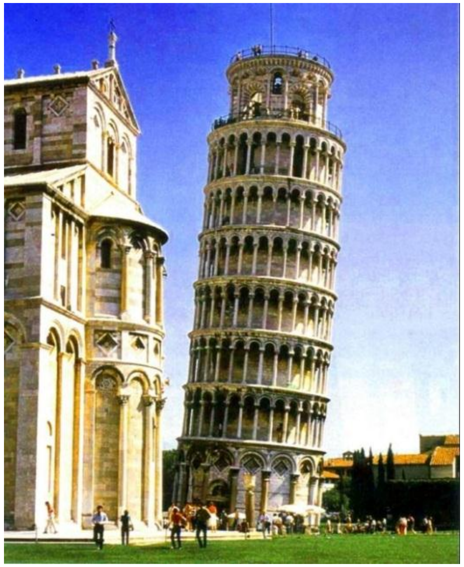
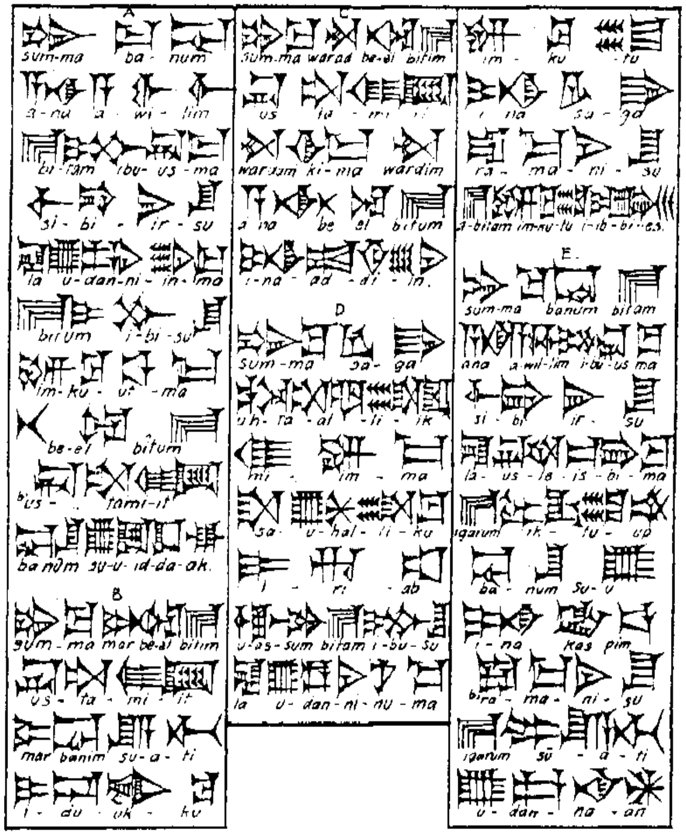
STRUCTURAL SAFETY

Structural Safety - Introduction



Importance of intuition ==> Engineering judgment

Structural Safety - Introduction

- If the builder has made a house for a man and has not made his work sound, and if the house, which he has built, has collapsed and so caused the death of the owner, the builder shall be put to death.
- If it causes the death of owner's son, a son of the builder shall be put to death.
- If it causes the death of a slave of the owner of the house, he shall give to the owner a slave of equal value.
- If it destroys property, he shall restore whatever is destroyed and because he did not make the house, which he built firm and it collapsed, he shall rebuild the house, which collapsed, at his own expense.
- If a builder build a house for a man and do not make its construction meet the requirements and a wall fall in, that builder shall strengthen the wall at his own expense.

Structural Safety - Introduction

Obviously one cannot find a formal definition of **structural safety** in the "Code of Hammurabi." However, most probably the rules in the code discouraged building of unsafe structures.

IMPORTANCE OF ENFORCEMENT OF QUALITY ASSURANCE

CONCEPT OF STRUCTURAL SAFETY

The main objective of structural design is to provide economically a structural system, which will remain functional under different loadings foreseen for that structure.

To remain functional the structure should not collapse and should remain serviceable. Collapse can be caused primarily by material failure or instability. In general, both collapse and being unserviceable are considered as "failure."

Concept of Structural Safety

Collapse: Lack of sufficient strength, i.e. resistance against load effects.

