, with the configuration used in Section 5.4.3.8 was conducted with Sled velocity at mortar firing: 147 m/s (at 3.95 s) and sled velocity on parachute lines stretch: 143.3 m/s (at 4.45 s).

The peak load during filling of the drogue parachute was found to be 142.9 kN as shown in Figure 5.16. The summary of test results is given in Table 5.8.

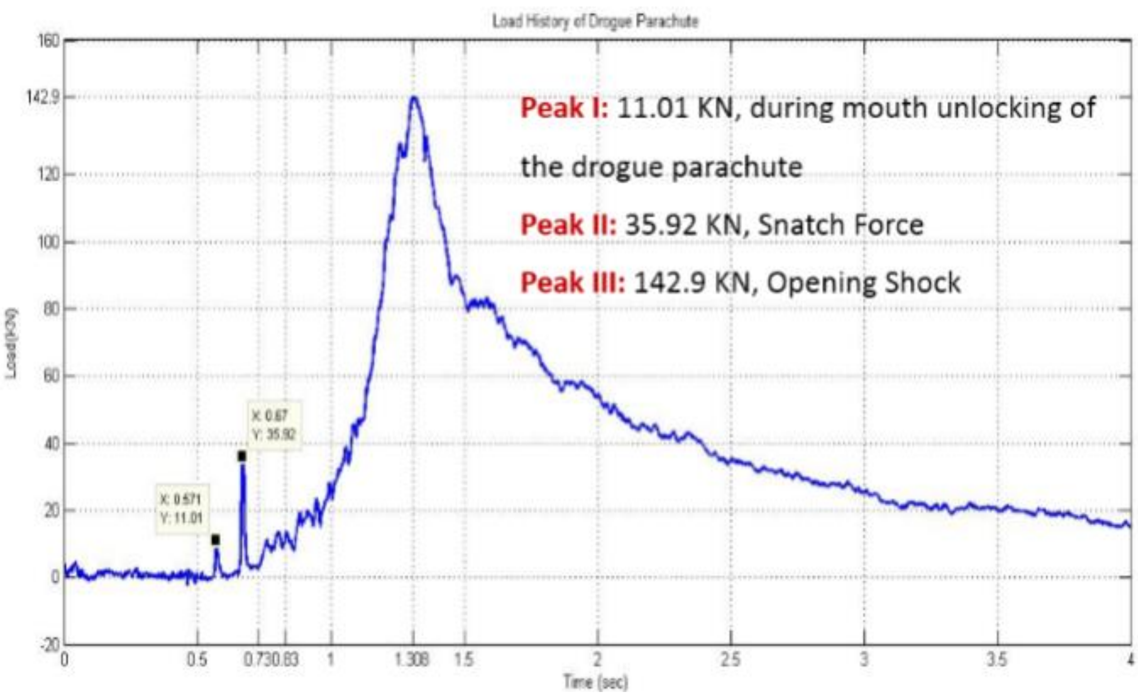


Figure 5.16: Measured load profile of drogue parachute

Table 5.8: Comparison of planned and achieved performance parameters of drogue parachute

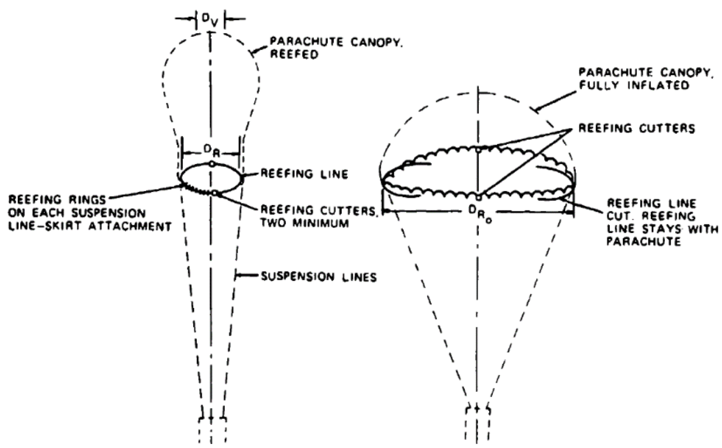
S. No.	Parameter	Planned value	Achieved value
1	Speed at parachute stretch	142 m/s	143.50 m/s
2	Deployment time	0.517 s	0.511 s
3	Opening Shock force	140 kN	142.90 kN

The above table shows that the drogue could bear more force and speed than their targeted values. With the deployment time also being less, it can be concluded that a cluster of two conical ribbon parachutes is most suitable for first stage deceleration of CM.

