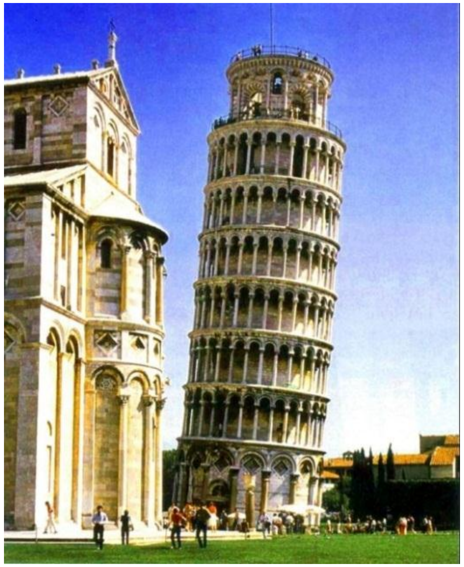
STRUCTURAL SAFETY

Structural Safety - Introduction





Importance of intuition ==> Engineering judgment

Structural Safety - Introduction

Hammurabi Code

- 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 <u>the actual resistance of the structure</u>. 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 $\varnothing 8$ bar (nominal diameter of 8 mm) is 7.7 mm, the steel area provided becomes 12% less than the specified value.

Variation of Resistance

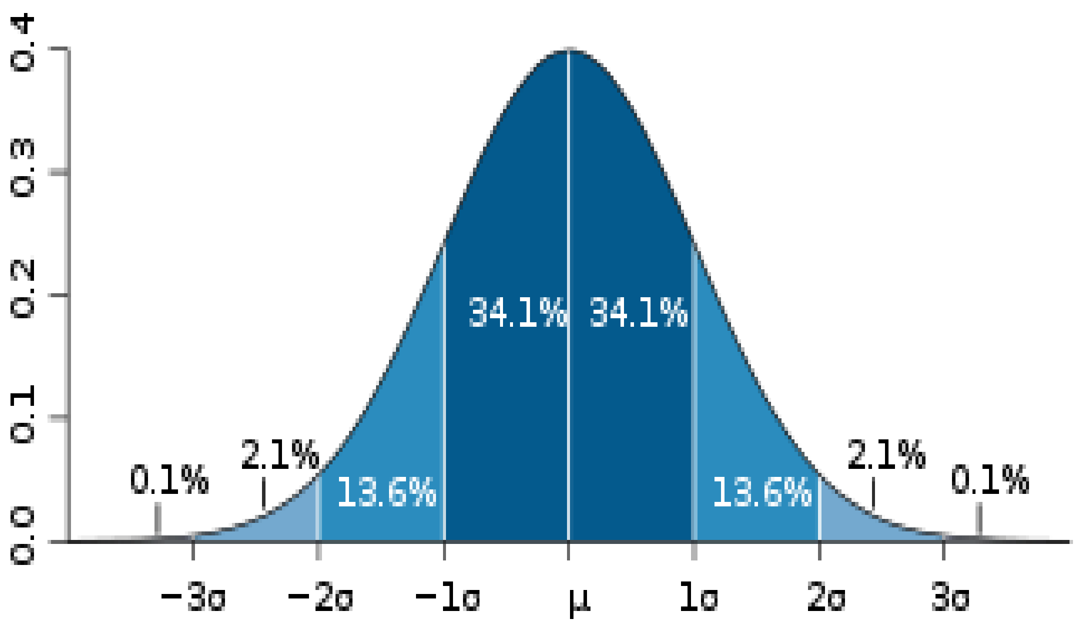
The behavior and strength of the material can change as a function of time. As an example, consider concrete that is subjected to sustained loading. Experimental results reveal that the strength decreases as a function of time although this decrease is not more than about 20%. More important than this,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

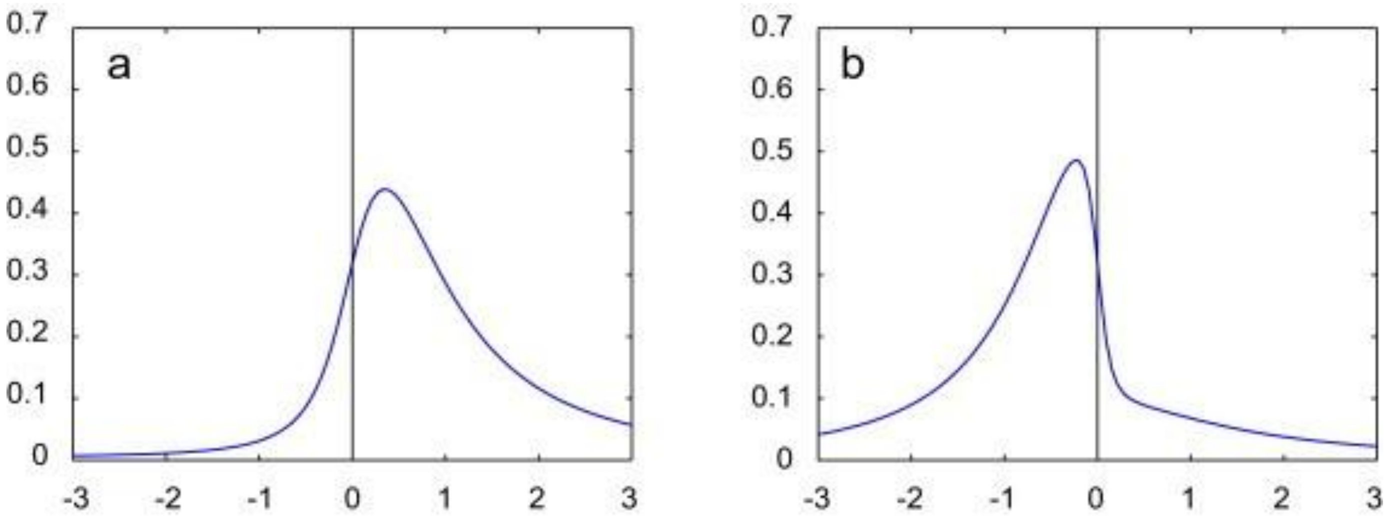
Normal Distribution



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).

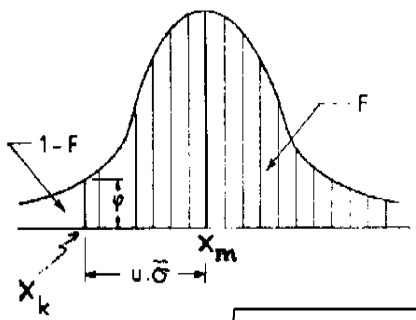


Variation of Design Loads

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.