Loss of serviceability: Exceedance of tolerable limits violating service conditions. Excessive deformations, excessive vibrations and excessive cracking are examples of this violation.

Concept of Structural Safety

The amount of vibration, deformation or cracking which can be tolerated depends on the function of the structure or structural member and its interaction with nonstructural components.

For example, less deformation is tolerated for beams carrying partitions, because such deflection can cause undesirable cracks in the partition walls.

Concept of Structural Safety

In general, a structure is said to be safe if the resistance of the structure is equal to or greater than the load effect.

Denoting resistance as R and load effect as F, safety can simply be expressed by the following equation.

$$R > F$$

Modern Approach to Structural Safety

a) General: " Working Stress Design" or "Elastic Design

Factor of Safety: A single reduction factor applied on strength to get allowable values (ultimate or yield) in design.

The safety factors (or allowable stresses obtained using these safety factors) specified in the design codes were determined empirically and were usually very conservative.

Modern Approach to Structural Safety

As time passed, design techniques improved, more sophisticated approaches to analysis became available, material, member and system behavior became better understood through extensive testing. As a result of these, the classical conservative approach to structural safety was reconsidered.

This reconsideration resulted in a new approach, which may be called "*Probabilistic* or *Semi-probabilistic Approach.*"

MODERN APPROACH TO STRUCTURAL SAFETY

b) Probabilistic or Semi-probabilistic Approach

If both resistance and load effect could be considered as deterministic variables, then safety could conveniently be expressed by:

$$R > F$$

Question: Are "R" and "F" deterministic values?

Variation of the Design Load

Loads acting on a structure would vary considerably. While some types of loading can be predicted with sufficient accuracy (like own weight of structural members), for most types of loading there was no adequate data, therefore values recommended in the codes were based on past experience and usually much higher values were used than the expected values.

Variation of the Design Load

Today for some types of loading adequate statistical data is available; therefore, the design load can be established realistically. For some other types of loading, for example earthquake loading, the statistical data is limited and it is not yet possible to establish the load realistically. It is important to realize that there is always a possibility of having a load effect exceeding the assumed design value.

VARIATION OF RESISTANCE

The actual resistance at a certain time can be quite different from the resistance assumed in design. Due to uncertainties involved, it is not even possible to compute the actual resistance of the structure. Some of these uncertainties are given in the following slides.

Variation of Resistance

- The actual strength of the material can be different from the assumed strength. For steel reinforcement, variation in strength of $\pm 5\%$ is unavoidable. If the variation of concrete strength on the job is within $\pm 20\%$ of the assumed strength, this would be considered to be quite satisfactory.

Variation of Resistance

- The actual dimensions of structural members can be different from those shown on the design drawings. An error of 15 mm in the depth of a beam whose dimension is 800 mm may not be critical. However, if the same magnitude of error is made in a slab with a thickness of 100 mm, the strength of the slab changes at least by 15%, which is quite significant.

Variation of Resistance

- Steel areas can be different from the specified values. For example, when the actual diameter of a ∅8 bar (nominal diameter of 8 mm) is 7.7 mm, the steel area provided becomes 12% less than the specified value.