5.4.4 Main Parachute: Second Stage Decelerator

The main parachute system consists of two main parachutes, each with pack cover, attachment fitting (adapters) and separate risers. The main parachute is attached to the CM by riser's loop that suspends the CM from point located at the top of the forward compartment gussets. The system used two drogue parachutes for deployment as discussed above. As the drogue parachute pulls the main parachute's pack away from the CM, the main parachute is extracted from the pack-cover in orderly manner beginning with the connector link, followed by the suspension-lines, and canopy. The main parachute has one stage reefed canopy and to be deployed at 3 km altitude.

The main parachute must have better stability, less angle of oscillation, minimum opening shock force and less drift so that CM lands at the desired site. Each main parachute is independently deployed by the drogue parachute. The main parachute opens in sequence of reefed and disreefed states as shown in Figure 5.17. The reefing delay of 4 second is provided to reefing lines-cutter to reduce the opening shock force and permits the incremental opening of parachute canopy. In general, reefing and disreefing of parachute causes the load profile as shown in Figure 5.18.



(a) Reefing-line in reefed state (b) Reefing-line in disreefed state

Figure 3.17: Main parachute with reefed and disreefed in deployed conditions (Stephen *et.al.*, 2004)

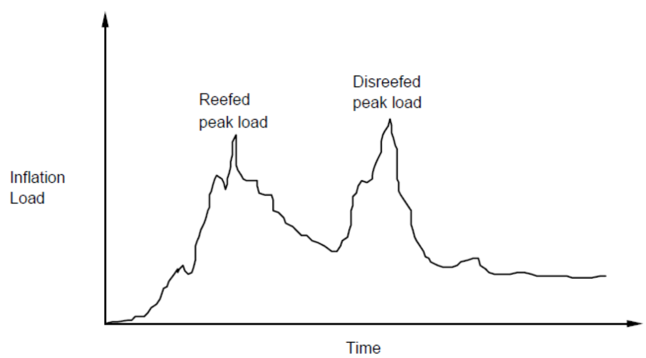


Figure 5.18: Typical inflation load vs time profile of reefed and disreefed parachute (www.BRSaerospace.com)

5.4.4.1 Design Specification

The following inputs have been taken for the design of the main parachutes.

CM (AUW)	: 3370 kg
Mass of pilot chute	: 2 kg each
Mass of drogue parachute	: 18 kg

Nominal C_D of CM	: 0.63
Parachute type	: Solid circular slotted
Parachute nominal C_D	: 0.75 (Knacke, 1992)
Terminal altitude	: Sea level
Air density at sea level	: 1.169 kg/m^3
Terminal velocity	: < 10 m/s, with single main parachute
Inflation time	: < 2 sec
Reefed interval time	: 4 sec
Inflation Speed	: 80 m/s

5.4.4.2 Size of Parachute

(i) Canopy diameter

The canopy size can be obtained by balancing the forces in vertical direction at the terminal speed as given by equation (5.7).

$$mg = (F_D)_{parachute} + (F_D)_{CM}$$

(Mass of CM – Mass of pilot chute – Mass of drogue parachute) g

$$= \{1/2\ \rho_{msl} V_t^2 (C_d\, S_o)_{parachute}\} + \{1/2\ \rho_{msl} V_t^2 (C_d\, S_o)_{CM}\}$$

Substituting the known values in the above relationship, we get,

$$(3370 - 2 - 18) \times 9.81 = ½ \times 1.169 \times 10^2 \times (0.75 \times \pi/4 \times D_o^2) + ½ \times 1.169 \times 10^2 \times (0.626 \times \pi/4 \times 3.1^2)$$

or, Size of main parachute (D_0) = 31 m

Therefore, canopy surface area $(S_o) = \pi/4\ D_o^2$

$= 754.77$ m^2

(ii) Parachute reefed diameter and reefing-line length

Parachute reefing permits the incremental opening of a parachute canopy and restrains the canopy from full inflation or over inflation. A mid gore reefing at the skirt of the parachute is worked out, in which the reefing rings are stitched to the skirt of the parachute in the center of each gore. This increases the restraining points and thus causes less flutter of the non-inflated parts of the reefed parachute canopy. The reefing-line is guided through the reefing rings and several reefing-line cutters. Each cutter contains a pyro-time train and a cutter knife (Pepper, 1973) and is initiated at canopy stretch by pull-cords attached to the suspension-lines. At a preselected time, the cutter fires and the knife sever the reefing lines, allowing the parachute canopy to disreefed and open fully. A skirt reefing scheme is illustrated in Figure 5.19.