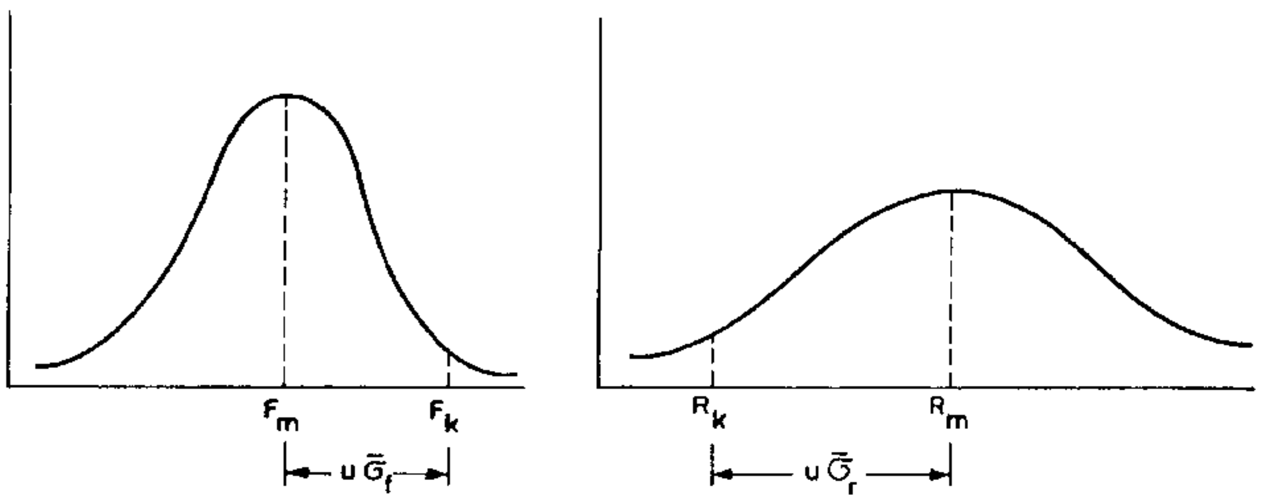
$$R > F$$

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

$$R_m > F_m$$

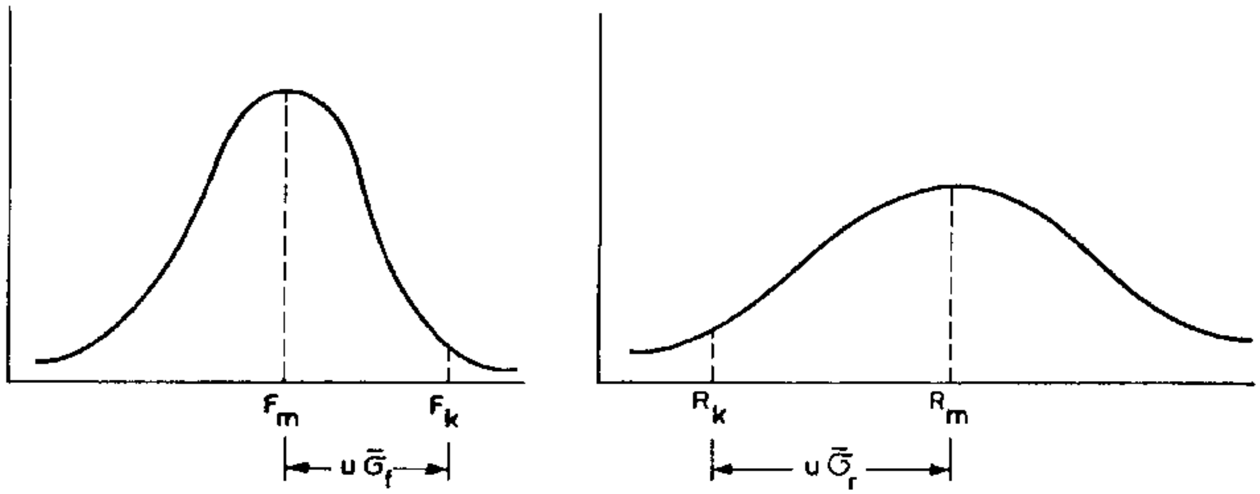
Note that, 50% of all possible resistances are < R_m and 50% of all load effects are > F_m. Probability of Failure = $0.5 \times 0.5 = 0.25$, i.e. 25% this is unacceptably high.

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:

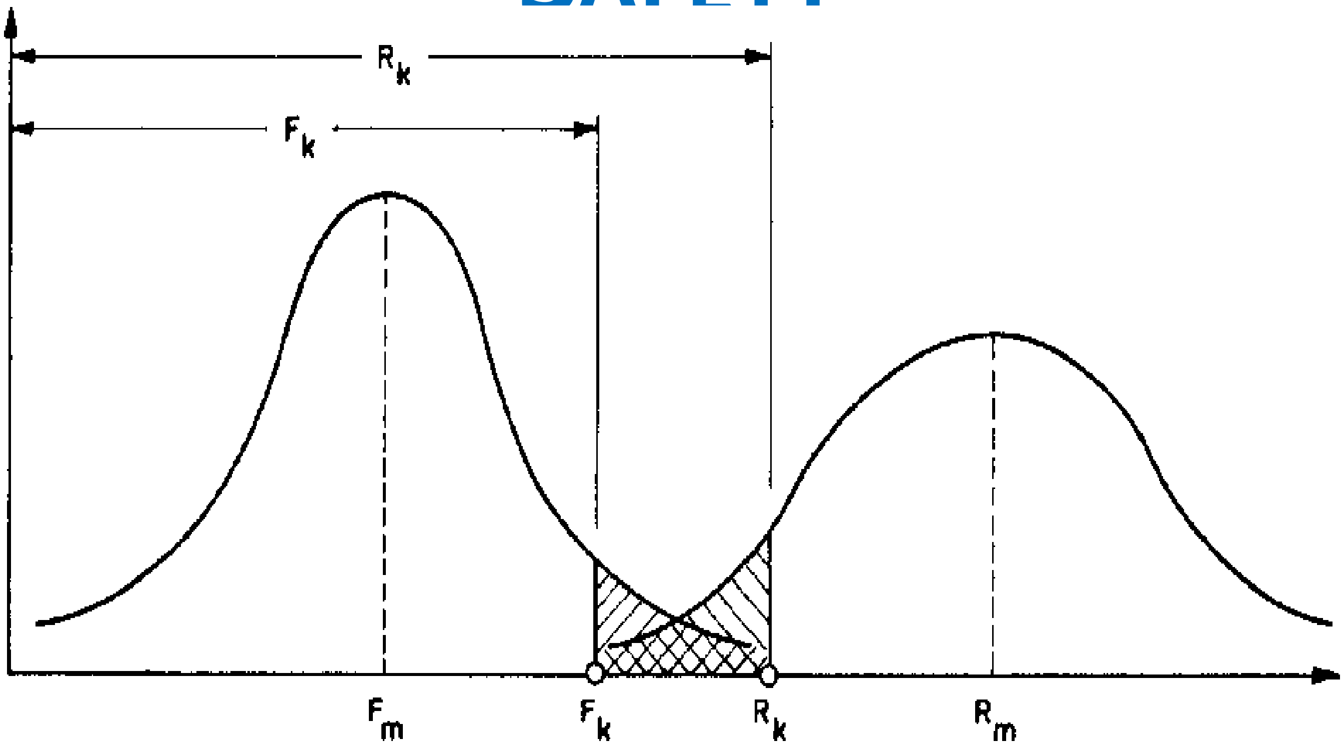
$$R_k = R_m - u\overline{\sigma}\,; \quad F_k = F_m + u\overline{\sigma}$$

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:

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

Modern Approach to Structural Safety

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

Modern Approach to Structural Safety

In working stress design, γ_m and γ_f are combined into one factor, called, "factor of safety". If the factor of safety is denoted as "FS", then the safety equation can be rewritten as shown below.

$$\frac{R_k}{\gamma_m \gamma_f} = \frac{R_k}{(FS)} \geq F_k$$

Modern Approach to Structural Safety

$$\cancel{\frac{R_k}{\gamma_m \gamma_f} = \frac{R_k}{(FS)} \geq F_k}$$

Unfortunately, for reinforced concrete structures R_k and F_k are not independent variables, hence the transformation given in above expression is not permissible.