VARIATION OF RESISTANCE

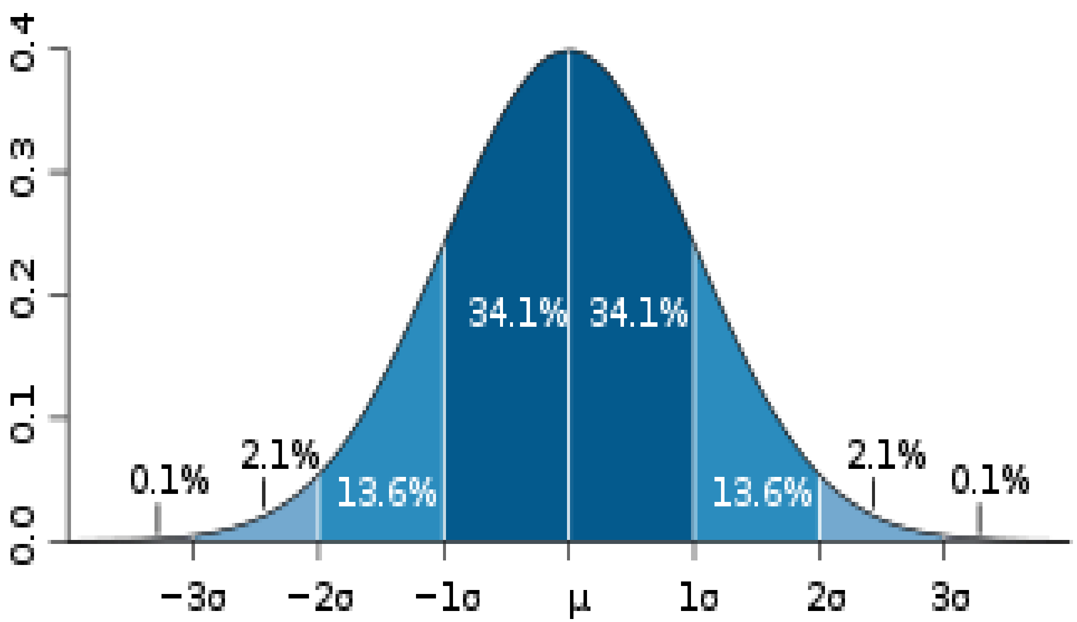
- The behavior and strength of the material can change as a function of time. As an example, consider concrete that is subjected to sustained loading. Experimental results reveal that the strength decreases as a function of time although this decrease is not more than about 20%. More important than this, the modulus of elasticity can change significantly, 200% or even 300%.

Variation of Resistance

Variations in resistance and load effects have been shown that both resistance and load effects are random variables and can be represented by statistical distributions.

Researchers have concluded that resistance (mainly strength of the material used) can be represented with reasonable accuracy using the **normal distribution function**.

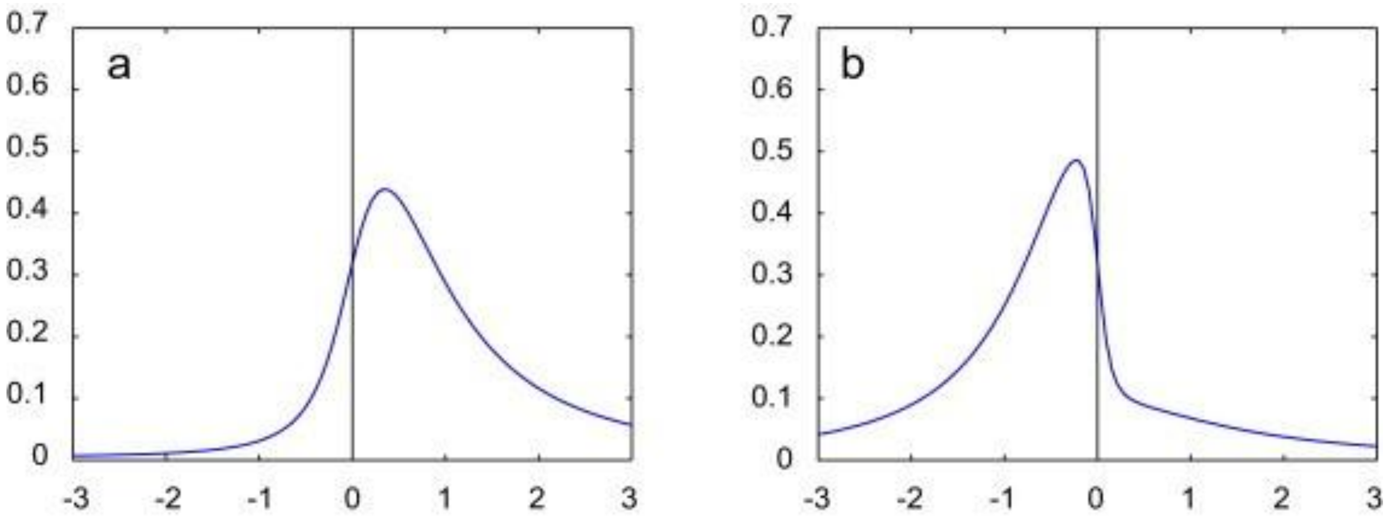
Normal Distribution



Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for about 68% of the set (dark blue), while two standard deviations from the mean (medium and dark blue) account for about 95%, and three standard deviations (light, medium, and dark blue) account for about 99.7%.

