CHAPTER 9

RELIABILITY BASED OPTIMIZED DESIGN OF HYBRID TETHER

Notations

μ_X	Sample mean of strength (N)
σ_x	Standard deviation for strength *X*
μ_Y	Sample mean of stress (N)
σ_y	Standard deviation for Stress *Y*
σ_x^2	Variances of the stress
σ_y^2	Variance of strength
μ_U	Mean value of *U*
σ_u	Standard deviation value of *U*
A	Cross section area of tether (mm^2)
D	Diameter of tether (mm)
m	Margin of safety (%)
n	Factor of safety
R	Reliability
U	Strength (*X*) - Stress (*Y*)
X	A random variable representing strength (N)
Y	A random variable representing stress (N)

9.1 Introduction

The tether taken for the analysis in this study is designed and developed for anchoring medium size aerostat for carrying 300 kg payload to an altitude of 1000 m AMSL for security and surveillance purposes (Ashok *et al.,* 2010; Sharma *et al.,* 2014). The top end of the tether is connected to nylon cordages (14 in number with 7 on each side of the balloon envelope) through epoxy "U" shape cup fixed on tether's end, and the other end is wounded on winch drum. It is a well-known fact that aerostat flight performance, system safety and reliability will depend upon the proper designing of the tether. The overall length of the tether is 1500 m. Out of this, 500 m is kept extra for winding on the drum to avoid any chances of slippage and also to serve as spare against the work-out part of the tether attached to the balloon.

A proper design has to have allowances for accidental overloading, improper handling, inherent manufacturing defects and many such other factors. The diameter of the tether also varies across its length. As a result, the classical design approach for the tether may not serve the purpose. For this purpose, a reliability-based design of hybrid tether is discussed in this chapter.

9.2 Probabilistic Design Model

Tether self-weight should be optimum to maximize the carrying payload capacity of the aerostat. Considering the field environment and rugged application, its material and manufacturing process should be selected in such a way that the maximum reliability and operational performance can be achieved within permissible diameter and weight. Tether is covered with PU coated nylon sheath to protect each wires/conducting wire and to reduce degradation in the prolong use. Tests like spark test, destructive test, fatigue test, and breaking-strength and twisting tests are performed for qualification and acceptance.

Tethers potentially experience single-point structural failures that normally take place when applied load exceeds the strength of the material or due to its repeated use. Since the load and the environment condition do not remain stationery, safe and reliable operation becomes an issue. So, the design of the tether should also accompany the information on its reliability. A proper design can take care of stress related issues. However, its reliability needs to be computed using stress-strength interference model from the aforementioned perspective. This model is useful in situations where the reliability of a component or a system is defined by the probability that a random variable *X* (representing strength) is required to be greater than another random variable *Y* (representing stress). It is equally applicable in the present analysis where the strength of the tether has to be more than the applied stress to avoid failure. It has already been mentioned that underlying randomness in the application domain has to be acknowledged. Thus, the design has to be for a reasonable reliability (Haugen, 1968); Kececioglu *et al.*, 1968). Since the input to the design and also the inherent design parameters are random, the design methodology has to consider them as random variables. The factor of safety (*n*) is the ratio of strength (*X*) to stress (*Y*), and the margin of safety (*m*) is the expected value of *U* (being the excess of the mean value of strength over stress). To avoid failure based on strength consideration, whether taking deterministic or stochastic framework, the safety factor is taken to be greater than 1 or equivalently safety margin should be positive to ensure survival of the system.

9.3 Classical Design Approach

The loads on tether are due to aerodynamic parameters, temperature, helium purity, wind speed and gust. The load on tether (Subramanyam *et al.,* 2008 and Hunt *et al.,* 1981) due to balloon buoyancy is directly proportional to the volume of helium. The estimation of volume of an aerostat envelope is carried out based on Archimedes' principle for a given payload capacity and height of operation. Kumar *et al.,* (2016) and Mittal *et al.,* (2014) have carried out the wind tunnel model test, finite element modeling and geometric nonlinear analysis for critical operational cases to estimate the distribution of stress on the aerostat envelope, forces in guy wires and confluence lines, as well as tension in the tether. The classical design approach is based on the estimation of tension in the tether.