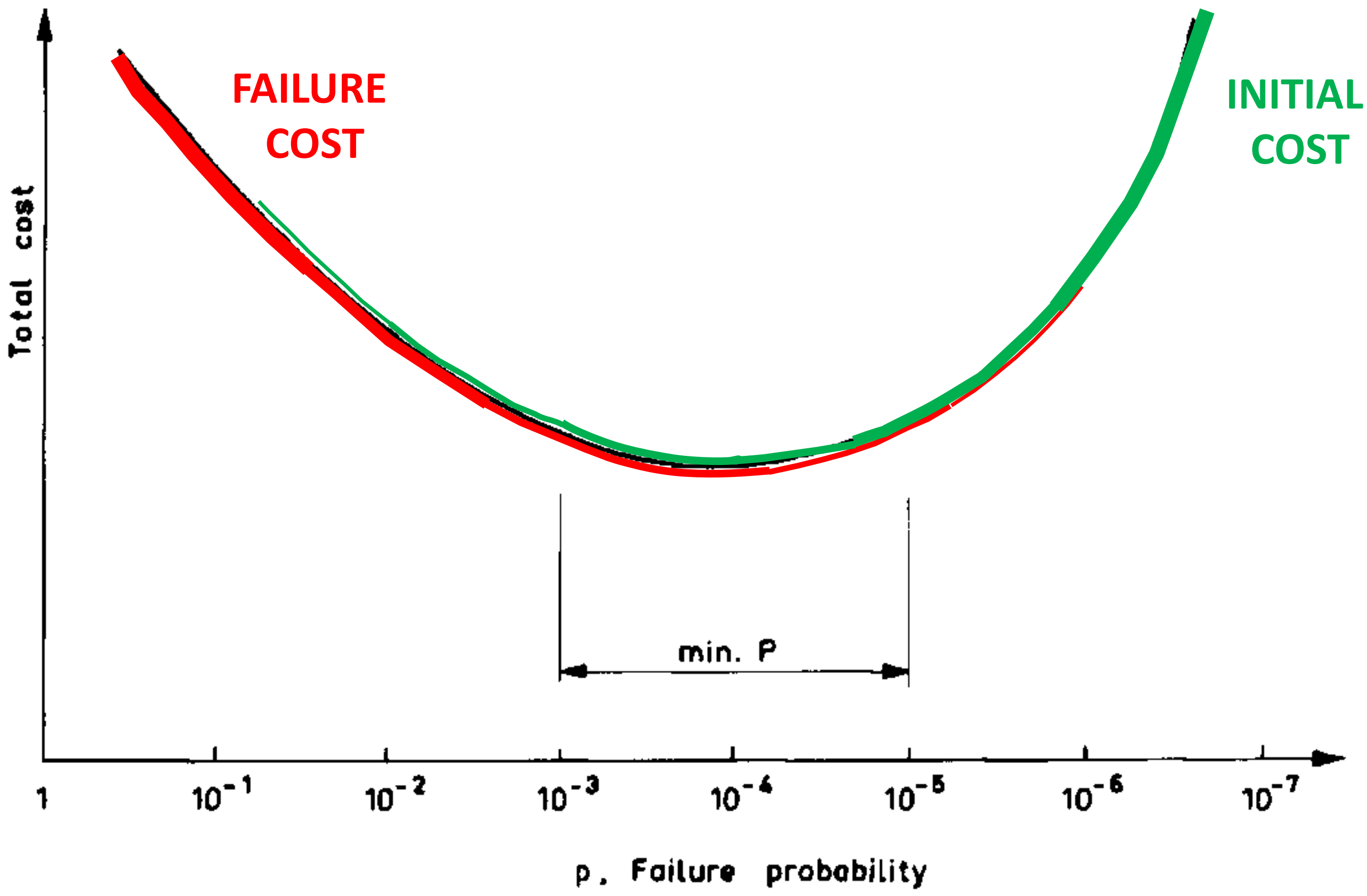
Modern Approach to Structural Safety

The magnitudes of γ_m and γ_f depend on many factors, among which perhaps the probability of failure assumed is the most important one. The main objective in applying γ_m and γ_f factors is to reduce the probability of failure to a certain level. Besides, γ_m and γ_f depend on the type and purpose of the structure, type of material, type of loading etc. These will be discussed later in this chapter.

Structural Safety and Cost

"*The strength of the structure must be weighed against the corresponding risk of failure or other damage so that the total cost of the structure, which is equal to the capital expenditure plus the probable cost of failure or other damage, shall be minimum.*"

STRUCTURAL SAFETY AND COST



Limit State Design

There are mainly two limit states. These are (a) the Ultimate Limit State and (b) Serviceability Limit State.

Ultimate Limit State (ULS) may be reached due to:

- Loss of equilibrium of a part or the whole of the structure,
- Rupture of critical sections,
- Loss of stability (formation a mechanism),
- Buckling due to instability,
- Fatigue.

Ultimate Limit State

In the ULS, loads considered should be the characteristic loads

$$F_k = F_m + u\,\overline{\sigma}$$

This requires the knowledge of F_m, u and σ. In the absence of this information the nominal load values given in the National Codes should be used as the characteristic values.

Ultimate Limit State

At the ULS, each type of loading should be multiplied by a different load factor depending on how accurately the load can be estimated. For example, the load factor applied to the dead load is smaller as compared to the factor applied to the live load, because the dead load can be calculated with fairly good degree of precision.

ULTIMATE LIMIT STATE

When several types of loads act at the same time, probability of each load reaching the characteristic value decreases. Therefore, for such combinations an additional factor, called, the "**Combination Factor**" (which is $\psi_0 \leq 1.0$) is introduced.

$$F_d = \gamma_g G + \gamma_q \{Q_{lk} + \sum \psi_{oi} Q_{ik}\}$$

F_d = design load	**Q_{ik} = other live load**
G = dead load	**Q_{lk} = basic live load,**
γ_g = load factor for the dead load	**ψ_{oi} = combination factor which less than unity.**
γ_{qv} = load factor for the live load	

ULTIMATE LIMIT STATE

For the ULS, the material strengths to be used are called “the Design Strength". Design strengths are obtained by dividing the characteristic strength by the proper material factors.

$$f_d = \frac{f_k}{\gamma_m}$$

where; f_d = design strength, f_k = characteristic strength and γ_m = material factor which is equal to or greater than unity.

Ultimate Limit State

Design strengths are defined for concrete and steel using different material factors.

Steel: $f_{yd} = \dfrac{f_{yk}}{\gamma_{ms}}$; Concrete: $f_{cd} = \dfrac{f_{ck}}{\gamma_{mc}}$

Since variation in concrete strength is much greater than the variation in steel strength, γ_{mc} should be greater than γ_{ms}.

ULTIMATE LIMIT STATE

The greatest advantage of the limit state design is that, different load factors and different material factors can be applied to different types of loads and materials. Then the designer can adjust these factors depending on the degree of precision in determining the loads or the material strengths and their distributions. This of course cannot be done in working stress design method, where only a single factor of safety is used.

THIS MEANS ===> ECONOMY!

Serviceability Limit State (SLS)

A structure can be unserviceable if there is:

(a) excessive cracking,

(b) excessive deformations, or

(c) excessive vibration.

Then, for every structure and structural component, the serviceability limit state should be checked because the structure has to remain functional as well as safe against collapse.

Serviceability Limit State (SLS)

A structure can be unserviceable if there is:

(a) excessive cracking,

(b) excessive deformations, or

(c) excessive vibration.

Then, for every structure and structural component, the serviceability limit state should be checked because the structure has to remain functional.

In SLS, loads are multiplied by load factors and material strengths are divided by material factors similar to ULS. However, for serviceability limit state, all load factors and material factors should be taken as 1.0.

Safety Provisions in TS-500

The Turkish Code released by the **Turkish Standards Organization** in 1984 takes **Limit State Design** as the basis for the safety provisions. The Turkish Code uses the same principles as **European Code**, i.e. load and combination factors are applied to the characteristic loads and characteristic material strengths are divided by the material factors to obtain what is called **"the design strength.“**

Although the procedure is same, factors used are somewhat different from the European Code.

Safety Provisions in TS-500

Load factors and possible combinations for the ultimate limit state are as follows:

GRAVITY + EARTHQUAKE	GRAVITY + WIND
1.4G + 1.6Q	1.4G + 1.6Q
1.0G + 1.0Q + 1.0E	1.0G + 1.3Q + 1.3W
1.0G + 1.2Q + 1.2T	1.0G + 1.2Q + 1.2T
0.9G + 1.0E	0.9G + 1.3W

Safety Provisions in TS-500

E is the earthquake load and **W** is the wind load. It is assumed that wind and earthquake loadings do not occur at the same time. **T** is the load effect created by deformations, like differential settlement, creep, shrinkage or temperature changes.

Since adequate statistical data is not yet available, it is recommended to assume that the loads given in the related standard (TS-498) are the characteristic loads.

Safety Provisions in TS-500

In TS-500, it is stated that the **characteristic yield strength for steel can** be taken as the **minimum yield strength** specified in the related standard, (TS-708). The **design strength of steel** is defined as:

Safety Provisions in TS-500

$$f_{yd} = \frac{f_{yk}}{\gamma_{ms}} \qquad \text{or} \qquad f_{ywd} = \frac{f_{ywk}}{\gamma_{ms}}$$

γ_{ms} = 1.15 (reinforcing steel)

f_{yk} and f_{ywk} are the characteristic strengths of longitudinal and transverse steels.

Safety Provisions in TS-500

For concrete, **<u>the characteristic value is the strength</u>** on which the design is based (strength marked on the design drawing). The **<u>design strength for concrete</u>** are defined as,

$$f_{cd} = \frac{f_{ck}}{\gamma_{mc}} \qquad \text{or} \qquad f_{ctd} = \frac{f_{ctk}}{\gamma_{mc}}$$

Safety Provisions in TS-500

$$f_{cd} = \frac{f_{ck}}{\gamma_{mc}} \qquad \text{or} \qquad f_{ctd} = \frac{f_{ctk}}{\gamma_{mc}}$$

where;

f_{ck} = Characteristic compressive strength of concrete.

f_{ctk} = Characteristic tensile strength of concrete.