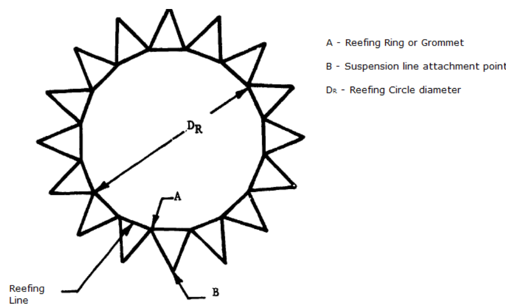


Figure 5.19: Reefing arrangement in canopy for reefing-line

The length of the reefing lines is determined by the required reduction in parachute drag area. Reefing-lines ratio (D_R/D_0) is to be taken for reefing lines length calculation. This value corresponding to 8% of reefing ratio was taken from the work of Knacke (1992).

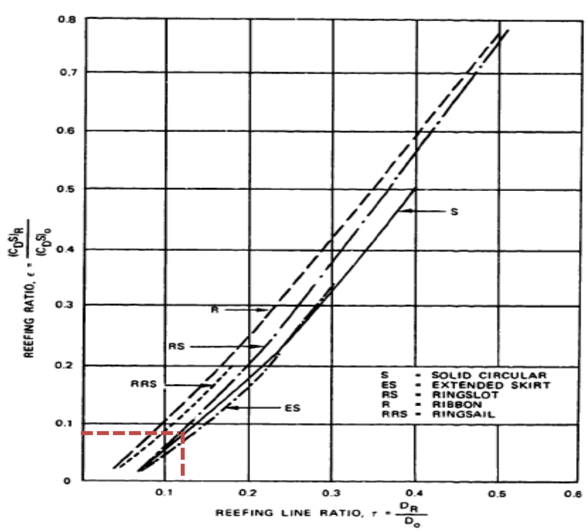


Figure 5.20: Reefing ratio vs reefing-lines ratio for various parachutes (Knacke,1992)

From Figure 5.20, corresponding to reefing ratio $(C_dS)_R/(C_dS)_o = 0.08$, reefing-lines ratio $(D_R/D_0) = 0.12$. Thus,

$$\text{Reefed parachute diameter } (D_R) = 0.12 \times 31$$
$$= 3.72 \text{ m}$$

$$\text{Reefing lines length is} = \pi\, D_R$$
$$= 11.68 \text{ m}$$

(iii) Terminal speed with cluster of two parachutes

Balancing the forces in vertical direction at terminal speed (V_t), the equilibrium equation is as given by equation (5.7).

$$(\text{Mass of CM - Mass of pilot chute – Mass of drogue parachute})\ g$$
$$= (\eta_c\, n_c\, ½\, \rho_{msl}\, V_t^2\, C_D\, S)_{\text{parachute}} + (½\, \rho_{msl}\, V_t^2 C_D\, S)_{\text{CM}}$$

Substituting the known values in the above relationship, we get,

$$[(3370 - 2 \times 2 - 18 \times 2) \times 9.81]$$
$$= [0.9 \times 2 \times 0.5 \times 1.169 \times V_t^2 \times 0.75 \times \pi/4 \times 31^2 + ½ \times 1.169 \times V_t^2 \times 0.626 \times \pi/4 \times 3.1^2]$$

or,

$$V_t = 7.40 \text{ m/s}$$

5.4.4.3 Constructional Design and Stress Distribution

The solid slotted canopy is a regular polygon of N sides, constructed as a flat surface with a central vent (Figure 5.21). The canopy has slots at the gore and near to the skirt. It is made for a specific constructional geometry to maintain high drag coefficient and material porosity.

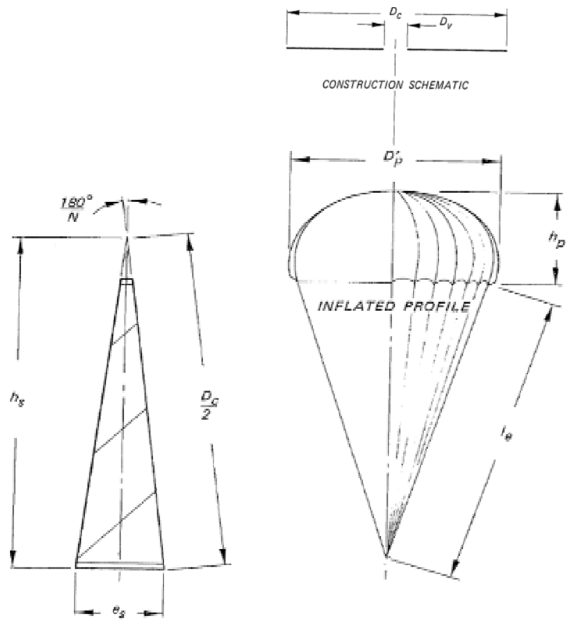


Figure 5.21: Constructional parameters for slotted solid canopy

The other dimensional parameters are estimated using the following relation.

$$h_s = \left\langle \frac{S_o}{N \tan\left(\frac{180}{N}\right)} \right\rangle^{\frac{1}{2}}$$

$$e_s = 2\, h_s \tan\,(180/N)$$

For $S_v < 0.001\, S_o$, Knacke (1992) suggests

L_e/D_o =0.80 to 1.25

D_p/D_o= 0.70,

and $h_p/D_p = 0.41$.