VARIATION OF DESIGN LOADS

Surveys on different types of loads have shown that the type of distribution depends on the type of loading. These studies have also shown that in most cases distribution for the load is unsymmetrical (skew).

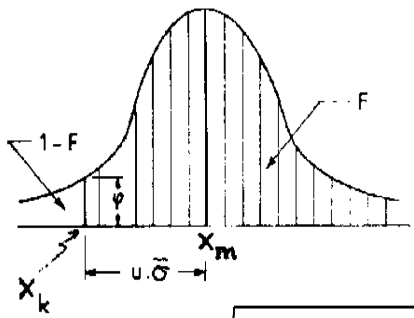


Variation of Design Loads

Although this is the case, for simplicity, both resistance and load effects are represented by normal distribution curves.

Many researchers agree that this does not introduce any serious error in our safety calculations.

Normal Distribution



$$x_m = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \bar{\sigma} = \sqrt{\frac{\sum (x_i - x_m)^2}{n-1}}$$

If the area under the curve is unity, then the probability having a sample less than the specified value x_k is expressed as 1-F. The difference between the mean value, x_m and the specified value, x_k is $u \cdot \sigma$.

u	φ	F	1 - F
0,000	0,399	0,500	0,500
0,253	0,389	0,600	0,400
0,500	0,352	0,691	0,309
0,524	0,347	0,700	0,300
0,842	0,280	0,800	0,200
1,000	0,242	0,841	0,159
1,282	0,176	0,900	0,100
1,500	0,129	0,933	0,067
1,645	0,103	0,950	0,050
1,960	0,058	0,975	0,025
2,000	0,054	0,977	0,023
2,326	0,027	0,990	0,010
2,500	0,018	0,994	0,006
3,000	$4{,}43 \cdot 10^{-3}$	$1 - 1{,}35 \cdot 10^{-3}$	$1{,}35 \cdot 10^{-3}$
3,500	$8{,}73 \cdot 10^{-4}$	$1 - 2{,}33 \cdot 10^{-4}$	$2{,}33 \cdot 10^{-4}$
4,000	$1{,}34 \cdot 10^{-4}$	$1 - 3{,}17 \cdot 10^{-5}$	$3{,}17 \cdot 10^{-5}$
4,500	$1{,}60 \cdot 10^{-5}$	$1 - 3{,}40 \cdot 10^{-6}$	$3{,}40 \cdot 10^{-6}$
5,000	$1{,}49 \cdot 10^{-6}$	$1 - 2{,}87 \cdot 10^{-7}$	$2{,}87 \cdot 10^{-7}$
6,000	$6{,}08 \cdot 10^{-9}$	$1 - 9{,}87 \cdot 10^{-10}$	$9{,}87 \cdot 10^{-10}$
7,000	$9{,}14 \cdot 10^{-12}$	$1 - 1{,}28 \cdot 10^{-12}$	$1{,}28 \cdot 10^{-12}$
8,000	$5{,}05 \cdot 10^{-15}$	$1 - 6{,}22 \cdot 10^{-16}$	$6{,}22 \cdot 10^{-16}$

Modern Approach to Structural Safety

We now know that, as "R" and "F" are not deterministic we cannot use the following expression.