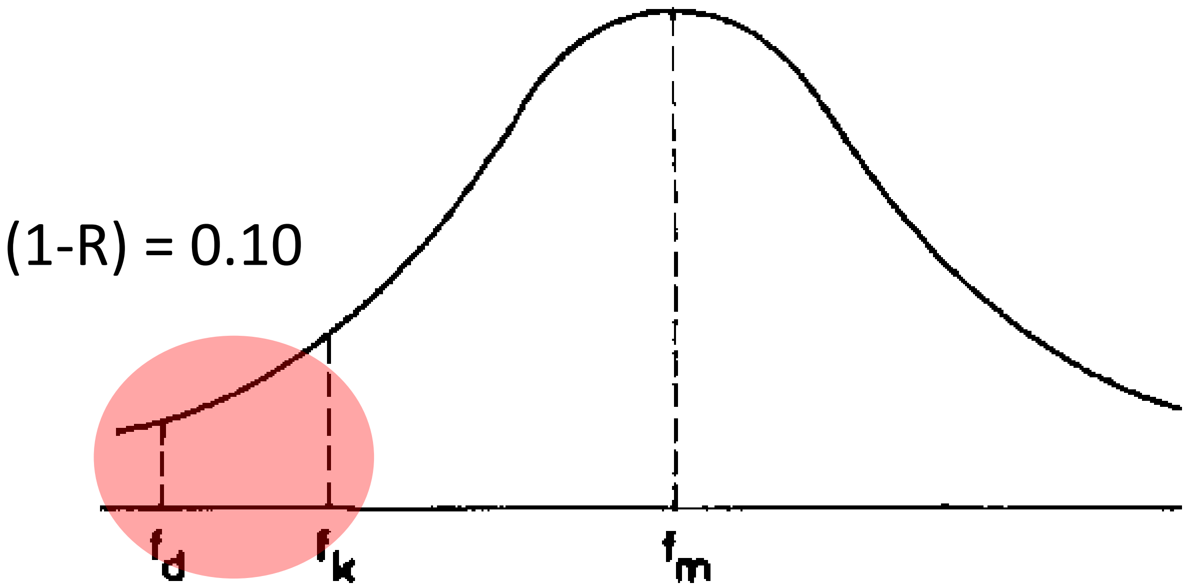
Values of material factors to be used in ultimate limit state are,

γ_{mc} = 1.5 (cast in place concrete)

γ_{mc} = 1.4 (precast concrete)

γ_{mc} = 1.6 or 1.7 (if standard control is not available)

SAFETY PROVISIONS IN TS-500



Mean, characteristic and design values for concrete strengths are marked on normal distribution curves shown in figure.

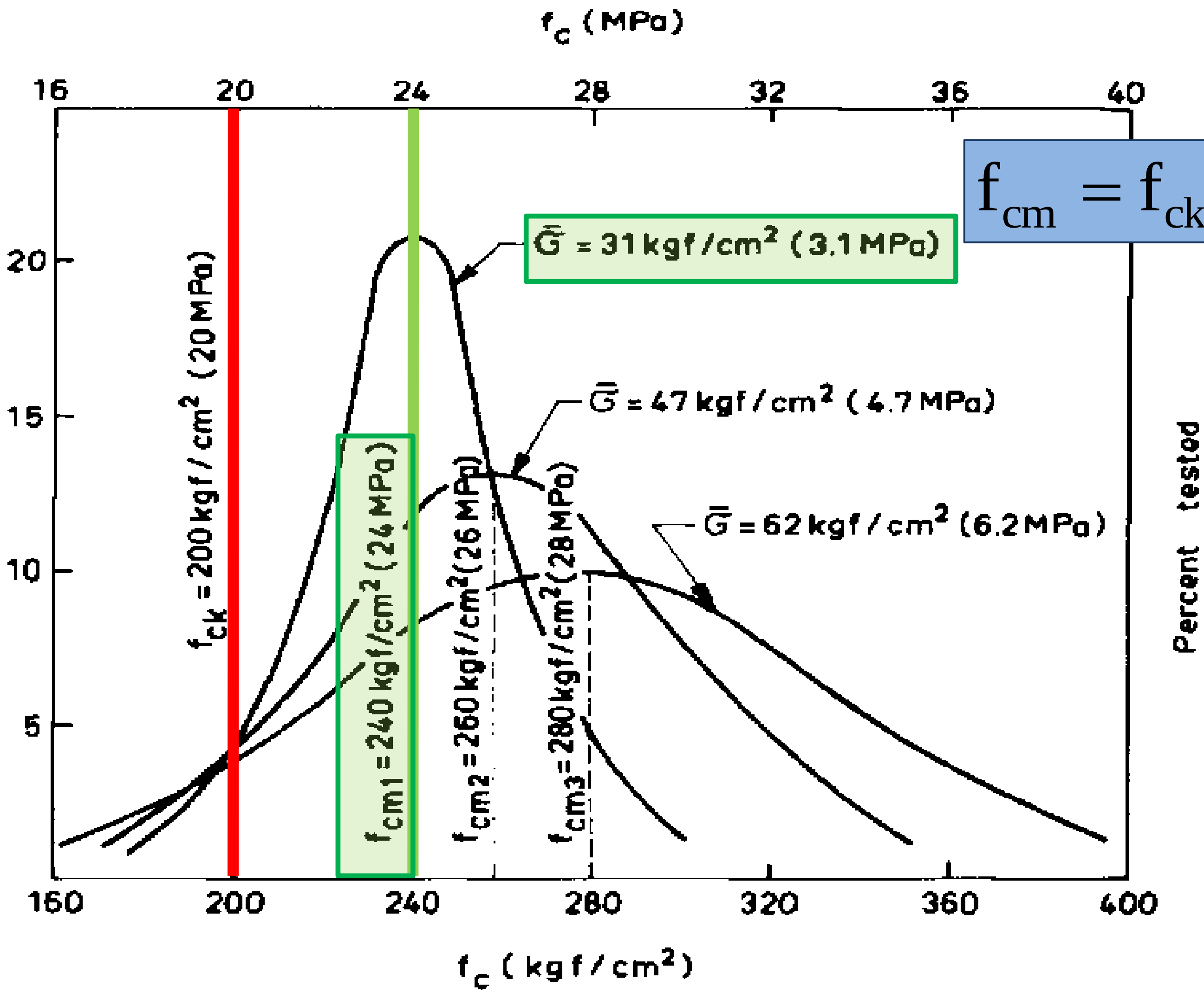
f_{ck} (or f_{ctk} if tension) is the value on which the design is based. It refers to the grade of concrete given in Chapter 1.

f_{cd} (or f_{ctd}) is the strength to be used in all design computations.

f_{cm} is the strength on which the mix design is based, or it is to strength to be specified to the contractor. In TS-500 the relationship between f_{cm} and f_{ck} is expressed as,