Construction design parameters

(i) Number of gores (N_G) = 96

(ii) Gore area (S_g)

$$S_g = S_o / N_G$$

$$= 7.86 \text{ m}^2$$

(iii) Gore half angle ($\beta/2$)

From Figure 5.21, we get the relation

$$\sin(\beta/2) = \sin(180/N_G)$$

Thus, $\beta/2 = 1.875^o$

(iv) Gore radius (r_s) = $D_o/2$

= 15.5 m

(v) Gore height (h_s)

$$h_s = r_s \cos(\beta/2)$$

= 15.5 x cos (1.875)

= 15.50 m

(vi) Gore width (e_s)

$$e_s = 2r_s \sin(\beta/2)$$

= 2 x 15.5sin (1.875)

= 1.014 m

(vii) Vent diameter (D_v)

From the wind tunnel test, Swadesh et. al., 201 found that Vent area (S_V) as 0.0372 % of canopy surface area (S_0) works satisfactorily. Therefore,

$$S_V = (0.0372/100) \times 754.77$$

$= 0.281 m^2$

Thus, Vent diameter (D_v) = 0.598 m

(viii) Vent width per gore (e_v)

$$e_v = 2\, r_v \sin(1.875)$$

= 0.0196 m

(ix) Vent height (h_V) = $r_v \cos(\beta/2)$

$= 0.299 \times \cos(1.875)$

$= 0.299$ m

(x) Ring-grid height (h_g)

$h_g = h_s - h_v$

$= 15.50 - 0.299$

$= 15.20$ m

(xi) Number of suspension-lines (N_r)

N_r = number of gores = 96

(xii) Length of suspension-line (l_e) and of riser (L_r)

The ratio of the suspension-lines to nominal diameter of canopy (L/D_o) is taken as 1. Therefore, Length of suspension-line (l_e) = D_o = 31 m

Total length of suspension-line and riser is taken as ($\sqrt{2}D_o$), therefore,

Riser length = Total length - length of suspension line

$= \sqrt{2} \times D_o - D_o$

$= 6.42$ m

5.4.4.4 Parachute Force Estimation

The drogue parachute is disconnected from CM at the speed of 70 m/s while start pulling the main parachute through bridle link. During the unfurling of the main parachute, the CM falls free till lines are stretched. During this time, 70 m/s speed enhances to 80 m/s at the time of parachute inflation. Therefore, the main parachute has to be designed for the deployment speed of 80 m/s at 3 km altitude. The opening shock forces of the parachute are determined from force-time-trajectory analysis, and are corresponding to the two peaks as shown in Figure 5.22.

$$F_{D\ reefed} = 135400 \text{ N}$$

$$F_{D\ disreefed} = 132200 \text{ N}$$

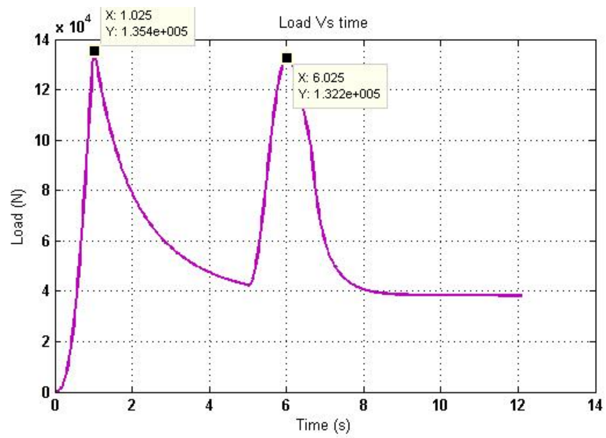


Figure 5.22: Opening shock force experience by the main parachute

5.4.4.5 Peak Deceleration

The peak declaration occurs when both of the parachutes inflate simultaneously. An analysis shows time varying deceleration as shown in Figure 5.23. This figure shows peak deceleration to be 4.67*g* which is less than 6*g*, the specified maximum value for CM structural load.