Table 9.1: Estimated and measured tether tension during limited trials conducted (without safety factor)

Parameters	Design values (Kumar et al., 2016) for entire operating conditions with wind speed in range (0-30 m/s)	Measured values during limited trials and wind speed being in the range (5-29 m/s)
Payload	300 kg (minimum)	300 kg
Flight altitude	1000 m	1000 m
Tether tension	30.4 kN (maximum)	19 kN, 29 kN, 50kN and 55 kN (μ_y = 38250 N, σ_y = 25456 N)

Table 9.1 presents tension in the chosen tether (of 16 mm diameter) during the limited flight trials conducted on an aerostat, against the design values considered for the tension in the tether. The minor crack and damages were noticed on the outer sheath of tether on the first 100 m of the tether from the balloon end. The one such failure of tether is shown in Figure 9.1. It may due to gust at altitude, environmental exposure of tether and or repeated usage.

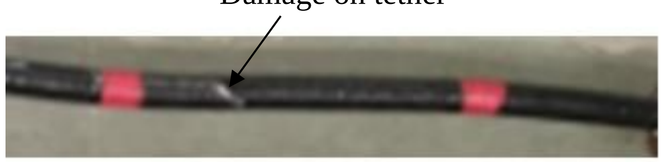

Figure 9.1: Damaged tether part towards the balloon end

It is observed that both estimated and measured trim angle lie within the specified range of ± 15 degrees**.** From Table 9.1, it can also be observed that almost 50% the tether tension has gone beyond the maximum design load 30.40 kN. The tether survived as the values were still below the ultimate strength. With the passage of time, the tether degrades due to its usage and repeated winding/unwinding on winch drum. It is observed that the tether mostly gets damaged at the top which gets maximum tension due to its self-weight and balloon buoyancy. So, the damaged part of the tether is cut off and removed from the top end for smooth flight operations. It is with the rest of the length of the tether, trials were continued.

The estimated maximum load on the tether (Table 9.1) is 30.40 kN. Considering the factor of safety 2, the design load will be equal to 60.80 kN. This load is considered for the selection of the material in the classical design approach. Available hybrid tether has the mean value of ultimate tensile strength as 944 N/mm^2. To determine their load carrying capability, 8 samples were tested with epoxy joint at both of the ends of the sample tether as shown in Figure 9.2. The test results are shown in Table 9.2.

(a) (b)

Figure 9.2: (a) Tether epoxy joint with mild steel cap, (b) Testing of tether sample on UTM

Table 9.2: Tether sample test results with epoxy joint

Sample No.	Load (X), kN
1	91.64
2	95.72
3	97.37
4	97.61
5	96.72
6	97.54
7	97.10
8	97.05
	μ_x = 96.35kN,
	σ_X = 2.0 k N

Data provided in Table 9.2 is used to determine the diameter of the tether.

Since, Mean Strength $\geq$ Mean Stress x Factor of safety

Therefore, $944 \geq \left(\frac{96350}{A}\right) \text{x } 2$

Hence, $A \geq 204.13\ mm^2$

Therefore, $D \geq 16.12\ mm \approx 16$ mm

According to the above analysis, the 16 mm diameter tether should not have any failure, but it had. The reason is obvious from the fact reported in Table 9.1 showing the stress being above strength in some instances. This proves the necessity of going with the probabilistic design approach where the problem parameters are also stochastic in nature.

9.4 Probabilistic Design Approach

In the traditional design approach, the factor of safety or margin is kept large enough to accommodate the uncertainties in stress and strength. Typically, the factor of safety is not taken based on the probabilistic characterization of the tether performance. The probabilistic design of any structure is based on the design reliability, i.e., the probability that the system will perform its mission adequately as desired. The classical design approach does not consider the reliability aspect. Thus, it fails to specify the reliability of the design that is certainly desired in such a strategic operation. Besides, this approach cannot help to determine the correct diameter of tether, the design variable, for a specified value of reliability for a given mode of failure.

It has been mentioned earlier that the load on the tether is random in nature and it keeps changing depending on wind conditions, altitude, and helium quantity available inside the balloon. The ultimate tensile strength of the tether is also a random variable due to variation in property of the material and also in factors governing its manufacturing process. All these types of stochastic variability will affect reliability of the tether. Therefore, there is a strong need to objectively determine the safety factor value rather than to take some value arbitrarily as is carried out in the classical design approach. Right consideration of the factor of safety and the design of tether for a specified level of reliability for a single mode of failure is presented below.