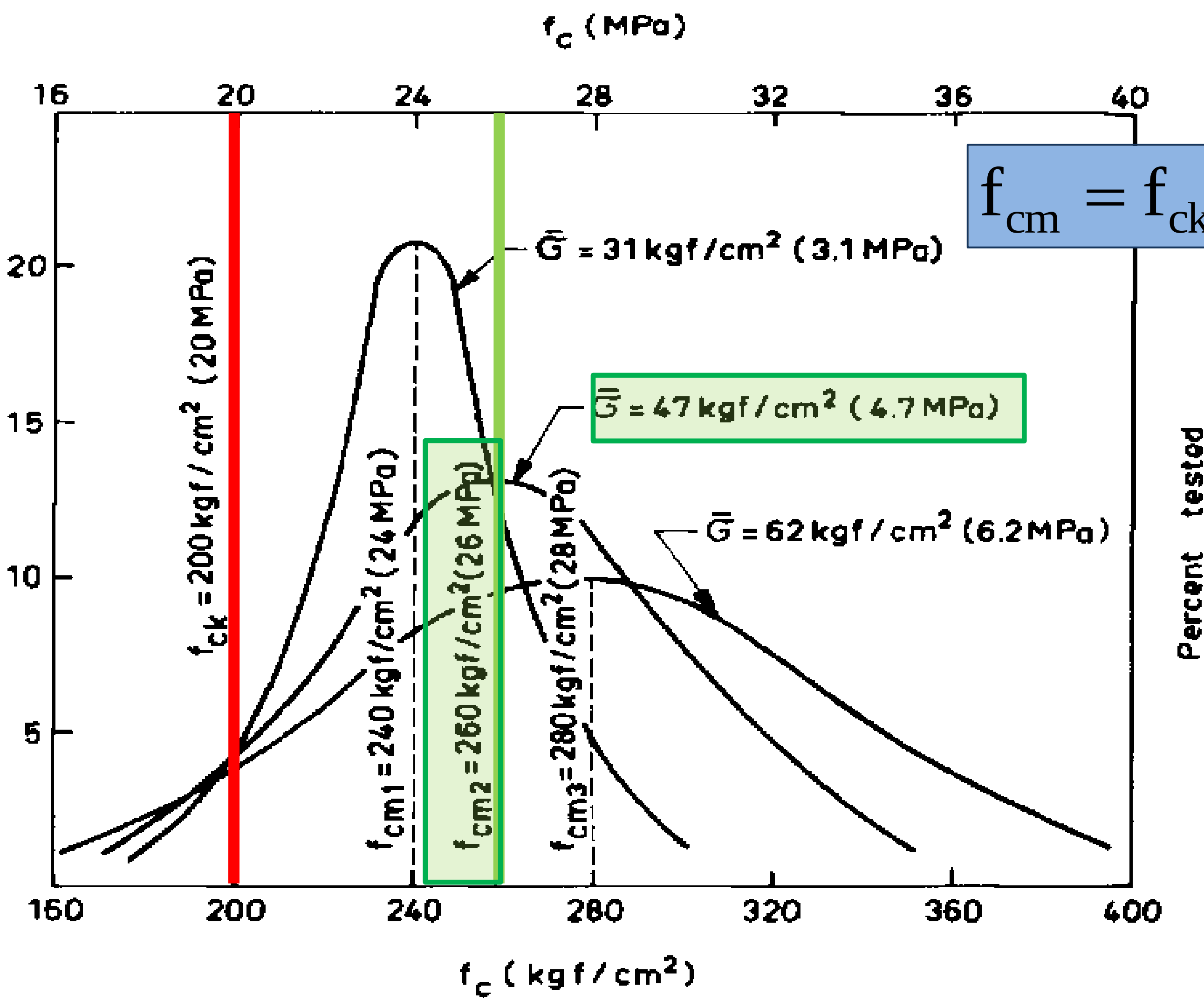
$$f_{cm} = f_{ck} + 1.28\overline{\sigma}$$

SAFETY PROVISIONS IN TS-500



$$f_{cm} = f_{ck} + 1.28\overline{\sigma}$$

SAFETY PROVISIONS IN TS-500



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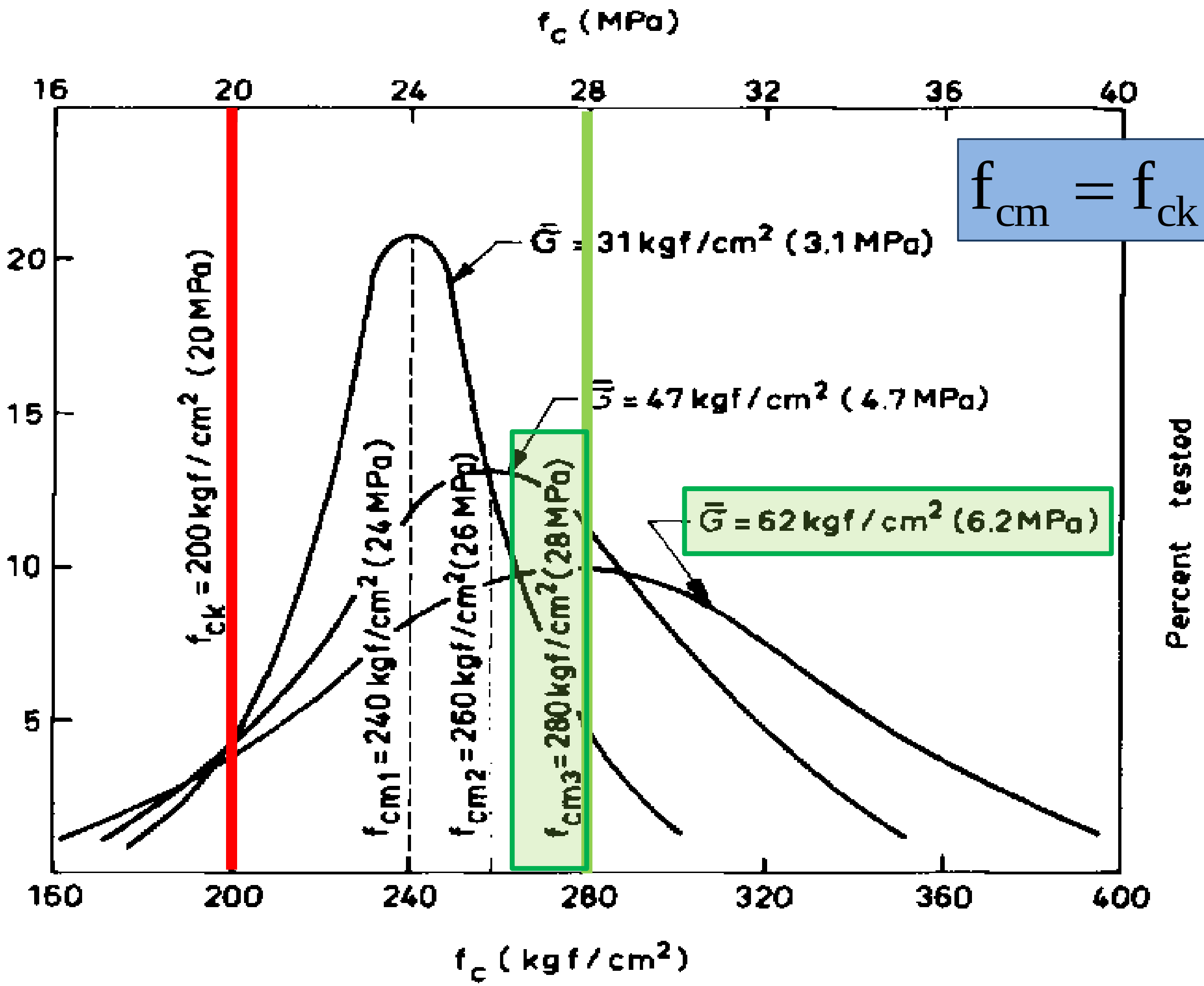
SAFETY PROVISIONS IN TS-500



$$f_{cm} = f_{ck} + 1.28\overline{\sigma}$$

SAFETY PROVISIONS IN TS-500

When it is not possible to estimate the standard deviation , the code recommends the following equation to be used.

$$f_{cm} = f_{ck} + \Delta f$$

Δf should be taken as 4 MPa for concrete grades of C12 and C16, 6 MPa for C20, C25 and C30 and 8 MPa for higher strength concrete.

LIVE LOAD ARRANGEMENTS

The dead load exists on all spans of the structure. However live load may or may not be present on a given span. Therefore TS500-2000 requires the live load to be arranged in such a way as to produce the maximum internal force at that point. The internal force can be moment, shear or axial load.

It is not difficult to find the necessary live load arrangements which will result in maximum internal forces. With the help of "***influence line***" knowledge it is very easy to decide on the most critical live load arrangements on structures.

What is an influence line?