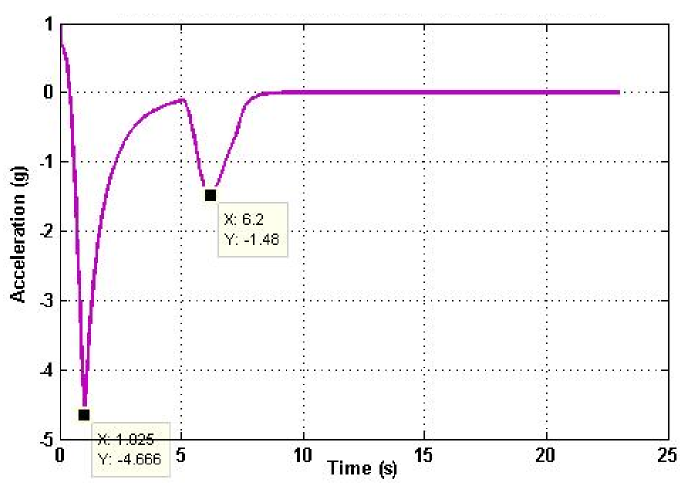


Figure 5.23: Peak deceleration of the main parachute

5.4.4.6 Design Loads

Parachute is to be designed over the actual expected loads to overcome the uncertainty in design, materials and other environmental factors. For all man-rated parachute recovery systems, design factors for critical and non-critical components have been mentioned in Section 5.2.3. Besides, an extra margin of 10 % on drag force (F_D) is also being kept due to uncertainty in reefing-line cutter delay time. Thus, the net parachute shock force will be,

$$F'_D = 135400 \text{ x } 1.1$$

$$= 148940 \text{ N}$$

Therefore, the design load on components will be

$L_c = F'_D \, x \, DF$ = 148940 x 2.76 = 411074 N for all critical components

$L_{nc} = F'_D \, x \, DF$ = 148940 x 2.21 = 329157 N for other components

5.4.4.7 Canopy Stress Distribution

Small and medium size canopies are designed using only a single variety of fabric for the whole canopy. But the large parachute canopies are made using fabrics of two or more varieties considering stress distribution over the canopy. In one of the experiments, Peggy (1976) has determined the stress distribution over the surface of a ringslot model parachute during the period of inflation and in steady state condition for the infinite mass operating condition during low speed in wind tunnels. His results present the general trend of parachute stress distribution for round canopy, and ringslot and ribbon parachutes. The high stress concentration was found to begin early during the canopy inflation in the vent area, while to be low at the skirt. Under the steady state conditions, the model parachute experienced the same stress distribution trend as during inflation. The stress concentration was higher in the vent area and lower in the middle and lowest in skirt region. The distribution of canopy stress is shown in Figure 5.24.

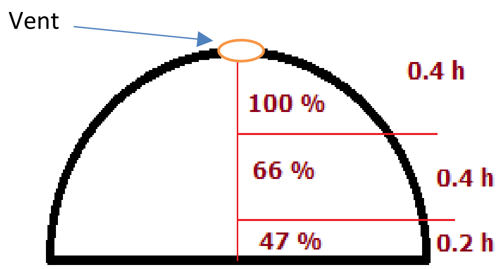


Figure 5.24: Stress distribution on parachute canopy

5.4.4.8 Material and Mass Estimation

The load on canopy surface ultimately converges on the suspension-lines attachment at the skirt and is transferred downwards through lines and riseres to the forebody. Based on the transferred loads on the components, maximum design loads are estimated as described in Section 3.3.3.6 for the selection of the materials. An extra 10 % mass is to be taken on account of additional weight of stitching, folding and overlapping of materials.

(a) Canopy

The shape and construction of the canopy as a whole defines the load transfer paths across the surface. Generally, the fabric will be subjected to critical stresses in those areas for which the local radius of curvature is maximum and when the differential pressure reaches its maximum value.

(i) Fabric

Following is a semi-empirical method for fabric stress calculation as suggested by Ewing et al. (1991) to determine the required fabric strength (t_c) of a solid canopy in terms of Newton per unit width as

$$t_c = k\ p\ r\ (DF)$$

where, k = shape factor, equal to 0.5 for a spherical surface

p = uniformly distributed pressure, equal to L/S_p (S_p (=л D_p^2)/4is the projected (inflated) canopy area)

D_p = projected **(**inflated) canopy diameter (0.70 D_o**)**

r = maximum radius of curvature, equal to $D_p/2$

DF = design factor

Therefore,

$$t_c = \frac{L}{\pi D_p}(DF)$$

For reefed parachute,

$$t_c = \frac{L}{\pi D_p}(DF)_{reefed}$$

Taking reefing ratio $(C_DS)_R/(C_DS)_o$ as 8% for reefed canopy (Figure 5.20), reefed inflated canopy drag coefficient $(C_D)_p$ as 0.55 and cluster efficiency (η_c) as 0.90 (Knacke, 1992).

