What is design of structures?

- Unknown cross-sectional details are to be determined
- Span lengths and basic dimensions are taken from architectural drawings
- Expected loads are determined using handbooks and codes according to occupancy of the structure
- Types of construction materials to be used and their properties are decided
- Sound knowledge of the principles of statics, dynamics, mechanics of materials and structural analysis is required for good design
- Construction practices, availability of materials, labor and machinery, etc. are also to be considered
- Experience for the structural behavior are also important

Capacity Analysis of Structures

- Carried out to check already made design or construction
- Material properties, spans and cross-sectional details are known
- Load carrying capacity of members or structure is evaluated
- Capacity is compared with the applied loads
- If applied load is lesser than capacity of member, design is safe

Basic Design Equation

- Used for design and capacity analysis in all types of design and analysis methods

Load effects x factor of safety = **maximum internal resistance offered by material of structure**

- Load effects may be axial force, shear force, bending moment and torque

Basic Design Equation (cont....)

- Corresponding to each applied load action, there is a resistive force such as resisting axial force, resisting shear and resisting moment
- In design, applied actions and material resistances are equated to each other with some FOS
- A bending moment of Pl/4 may never be obtained in a simply supported beam subjected to a central point load if the member is not sufficiently strong

Factor of Safety

- Value is always greater than one
- Brings the structure from state of collapse to a usable service state to avoid excessive deformations, cracking, and buckling, etc.
- Covers uncertainties in loads within limits
- Covers uncertainties in material strengths up to certain extent
- Covers, in part, poor workmanship
- Covers unexpected behavior in theory due to simplifying assumptions or limited knowledge
- Reduces the effect of natural disasters
- Fabrication and erection stresses are taken care of
- Presence of residual stresses and local stress concentrations are safely considered

Comparison of Factor of Safety

- FOS in ASD is about 1.67
- FOS for LL in original LRFD is 1.7/0.9 or 1.889
- FOS for DL in original LRFD is 1.4/0.9 or 1.556
- FOS for LL in latest LRFD is 1.6/0.9 or 1.778
- FOS for DL in latest LRFD is 1.2/0.9 or 1.333
- Average FOS in latest LRFD is 1.63

Limit State

- Stage in loading after which the structure cannot fulfill its intended function
- Limit state may be related with strength or serviceability considerations
- Actual collapse is not necessary
- Strength limit states corresponds to maximum strengths, such as ultimate ductile flexural strength, ultimate shear strength, buckling failure, fatigue, plastic mechanism, overturning and sliding, etc.
- Serviceability limit states are concerned with occupancy such as excessive deflections, undesirable vibrations, permanent deformations, excessive cracking and behavior in fire, etc.
- Structure should not cross any strength or serviceability limit for a perfect design

Strength and Ductility

- In general, structures are designed for strength against loads.
- Strength of a material means what maximum stresses may be developed
- Ductility means how much deformations are produced before final collapse
- Sometimes, the design is more based on ductility than strength such as for earthquake loading
- For heaviest earthquakes, only ductility is provided for safety of life and perhaps not for complete safety of structure
- Time available before final collapse due to ductility is called warning before failure, persons may escape

Types of Design Methods

- **Allowable Stress Design (ASD)**
- **Strength Design, Load and Resistance Factor Design (LRFD), or Limit State Design**
- **Plastic Design**

Allowable Stress Design (ASD)

- Factor of safety is taken on RS of basic design equation, called safety factor, and denoted by Ω.

$$\text{External Load Effects} = \frac{\text{Material Resistance}}{\text{Safety Factor}}$$

$$R_a \leq R_n / \Omega$$

Advantages of ASD Method

- Elastic analysis for loads and elastic material behavior become compatible for design
- Senior engineers are used to this method
- Old famous books are according to this method
- Was the only method of design in past
- Is included as alternate method of design in AISC-05 Specifications.

Disadvantages of ASD Method

- Latest research and literature is very much limited
- Same factor of safety is used for different loads
- The failure mode is not directly predicted
- With some overloading, the material stresses increase but do not go to collapse (How to observe failure mode?)