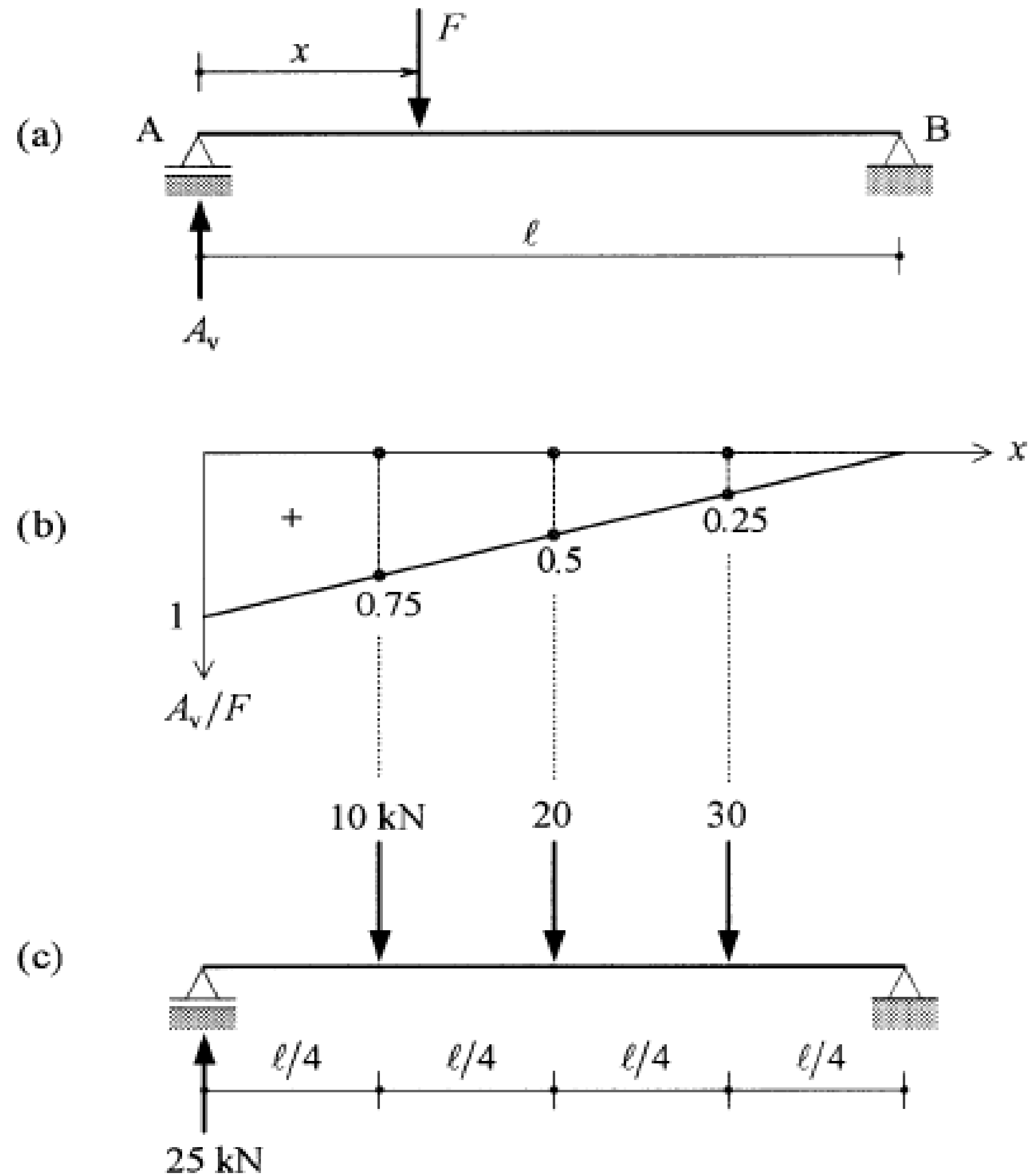
In many structures, the support reactions and section forces depend not only on the magnitudes of the loads, but also on their placement. This is particularly true for bridges, where an important part of the load consists of moving vehicles.

If we want to choose the dimensions of a structural element to check it for strength and rigidity, it is important to know the location at which the load or set of loads generate the most severe effects.

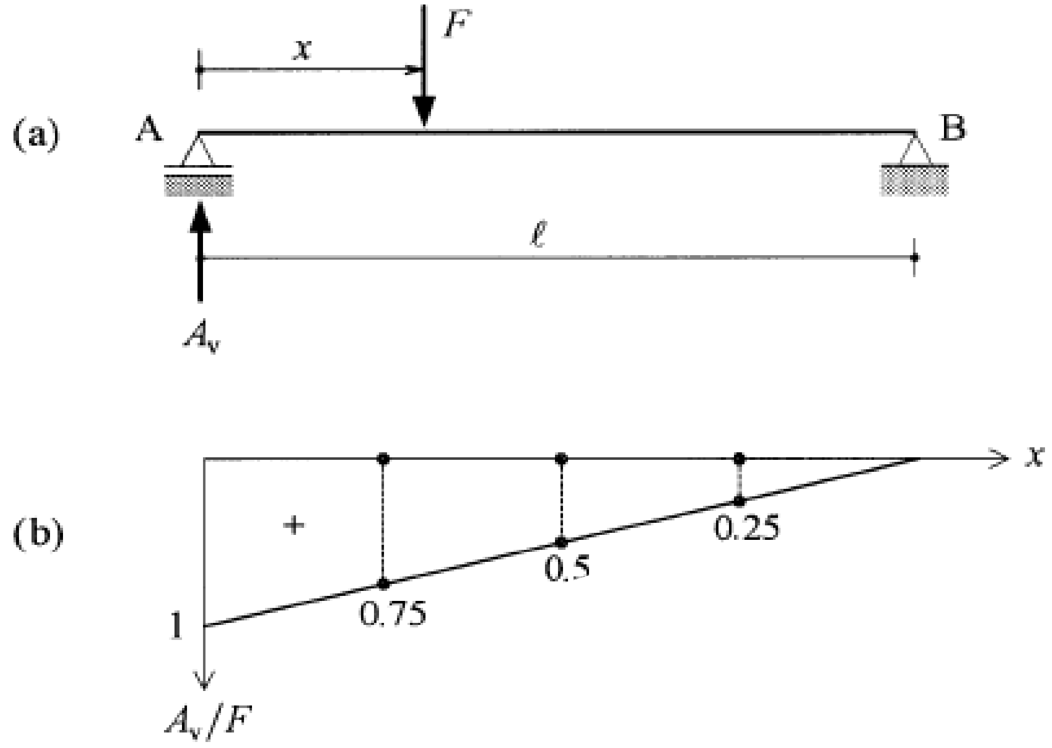
What is an influence line?

Important tools for finding the most unfavorable placement of loads are the so-called ***influence lines***. ***Influence lines*** are graphic representations of the magnitude of a support reaction or section force at a fixed location due to a single point load with variable position, i.e. moving load.

Example: Influence line for a support reaction



Example: Influence line for a support reaction

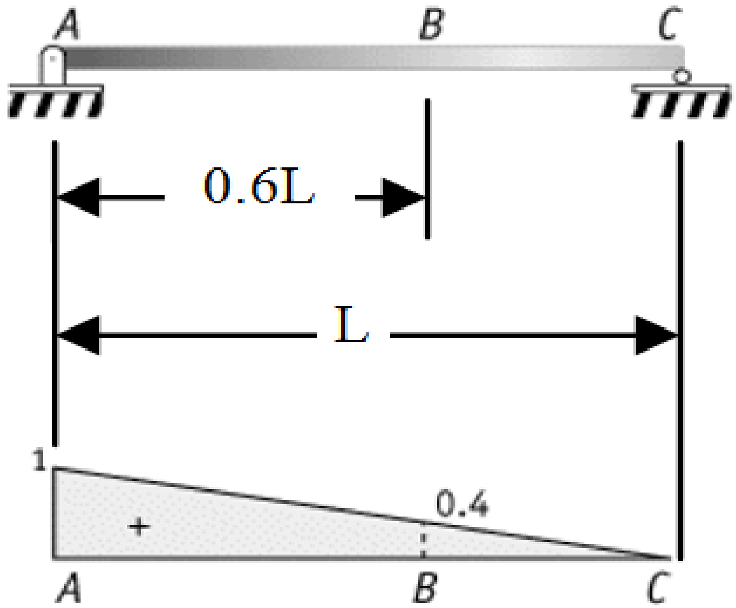


How to Draw Influence Lines

Müller-Breslau Principle: The Müller-Breslau Principle is a tool to draw the influence lines for statically determinate and indeterminate structures.

This principle simply states that the influence line for a support reaction or a section force is proportionally equivalent to the deflected shape of the structure when it undergoes a displacement as a result of the application of the corresponding support reaction or section force.

How to Draw Influence Lines



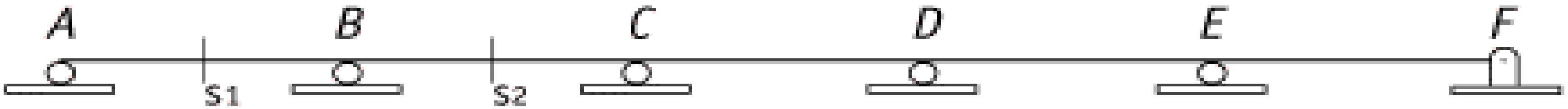
To determine the influence line for the support reaction at A, the "Müller-Breslau Principle" requires **the removal of the support restraint** and the **application of a positive unit deformation at this point** that corresponds to the direction of the force. In this case, apply a unit vertical displacement in the direction of A_v.