Inflated reefed canopy surface area (S_P) = 8 % of $(\eta_c\, C_D\, S)_o\,/(C_D)_p$

= (0.08 x 0.90 x 0.75 x 973.14)/0.55

= 77.63 m^2

Projected (Inflated) reefed diameter (D_p) = √(77.63 x 4/л)

= 9.94 m

Therefore,

t_c = 329157/(π x 9.94)

= 10538 N/m

or = 527 N/5cm

Thus, Margin of Safety (MoS) = (1275 - 527)/527

= 142 %

Material selection

(a) **Top 5 panels** (0.4h, Figure 5.24)

Based on above required strength (527 N/5cm), the selected material is fabric nylon 93 gsm and breaking strength (BS) as 1275 N/5cm.

(b) **Mid 5 panels** (0.4 h, Figure 3.24)

$$t_c = 66\ \%\ \text{of}\ 527$$

$$= 348\ \text{N/5cm}$$

Thus, Margin of Safety (MoS) = (588-348)/348

= 69 %

Selecting the material for the mid panels of canopy is as fabric nylon, 48 gsm, Breaking Strength (BS) as 588 N/5cm.

(c) **Lower 3 panels** (0.2 h, Figure 5.24)

$$t_c = 47\ \%\ \text{of}\ 527$$

$$= 248\ \text{N/5cm}$$

Thus, Margin of Safety (MoS) = (402 -248)/248 = 62 %

Selecting the material as fabric nylon 37 gsm, Breaking Strength (BS) as 402 N/5 cm.

Mass calculation

Mass of the canopy = (973.14/760) [(66 x 0.093) + (144 x 0.048) + (550 x 0.037)]

= 42.76 kg

(ii) Suspension-lines

Required strength of material = L_{nc}/N_S

= 329157/96

= 3429 N

Thus, Margin of Safety (MoS) = (3924-3429)/3429

= 14.4 %

Material selected as cordage para-aramid, Breaking Strength (BS) as 3924 N with mass as 4 g/m.

Mass calculation

Mass of the suspension-lines = 96 x (35.2 + 3.5) x 0.004

= 14.86 kg

(iii) Radial tapes

Required strength of radial tape = Strength required for suspension line

= 3429 N

Thus, Margin of safety (MoS) = (5886 – 3429)/3429

= 71 %

Material to be selected for radial tape astape para-aramid, 26 mm, Breaking Strength (BS) 5886 N with mass as 8 g/m.

Mass calculation

Total mass of the radial tapes = 17.25 x 96 x 0.008

= 13.25 kg

(iv) Vent lines

Required strength of vent lines = Strength of suspension-lines

= 3429 N

Thus, Margin of safety (MoS) = (3924-3429)/3429

= 14.4 %

Material to be selected as cordage para-aramid, BS 3924 N with mass as 8 g/m.

Mass calculation

Mass of the vent lines = 48 x (0.6789 x 0.95) x 0.008

= 0.257 kg

(iv) Circumferential bands

Material selection

Required strength of circumferential band = Strength required for radial tape

= 3429 N

Material to be selected for radial tape as tape para-aramid, 26 mm, Breaking strength (BS) 5886 N with mass as 8 g/m.

Mass calculation

Total length = 499 x 35.2/31

= 566.6 m

Mass of the circumferential band = 566.6 x 0.008

= 4.533 kg

Margin of Safety (MoS) = (5886 – 3429)/3429

= 71 %

(vi) Vent Band

L_c = 148940 x 2.76

= 411074 N

$$F_{VB} = \frac{L_c}{2\ N_r \sin\{\frac{360}{N_r}\}}$$

= 411074/(96 x 2 x sin (360/96))

= 32735 N

Thus, Margin of safety (MoS) = (26487 x 2 - 32735), by taking stitching factor 0.8

= 29.5 %

Material to be selected as tape para-aramid, 25 mm, Breaking Strength (BS) 26487 N, two layers with mass as 35 g/m.

Mass calculation

Mass of the Vend band = 96 x 0.022 x 0.035 x 2

= 0.152 kg

(viii) Skirt Band

Strength required, t_c = 5 % of design load (L)

= 0.05 x 329157

= 16458 N

Thus, Margin of safety (MoS) = (26487-16458)/16458

= 61 %

Material to be selected as tape para-aramid, 25 mm, Breaking Strength (BS) as 26487 N with mass per unit length as 35 g/m.