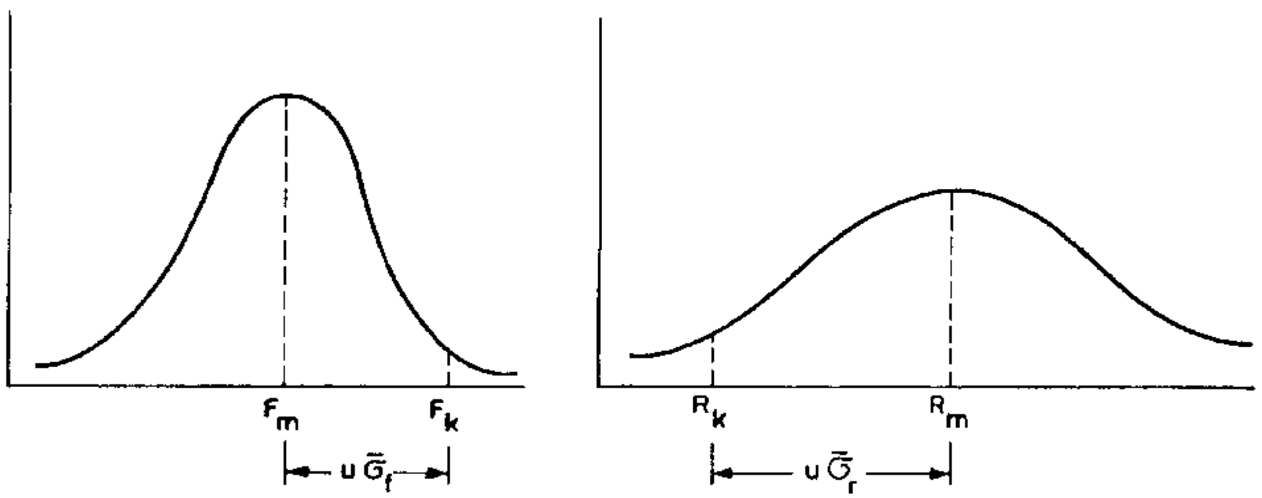
$$R > F$$

Q: Since both R and F are random variables, can we use the following?

$$R_m > F_m$$

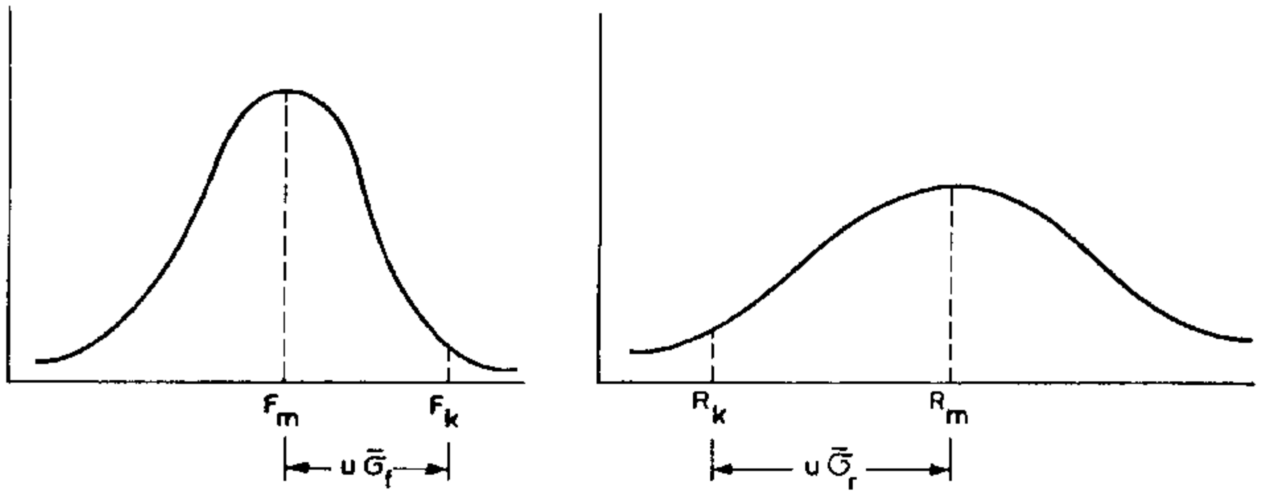
Note that, 50% of all possible resistances are < R_m and 50% of all load effects are > F_m. Probability of Failure = $0.5 \times 0.5 = 0.25$, i.e. 25% this is unacceptably high.

R_K and F_K: the Characteristic Values



R_k: The resistance below which only a small percentage will fall. The probability of having a resistance less than R_k is small and prespecified (5, 10 or 15%).

R_K AND F_K: THE CHARACTERISTIC VALUES



F_k: The characteristic load effect is the magnitude of the load effect which has a chance to be exceeded by a predetermined probability (probability of exceeding this value is 5, 10 or 15%).