CONTINUOUS BEAMS: THE INFLUENCE LINE FOR SUPPORT REACTIONS

Span Moment @ “AB”

Continuous Beams: The influence lines for moments

Support "A"

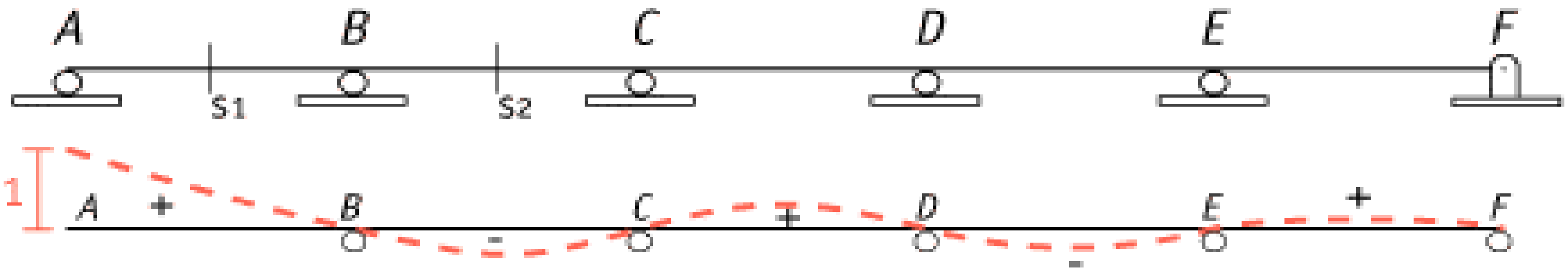


Continuous Beams: Loading cases for moment and shear envelopes

Using the influence lines found above, we are now going to illustrate the loading cases that are needed to calculate the maximum positive and negative A_v, M_B, V_{S1}, and M_{S1}.

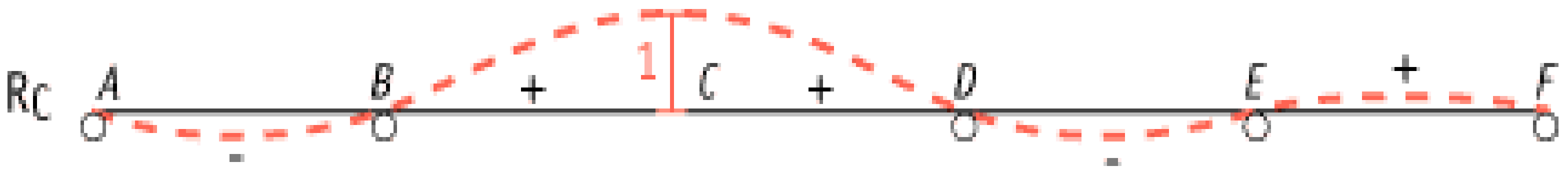
The load cases are generated for the maximum positive and negative values by **placing a distributed load on the spans where the algebraic signs of the influence line are the same**, i.e., to get a maximum positive value for a function, place a distributed load where the influence line for the function is positive.

CONTINUOUS BEAMS: LOADING CASES FOR MOMENT AND SHEAR ENVELOPES



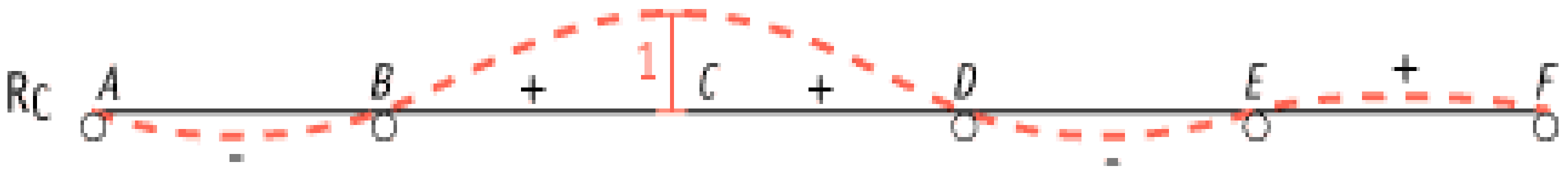
max (+)'ve reaction at support A

CONTINUOUS BEAMS: LOADING CASES FOR MOMENT AND SHEAR ENVELOPES



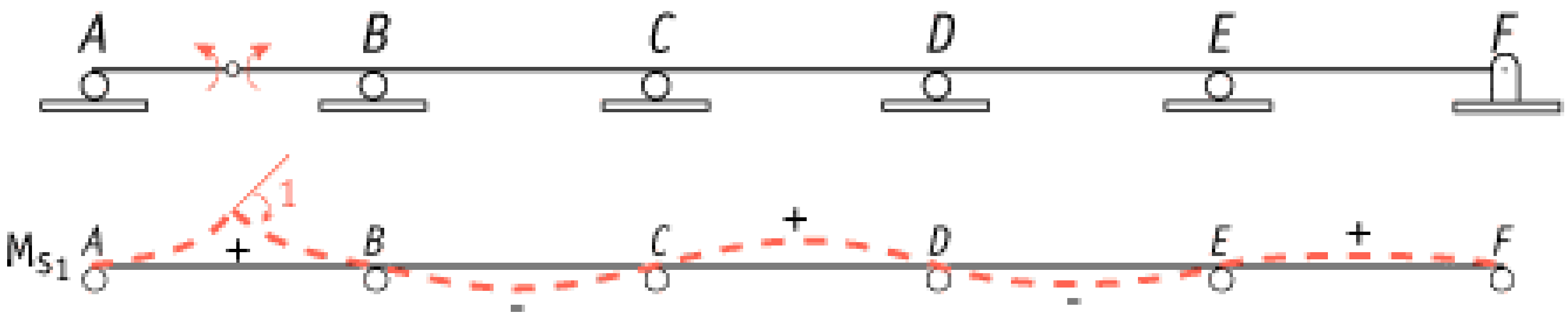
max (+)'ve reaction at support C

CONTINUOUS BEAMS: LOADING CASES FOR MOMENT AND SHEAR ENVELOPES



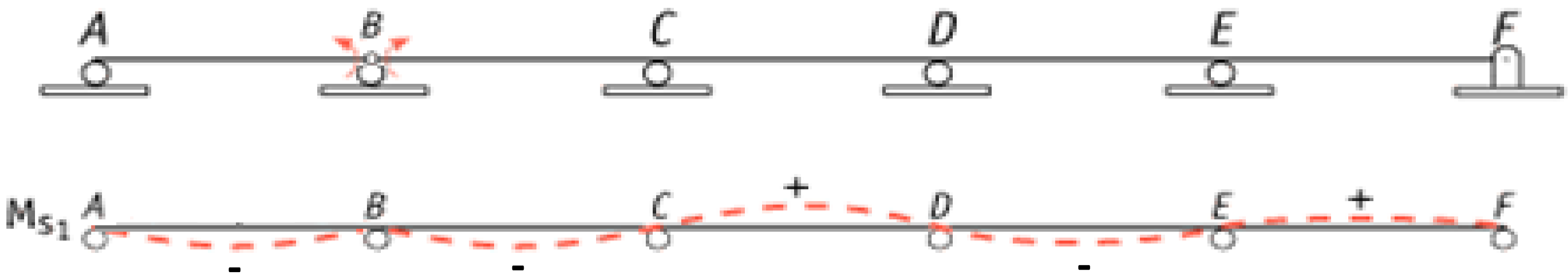
max (-)'ve reaction at support C

Continuous Beams: Loading cases for moment and shear envelopes



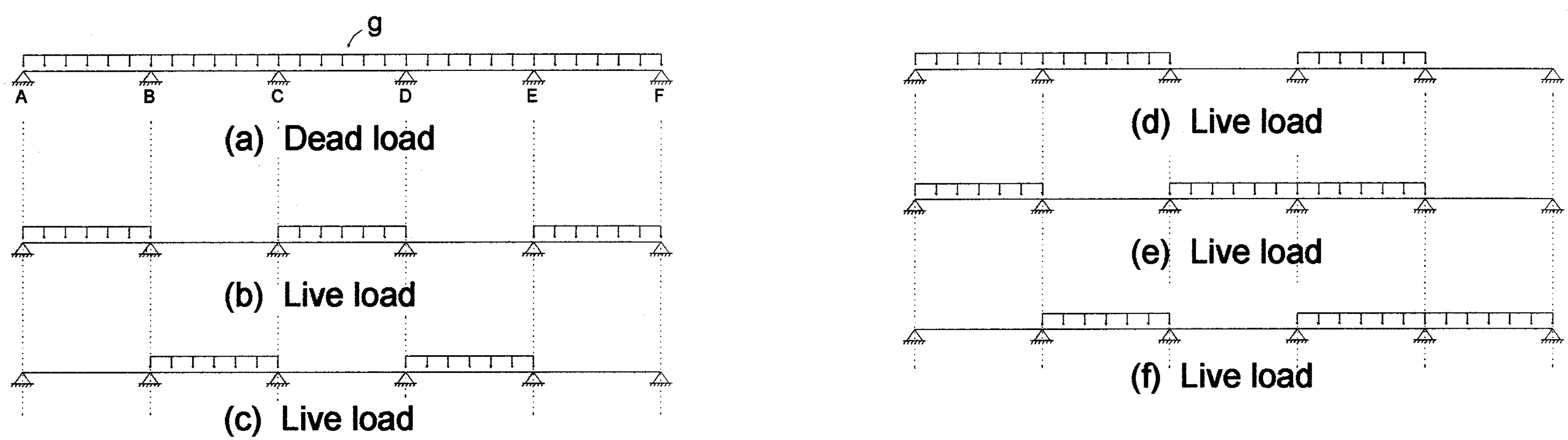
max (+)'ve bending moment, $M_{s1,}$ in Span AB

