CHAPTER 16. RELIABILITY

16.1 Historical developments

Reliability engineering is a young discipline, it came into existence essentially after the first world war. In older times, high reliability could be achieved by overdesign. In these situations, cost usually was not a problem. And lessons could be learnt from failures. The industrial revolution during the 18th and 19th centuries changed all that: new demands and large scale mechanized production changed the economic landscape.

16.1.1 Mass production

With the beginning of mass produced items and competition in the marketplace, a few things happened:

- failure data could be collected.
- cost saving became important
- the product development time shortened.
- complex systems (those with many interacting components) got to be built for the first time.

At the same time, with more complex and large systems being built – systems with serious failure consequences – "learning from failures" no longer remained an option.

After WWI – pre-1940: Concept of "quality" was introduced. In-process & pre-shipment tests were performed. Operational safety of one- two- or four-engine planes were studied, and measured in terms of number of accidents per hour of flight. Fatigue life was studied by Weibull, Gumbel, Campbell; Telephone trunk-line machine maintenance was studied by Khintchine, Palm, Erlang.

1940s: Statistical quality control was developed. Series and parallel system reliability were understood. Improvements in systems reliability was sought. Statistical basis of structural design was proposed by Freudenthal.

Post WWII: Increasingly more complex systems were built for the first time – TVs, computers, rockets etc. Early 1950s tube reliability studies by ARINC (Aeronautical Radio Inc. – a trade group). 1950s: missile reliability studies. 1951: start of widespread adoption of Exponential distribution for life (Epstein and Sobel, Davis. 1957: first report by AGREE (ad hoc group on reliability of electronic equipment). Minimum acceptable limits, reliability testing requirements, effect of storage on reliability were studied.

1960s: Jargons started coming up like "quality assurance" etc. Failure analysis was introduced. The IEEE Transactions on Reliability was launched in 1963. Mathematical developments in this decade include general systems reliability formulation by Birnbaum Esary Saunders, Barlow and Proschan; consideration of association and dependence; queueing theory in reliability etc.

1970s: The public's interest grew sharply in the safety of nuclear power plants. The reactor safety study (WASH1400) was published in 1975. Structural reliability as a field came into being in the 60s and 70s. Reliability of building, bridge, offshore, ship etc. structures became important.

1990s: Total quality management, six sigma etc. current standards, handbooks etc. Focus on Network reliability, Software reliability, Human reliability etc.

16.1.2 History of Structural Reliability:

Structural safety as a concept is as old as civilization. 1750 BC – Hammurabi's Law.

For centuries, until the medieval times, building design and construction was by experience and intuition.

Around the 17th century, the laws of mechanics started to be laid down and the mathematical basis of mechancis was better understood. "Factor of Safety" – around mid 1850s?

In 1849 the Royal Commission appointed to investigate the use of iron in railway bridges asked of the prominent engineers of the time, "**What multiple of the greatest load do you consider the breaking weight of the girder ought to be**?" The answers … ranged from 3 to 7. And when asked, "**With what multiple of the greatest load do you prove a girder**?" the panel responded with factors ranging from 1 to 3. The commission concluded that an appropriate factor of safety for railway bridges would be 6.

- From <u>To Engineer is Human</u> by Henry Petrosky, Vintage Books, 1992.

Example - factor of safety : **For mild steel in US:**

Year	Yield strength (MPa)	Factor of safety	Allowable stress (MPa)
1890	197	2	97
1918	190	1.72	110
1923	228	1.83	124
1936	228	1.65	138
1963	250	1.67	152

Question: why did the factor of safety change as it did above?