Mass calculation

Total mass of the skirt band = π x 35.2 x 0.035

= 3.87 kg

(ix) Riser

Riser is designed to carry the maximum load of one main parachute. Each parachute will have two set of risers and 96 suspension-lines. One riser will be attached to 48 bunches of suspension-lines as illustrated in Figure 5.25.

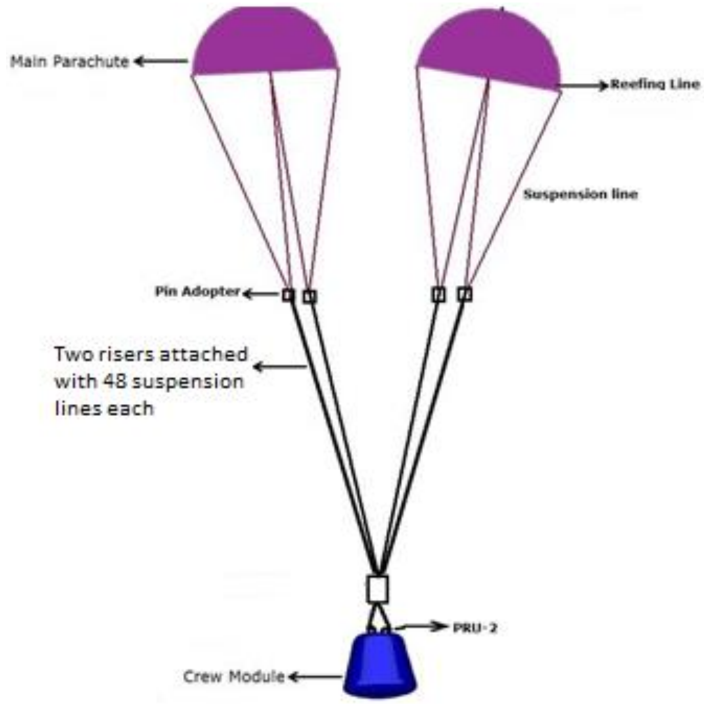


Figure 5.25: Main parachutes with two risers in each parachute

Therefore, the design load on each riser of one parachute = $L_c/2$

= 411074/2

= 205537 N

Thus, Margin of safety (with layering factor of 0.8) = (88290 x 4 x 0.80 - 205537)/205537

= 37.4 %

Thus, the material to be selected as webbing para-aramid 44 mm, BS as 88290 N, four layers with mass as 84 g/m.

Mass calculation

Mass of the riser = 2 x length of riser x mass per unit length x 4 layers

= 2 x (14.58) x 0.084 x 4

= 9.80 kg

(x) Reefing-lines

Experiments have shown that the high canopy loading parachute's reefing lines forces are 3 to 4 % of the reefed opening forces; whereas in large-diameter low canopy loading parachute, it is approximately 1 to 2.5 % (Knacke, 1992). Apollo's measured reefing-line load data shows that the reefing-line load never exceeded 1.53 % of reefed opening load. Hence to be on the safe side in the design, the maximum load of 2.5 % of reefed opening shock is considered.

Material selection

Strength required = 2.5 % of L

= 0.025 x 411074

= 10277 N

Thus, Margin of safety (MoS) = (12740-10277)/10277

= 24 %

Material to be selected for the reefing lines is as cordage nylon, Breaking strength (BS) as 12740 N with mass as 50 g/m.

Mass calculation

Since length of reefing lines = 11.68 m

Thus, the component mass = 11.68 x 0.05

= 0.584 kg

Based on the design loads on the various components of the parachute, materials were selected and the summary of chosen materials is listed at Table 5.9.

5.4.4.9 Design Validation of Main Parachute

The designed parachutes are qualified through various tests as discussed below.

(i) Wind tunnel model test

The wind tunnel model test of the main parachute was carried out to find the coefficient of drag and other aerodynamic parameters. The inflated parachute in wind tunnel is shown in Figure 5.26.