Taking measured tether tension values as reported in Table 9.1, the following values were found.

$$\mu_Y = 38250 \text{ N}$$

$$\sigma_Y = 25456 \text{ N}$$

Since standard deviation of the tension is very high, it is going to impact reliability quite heavily. From Table 9.2,

$$\mu_X = 96350\text{N}$$

$$\sigma_X = 2000\text{N}$$

Hence, $\mu_u = \mu_x - \mu_y = 58100$ N,

and $\sigma_u^2 = \sigma_x^2 + \sigma_y^2 = 652007936$.

Since the factor of safety is a ratio of the mean value of strength to the mean value of stress as given in equation (8.6), hence the minimum value of factor of safety will be,

$$n = \mu_X / \mu_Y = 96350/38250 = 2.52.$$

Corresponding to this factor of safety, achievable reliability can be determined from equation (8.5) as,

$$R = \emptyset\left(\frac{\mu_X - \mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\right) = \phi\left(\frac{58100}{\sqrt{652007936}}\right) = \phi\{2.28\} = 0.9887.$$

The above value of reliability as 0.9887 suggests that there will be 113 failures per 10,000 uses when the factor of safety is taken as 2.52 for the 16 mm diameter tether. For a better reliability, the factor of safety should be increased by working on design parameters of the tether such as dimension, material strength, etc.

The reliability of the 16 mm diameter is poor according to the strategic requirement defined in terms of the following.

(i) Safety factor = 1.5.

(ii) Environmental loss factor = 1.25. It was observed that the ultimate strength of the tether reduces during UV exposure testing which was conducted according to ISO 4892-2-1984(E).

(iii) Cyclic loss factor = 1.37. It is based on the fatigue test carried out for 500 cycles at 2000 kg_f load.

Since the above factors are independent of each other, the factor of safety taken for the design has to be the product of all these factors. Hence the minimum factor of safety will be equal to 1.5 x 1.25 x 1.37 ≈ 2.6. Considering the factor of safety as 2.6 and μ_x = 96350 N (Table 9.2) for the tether design, equation (8.6) would desire the mean stress to be as,

$$\mu_Y = 37058 \text{ N.}$$

This stress is lower than the stress value of 38250 N for a factor of safety 2.52.

Now, for a lower stress a higher reliability is expected as

$$R = \phi \left\{\frac{96350-37058}{\sqrt{652007936}}\right\} = \phi\,\{2.32\} = 0.9898$$

With a low stress resulting better reliability value of 0.9898, only 102 failures per 10,000 uses are expected. This is a much better position from the earlier condition of average 113 failures. Reliability here was increased by decreasing the stress and this would require increasing of the diameter of the tether. But it can also be achieved by controlling variation in stress and strength.

Callwood (2014) recommended the limits for the factor of safety as 3.5 for the tether. Lambert Casey (2006), and Tomlin *et al.*, (1997) have tested and verified the tether for space application with the safety factor as 5 at the ultimate maximum predicted tether load and as 2 at off-normal tether condition for basic tether qualification. Reliability values, even for these recommended factors of safety, have been estimated and are shown in Table 9.3 and Figure 9.3.

Table 9.3: Factor of safety and corresponding reliability

Factor of safety	Reliability	% Improvement in reliability
2.0	0.9706	-
2.6	0.9898	1.98
3.5	0.9964	0.67
4.5	0.9983	0.19
5	0.9987	0.03