The realization that loads and resistances are random variables arose after the first World War (Freudenthal 1947). Freudenthal in 1956 formalized the idea of probability based design standards for the first time. He suggested direct or indirect enforcement of target reliability in design. Practical applications began around 1969 with Cornell's reliability index. The "invariance" problem was solved by Hasofer and Lind in 1974. Reliability based codes began to appear in the 1970s. The 1980's saw the advent of computationally efficient techniques and the 1990's saw greater focus on systems analyses. The 2000's has been the time of consolidation. Performance based engineering, economic bases of risk and target reliability, interaction of structural and non-structural failure (hence their contribution to overall systems reliability) are now being considered. Growth during the past decades can be summarized as:

1960s: Natural hazard data and modeling; Load capacity formulation; Reliability bounds; Limit state design

1970s: Progressive collapse; First generation reliability based design standards; First order reliability methods; Acceptable safety

1980s: System reliability; Variance reduction techniques; Modeling uncertainty; Time dependent reliability

1990s: Second generation reliability based design standards; Performance based design; High dimension problems

2000s: Nonlinear analyses; Robustness; Resilience; Interaction with other disciplines like economics, sociology

16.2 Definition of reliability

Reliability of an item is the probability that the item will perform its required function under given conditions for a reference time interval. [13]

"Item" here is a generic term. It can mean equipment, process, structure, machinery, electronic hardware, computer software etc.

Steps in reliability analysis:

i. Identify failure mode. There may be more than one failure mode, and several degrees of failure.
ii. Describe the failure mode mathematically in terms of parameters of the problem (some of which can be random variables or random processes). Then, failure can be described as excursion of a performance measure *M* from an appropriately defined "safe set," Γ_{safe}:

$$Failure = \{M(\tau, \underline{x}) \in \overline{\Gamma}_{safe}\}, \text{ for any } \tau \in (0,t], \text{ for any } \underline{x} \in \Omega \tag{16.1}$$

Here, $(0,t]$ is the reference time interval and $\underline{x}$ is the "coordinate" of a "point" in a distributed system of domain Ω.
iii. Obtain probabilistic information about the random variables and random processes involved.
iv. The last step is to find the probability of no excursion from the safe set any time during the reference time interval.

$$\mathrm{R}(t,\Omega) = P[M(\tau, \underline{x}) \in \Gamma_{safe}, \ \forall \tau \in (0,t], \ \forall \underline{x} \in \Omega] \tag{16.2}$$

[13] See for example the definition in Mine 1959. "Reliability of an item is the probability that the item will perform its purpose satisfactorily under the specified condition for the specified period of time."

The main benefit of reliability analysis especially at the design stage is not necessarily in the the absolute number of Pf, but in the ability to compare different designs. At the maintenance stage, the same argument applies.

There are other similar sounding terms that however have specialized meanings different from reliability: e.g., quality, durability, robustness, resiliency etc.

16.3 Reliability vs. Quality

Quality is a broad and in some sense a "softer" measure of a product's value. It measures satisfaction, pleasure, desirability etc. from the use of a product. Reliability is a subset of quality that is concerned with *failure*, or more generally non-performance, in an intended function of the product. It does *not* measure how *well* it is fulfilling the function; reliability only cares if the function is satisfied.

Safety is a subset of reliability that concerns hazards to life, health, environment and property.

There are other measures of value like durability, robustness etc. that also measure various specific aspects of quality. Robustness measures ability to withstand damage and not lead to breakdown. Durability measures how well quality is retained with time.

16.4 Reliability vs. Robustness vs. Resilience vs. Vulnerability

Reliability measures the ability to perform satisfactorily (i.e., not fail).

Robustness measures the ability to absorb given damage damage and not fail.

Vulnerability measures how likely a specified loss (commonly economic) is.

Resilience measures the ability to come back up after suffering damage.

16.5 Repairable vs. non-repairable component or system

Repairability depends on the context. Repair does not necessarily mean that the same failed item will be fixed. It may mean that a replacement (typically identical) is available which once inserted will make the system "as new" again. In any case, when a component or system is "repairable" we mean that a certain amount of downtime is allowed, the component/system can go offline, and breakdown maintenance can be performed following which the system comes back in "as new" condition. For non-repairable systems, failure usually means end of life.