R_K AND F_K: THE CHARACTERISTIC VALUES

With these definitions in mind, characteristic load effect and resistance can be expressed by the following equations:

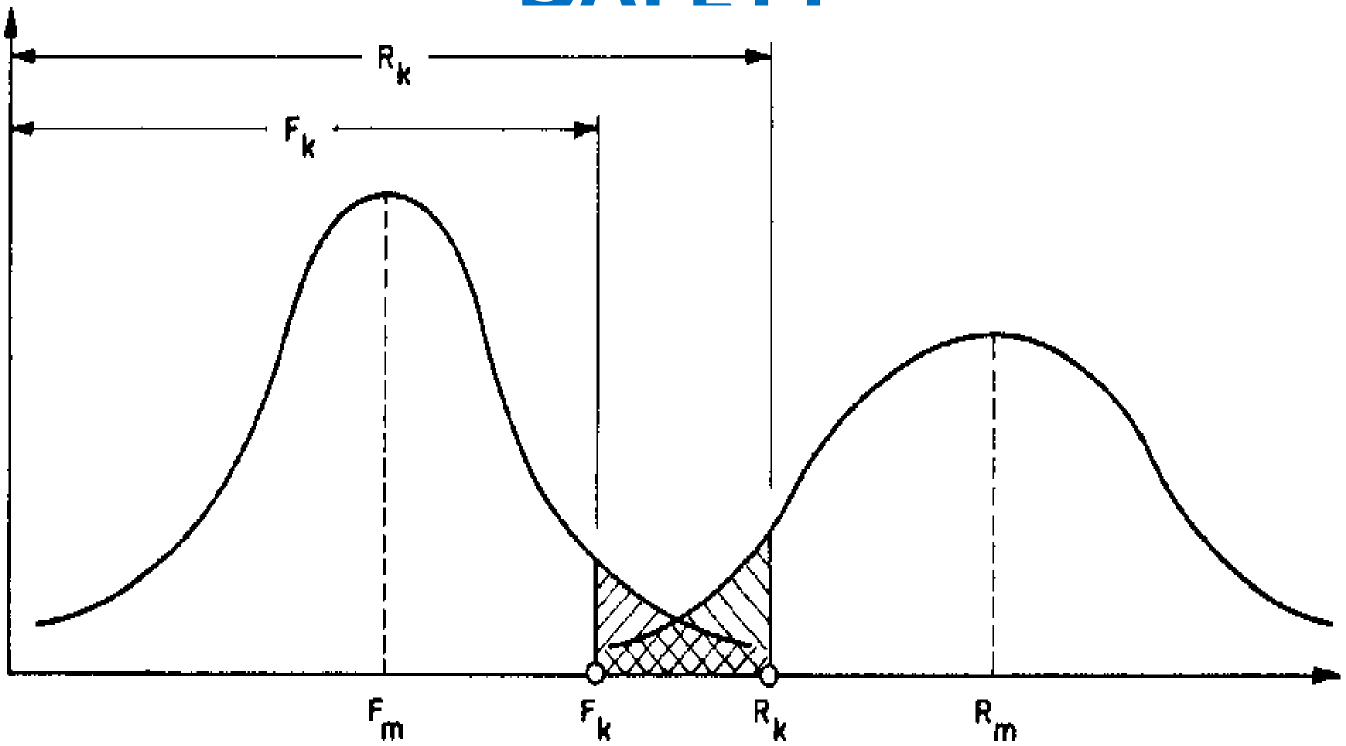
$$R_k = R_m - u\overline{\sigma}\,; \quad F_k = F_m + u\overline{\sigma}$$

Modern Approach to Structural Safety

From the above discussion, it becomes obvious that safety can only be expressed in terms of probability. To be more realistic and specific, R and F values to be used in the safety expression are the characteristic values, R_k and F_k. Thus;

$$F_k < R_k$$

Modern Approach to Structural Safety



$$F_k < R_k$$

Modern Approach to Structural Safety

In general the safety provided by $F_k < R_k$ is not adequate. Therefore to take care of the possibilities of having values less than R_k and greater than F_k, R_k is divided by a factor, γ_m and F_k is multiplied by another factor, γ_f.
γ_m is called the material factor and γ_f is called the load factor.

$$\text{Material factor} \qquad \gamma_m \geq 1.0$$

$$\text{Load factor} \qquad \gamma_f \geq 1.0$$

Modern Approach to Structural Safety

In the light of the above discussion safety can be defined as:

$$\frac{R_k}{\gamma_m} \geq F_k \gamma_f$$

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