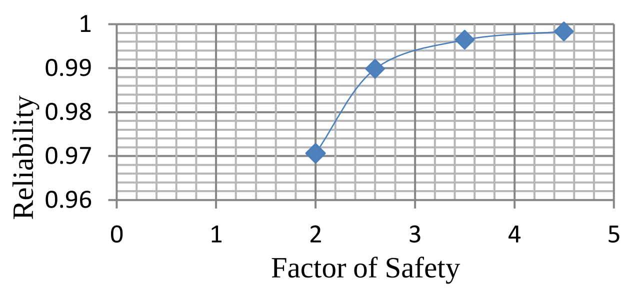

Figure 9.3: Reliability vs factor of safety of hybrid tether

From Table 9.3 and Figure 9.3, no appreciable increase in the reliability values can be witnessed beyond the factor of safety value of 3.5. Besides, going for a very high safety factor will cause tethers' self-weight to significantly increase and also cost to increase tremendously, and the balloon payload carrying capacity to significantly decrease. The reason for the same is the increased value of the diameter of the tether supporting enlargement to increase the strength of the tether much beyond the stress in order to achieve a higher factor of safety without changing the material of the tether. An analysis has been carried out to show changes in weight and reliability with respect to the change in the diameter of the tether. The results are shown in Table 9.4 and Figure 9.4. These two clearly indicate the severe consequences of the increase in the diameter beyond a particular value in order to increase the factor of safety, that too without having appreciable improvement in reliability. In view of these findings, it is suggested to go with with the factor of safety in the range of 2.6 to 3.5 to obtain corresponding reliability in the range of 0.9898 to 0.9983. Table 9.4 shows that the reliability equal to or more than 0.9898 can be achieved by tether of diameter 18 mm and above.

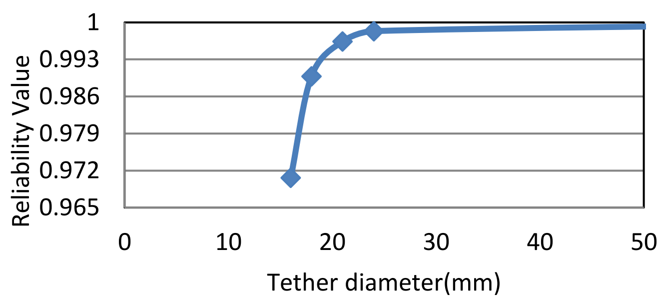

Figure 9.4: Change of tether reliability w.r.t. diameter

Table 9.4: Effect of tether diameter on weight and reliability

Tether diameter (mm)	Tether weight (gm/m)	% Change in weight	Reliability	Reliability improvement (%)
16	277	- 21	0.9706	-
18	350	00	0.9898	1.98
21	476	+36	0.9964	0.67
24	622	+78	0.9983	0.19

When a product fails, there is often a loss of service. Cost of repair or replacement can easily be estimated. But the loss of goodwill, particularly in strategic application of aerostat, is almost impossible to predict. The current price (in rupees per meter of tether's length) for three different tethers is plotted in terms of their diameter as shown in Figure 9.5. It shows that the cost of tether is found to naturally increase with its diameter. The characteristics observed from Figures 9.3 to Figure 9.5 clearly indicate that going for high factor of safety is not desirable as one needs to pay very much without having appreciable increase in reliability beyond a particular diameter of the tether.

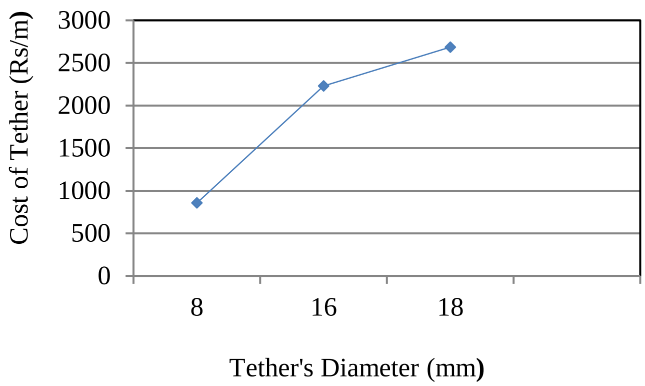

Figure 9.5: Cost (per unit length) vs diameter of hybrid tether

9.5 Summary

Based on trial and testing, an analysis has been carried out to estimate the reliability of tether in this chapter. Reliability versus tether's diameter graph has been plotted to obtain the optimum diameter of the tether. Strength test and flight trials were conducted to acquire limited data for the analysis. In actual field use, it was found that the top part of tether degraded due to maximum exposure and repeated usage. It is found that a factor of safety value of 2.6 results in 98.98% reliability. Experimentation and the analyses carried out show that taking the safety factor beyond 3.5 does not help in improving the reliability significantly, rather it causes the increase in tether's self-weight and thus the cost to increase significantly. It is being recommended to design the tether with factor of safety going beyond 2.6 and liming it to 3.5 for optimum size and cost effectiveness.