16.6 Measures of reliability: time defined

Repairable system	**Non-repairable system**
Downtime is allowed. Typically one has identical replacements. Z_i = time to failure of $(i\text{-}1)^{th}$ replacement	Downtime is not allowed/ not relevant. Measures: Time to failure (TTF) and various functions or point values estimated from it:

<table>
<tr>
<td>

H_i = duration of i^{th} repair

typically the Z's are iid, and the *H*'s are iid.

Measures:

- Point Availability, $K(t)$:

$K(t)$= P[system is up at time t].

Stationary value of K:

K_∞ = E[Z]/(E[Z)+E(H)]

- Interval availability:

$\bar{K}(T) = \frac{1}{T}\int_0^T K(t)dt$

- MTBF = E[Z], can be estimated as T_op/k where k replacements are made during operation time T_op.
- MTTR = E[H] can be estimated similarly

The above measures of availability are relevant when the system is mostly in a "waiting" regime, and is asked to perform only for a small duration. If there is a significant probability of failure during operation, we need to define the coefficient of internal availability:

$K_I(t,t_0)=K(t)R(t_0|t)$

where t_0 is the duration of the task, and R is the reliability.

</td>
<td>

- Reliability, Rel(t) (i.e., CCDF of the TTF),
- PDF of TTF
- CDF of TTF
- Hazard function h(t)
- MTTF

Factor of safety can also be a rudimentary measure of reliability.

</td>
</tr>
</table>

For a non-repairable system, or for a repairable system to its next failure: $\text{Rel}(t) \equiv K(t)$.

16.7 Reliability problem formulation

The general definition of reliabilty of an item can be stated as:

> $\text{Rel}(t,\Omega;\Gamma,\Theta)$ = the probability that an item occupying a logical or physical domain, Ω, will perform of its required function(s), Γ, under given conditions, Θ, for a specified time interval $(0,t]$.

The analyst needs to consider the following points while deciding on an appropriate approach to reliability analysis.

16.7.1 System or component

What details do I need to define the domain, Ω, of the item of interest? What resolution do I need to look at Ω? How many degrees of freedom are necessary for my purpose?

i. Is the item of interest made up of two or more units (logical or physical)?
ii. Are these units logically/physically connected?

iii. Can my item's performance be described only in terms of those of the units?

System reliability: If the answers to questions i – iii are yes, one has a systems reliability problem in hand. A *component* of such a system is that "unit" which cannot be resolved further into simpler units.

Component reliability: The item of interest is made up of only one unit that does not need any further resolution for the present purpose.

The above categorization has no bearing on actual size of the item. If the item can be described by a single degree of freedom for the purpose at hand, it amounts to a component reliability problem. For example, a prismatic bar in uniaxial tension subject to failure by fracture is a component reliability problem if details of the fracture process are not important. The same bar represents a system reliability problem if microstructural details of failure at the grain boundary level is required.

16.7.2 Physics based or phenomenological

What is my method of defining satisfactory performance, Γ?

Is the definition of satisfactory performance by the item:

i. Available in terms of the physics of the problem?
ii. Is the randomness in the physical variables known?
iii. Is their time-dependence known?

Physics-based reliability: If the answers to questions i – iii are yes, one has a physics based reliablity problem in hand. It is often called "capacity-demand" or "stress-strength-time" reliability problem, a special case of which is the structural reliability problem.

Phenomenological reliability: If instead failure is identified by observation, and time to failure is the only available random quantity describing each component, then one has a phenomenological reliability problem – typically a time dependent reliability problem given in terms of TTFs.

16.8 How to improve reliability

16.8.1 Simpify design

Remove common causes of failure as much as possible.

16.8.2 Make components stronger

This may not be possible beyond a point.

16.8.3 Introduce redundancy

Introduce additional load paths through the system. Identify weak components.