CONTINUOUS BEAMS: LOADING CASES FOR MOMENT AND SHEAR ENVELOPES



max (-)'ve bending moment, $M_{s1,}$ in Support B

In the light of this discussion, it can be concluded that with a few live load arrangements shown in figures above maximum positive moment at each span can be obtained. These load arrangements are called, “checker board loading.”



maximizes all span moments

maximizes support moments at B, D and E & maximizes the shear forces in these spans

EXAMPLE

Given: Five span continuous beam shown in Fig. 3.8.

All spans are 5 meters

Beam cross-section is, 250×500 mm

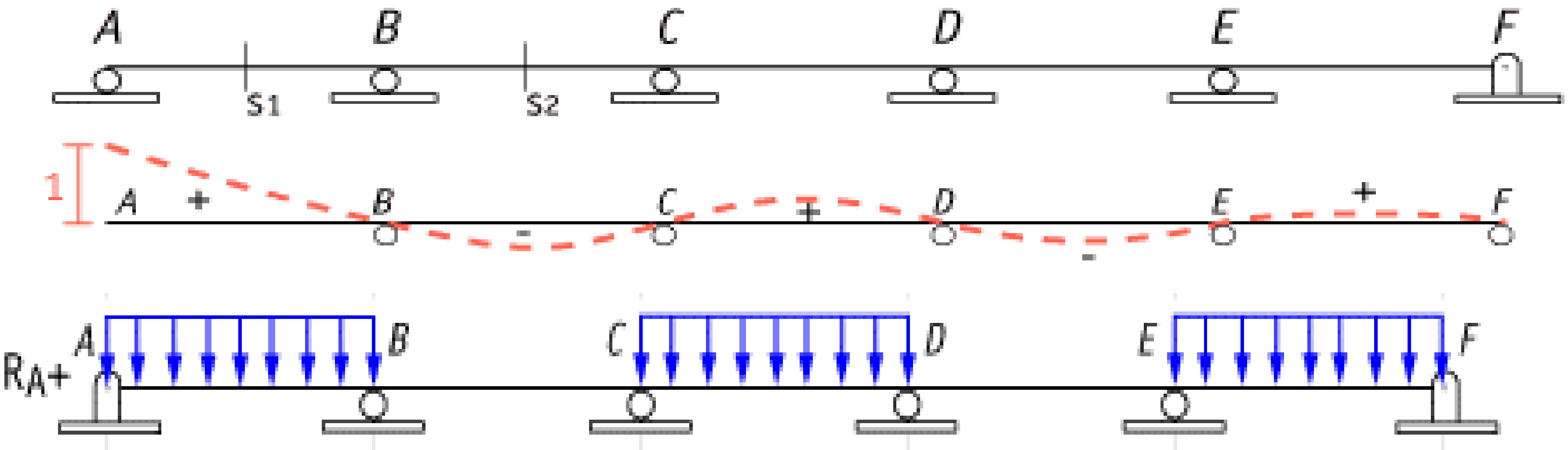
Dead load = 25 kN/m

Live load = 20 kN/m

Required : Using the load combination 1.4G+1.6Q

- Compute the maximum design moment at the span of beam CD
- Compute the maximum design moment at support C
- Compute the maximum design shear for beam CD at support C
- If C20 grade concrete and S420 grade steel are to be used, what would be the design strength for concrete and steel?

EXAMPLE

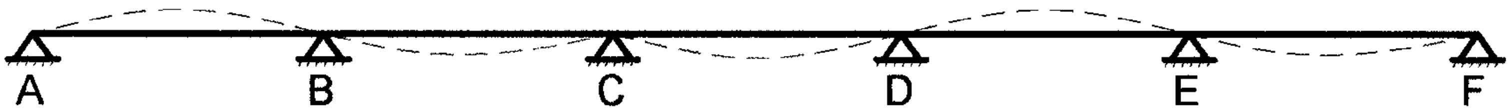


a) Dead load is placed on all spans, resulting in the span moment (positive) of 28.8 kN·m for span CD. For maximum live load moment, the load arrangement is the one shown in above figure, M_q = 42.8 kN·m .

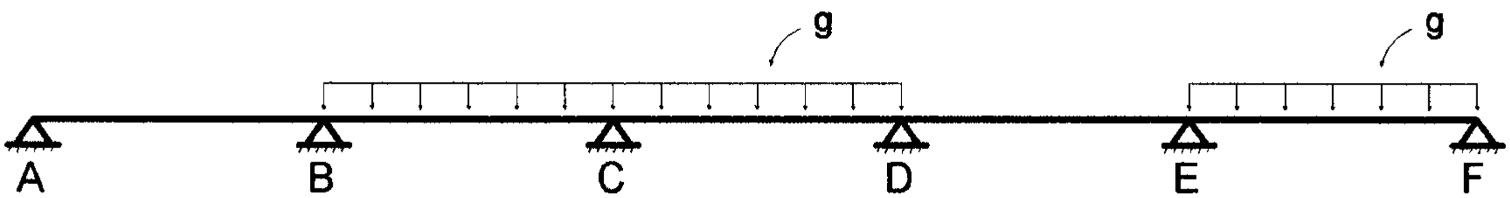
The design moment is,

$+M_d = 1.4 \times 28.8 + 1.6 \times 42.8 = 108.8$ kN·m

EXAMPLE



(a)

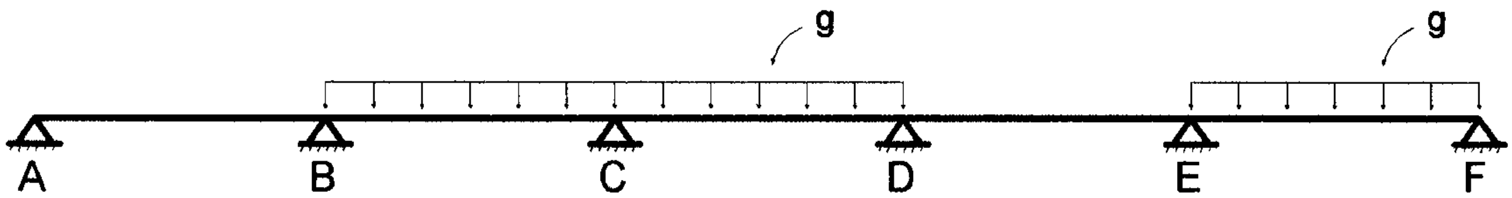


(b)

b) The dead load moment at support C is calculated by loading all the spans, M_g = -49.3 kN·m . For the live load, using the arrangement shown in the figure, M_q = -55.6 kN·m is found. The design moment at C is :

$$-M_d = 1.4(-49.3) + 1.6(-55.6) = -158 \text{ kN·m}$$

Example



(b)

c) Dead load shear of span CD at support C is calculated by placing the dead load on all spans, $V_g = 62.5$ kN.

The load arrangement is the one shown in figure, resulting in

$V_q = 59.1$ kN.

Then:

$V_d = 1.4(62.5) + 1.6(59.1) = 182$ kN

Example

d) f_{ck} = 20 MPa and f_{yk} = 420 MPa.

The material factors are, γ_{mc} = 1.5 and γ_{ms} = 1.15.

The design strengths would be,

f_{cd} = 20/1.5 = 13.3 MPa or simply 13 MPa

f_{yd} = 420/1.15 = 365 MPa