Table 5.9: Component mass, materials and MoS of main parachute

Component	Sub-component	Required strength	Materials	Designed strength	MoS (%)	Mass (kg)
Canopy	Fabric	527 N/5cm 348 N/5cm 248 N/5cm	Nylon Fabric 93 gsm Nylon Fabric 48 gsm Nylon Fabric 37 gsm	1275 N/5cm 588N/5 cm 402 N/5cm	142 69 62	42.76
	Suspension-lines	3429 N	Cordage para-aramid	3924 N	14.4	14.86
	Radial Tape	3429 N	Tape para-aramid 26 m	5886 N	71	13.25
	Circumferential band	3429 N	Tape para-aramid 26 mm	5886 N	-	4.54
	Vent lines	3429 N	Cordage para-aramid	3924 N	14	0.26
	Vent band	32735 N	Tape para-aramid 26 mm, two layers	26487 N	29	0.15
	Skirt band	16458 N	Tape para-aramid 26 mm	26487 N	61	3.87
	Reefing lines	10277 N	Cordage Nylon	12740 N	24	0.58
Riser	-	205537 N	Webbing Kevlar 44 mm, 08 layers	88290 N	37.4	9.80
						Total mass = 90.07 kg

Adding extra 10% additional weight of overlaps, folding and stitches, etc, Total mass 99 kg

Figure 5.26: Circular slotted solid canopy in wind tunnel test

In the model test, it was found that the parachute was stable, and no rotation or revolution was noticed. Two models were tested, one at 40 m/s and the other at 65 m/s velocity. At 65 m/s velocity, few suspension-lines were found to be broken. The drag coefficients for the two models were 0.717 to 0.737, respectively. Therefore, the coefficient of drag considered in the design as 0.75 is acceptable and comparable to wind tunnel study.

(ii) Air Drop test

The instrumented air drop test of the main parachute was carried out from an aircraft at 67 m/s velocity at 500 m altitude. The load cell measured the peak forces in reefed and disreefed states of parachute as shown in Figure 5.27. The measured loads are given below.

(a) 1st peak load (reefed) = 74301 N against designed load of 135400 N (reefed canopy)

(b) 2nd peak load (disreefed) = 80266 N, against designed load of 132200 N (disreefed canopy)

The measured opening shock forces values are lower than the design values. It is due to the limitation of aircraft speed of 67 m/s, being lower than required speed of 80 m/s.

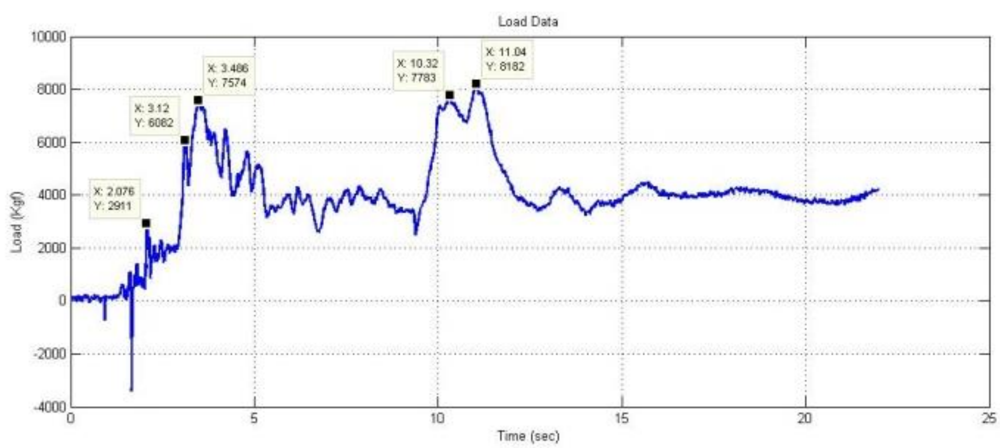


Figure 5.27: Load profile of the main parachute with reefed and disreefed canopy

The textile made items are over-designed considering all precautions and also carrying out the simulated tests matching with the user environment conditions. The behavior of textile made parachutes often witnessed to change in the field use from what was observed during the testing. Failures are unpredictable. It can occur with time, repeated use or during handling. Forthcoming chapters describe the risk and reliability assessment methods to take care of the system failures in operation.

5.5 Summary

This chapter proceeds with the input from the earlier chapter regarding the shape and size of the main canopy. Its complete design at its components level has been carried out in this chapter. These components include, riser, suspension-lines, etc. In addition, the other parachutes as TCS chute, Pilot chute and drogue parachutes are completely designed. The factors considered are external loads and the wake on the forebody. The design includes specifying the size and the material for each component. Besides the qualification testing, design validation has been carried out through dynamic and simulated flight testing.

To overcome the weakness in material strength, uncertainty in atmospheric conditions, etc. sufficient design factor is taken as 2.21 for non-critical components and 2.76 for critical components. Since textile items are prone to failure because of defect and degradation of materials in use, sufficient margin of safety is ensured during the design for reliable performance.

The results of wind tunnel test, and dynamic and flight tests, conducted for design validation have also been presented in this chapter.

Since parachute volume and mass are important factors particularly in space application, high strength fabrics have been chosen to have lower mass and ease in packing in available space of the module.