Disadvantages of ASD Method

- The ductility and warning before failure cannot be studied precisely
- Results cannot be compared with experimental tests up to collapse

Strength Design or LRFD or Limit State Design

- Major part of FOS is applied on load actions called overload factor
- Minor part of FOS is taken on RS of design equation, becomes reciprocal of FOS, called resistance factor or capacity reduction factor (ϕ)
- Resistance factor (ϕ) is lesser than or equal to 1.0 and is applied on material strength
- The design equation is checked for each strength and serviceability limit states one-by-one
- The design equation becomes:

$$R_u \leq \phi R_n$$

Advantages of Using LRFD

- Behavior at collapse including ductility, warning before failure and strain-hardening, etc. may be considered directly
- Every type of load may be given a different FOS depending upon its probability of overload, number of severe occurrences and changes in point of application
- More safe structures result due to better awareness of structural behaviour near collapse
- Results can be compared with experiments up to collapse and with structural failures in the past
- Latest research and literature is available in this method
- Even if using ASD, this method provides a second alternative to check the designs

Advantages of Using LRFD

- Economical in case dead loads are larger, such as in concrete structures
- More safety than ASD if live loads are greater in magnitude

Disadvantages of Using LRFD

- Elastic behavior considered for load analysis and ultimate plastic behavior for material strengths are not compatible, however, percentage difference is less
- Engineers experienced in ASD have to become familiar with this technique
- Old books and design aids become ineffective
- Validity of previous designs is still to be checked according to ASD

Plastic Design

- Same as LRFD with the difference that plastic analysis is used for load analysis
- Best available method
- Incompatibility in load analysis and material behavior is removed
- Very lengthy even for computer application due to plastic analysis

Current Situation Regarding Design Codes

- For concrete design, engineers have almost shifted to strength design or LRFD
- ACI has discontinued ASD as an alternate method of design
- For steel design, engineers are gradually shifting to Strength Design or LRFD, may take some time due to late start
- AISC has only issued the combined LRFD/ASD specifications in 2005 after AISC-ASD 1988
- AISC has included ASD only as an alternate method in specifications of 2005
- AASHTO has shifted its bridge and other designs to LRFD
- The last AASHTO-ASD specifications will only be used for evaluating previous designs

Current Situation Regarding Design Codes

- Most American states have opted not to use ASD for bridge design beyond 2005 or at the most 2007
- British specifications for concrete design are also according to this method, however, they refer to it as limit state design
- American universities are only teaching Strength Design/LRFD to new engineers
- Universities of Pakistan are also teaching this method for concrete design
- For steel design, some Universities of Pakistan have switched to this method
- It is expected that, in future, only one method will be used for practical design, that is, Strength Design or LRFD
- For research work and high-importance structures, plastic design is the best method

Objectives Of Structural Designer

Design is a process by which an optimum solution is obtained satisfying certain criteria.

Some typical criteria are:-

a. minimum cost
b. minimum weight
c. minimum construction time
d. minimum labour
e. maximum efficiency of operation to owner, etc.

If a specific objective criterion can be expressed mathematically in the form of an objective function, then optimisation techniques may be employed to achieve the goal.

The criterion of minimum weight is almost always satisfied in all steel structures.

Objectives Of Structural Designer

The structural designer must learn to arrange and proportion the parts of his structures so that they can be practically erected and will have sufficient strength and reasonable economy.

These important items, called ***safety***, ***cost*** and ***practicality***, are briefly discussed in the following slides.

1. The structure must safely support the loads to which it is subjected. The deflections and vibrations should not be so excessive as frighten the occupants or cause unsightly cracks
2. The designer must keep the construction, operation, and maintenance costs at the lowest level without sacrificing the strength.
3. Designers need to understand fabrication methods and should try to fit their work to the available fabrication facilities, available materials and the general construction practices. Some designers lack in this very important aspect and their designs cause problems during fabrication and erection.

Objectives Of Structural Designer

Designers should learn everything possible about the detailing, the fabrication, and the field erection of steel besides the loads, mechanics, and the expected material strengths.

The designer must have information concerning the transportation of the materials to site, labour conditions, equipment for erection, problems at site, field tolerances and the required clearances at the site.

This knowledge helps to produce reasonable, practical and economical designs.

Procedure for the Structural Design

The structural framework design is the selection of the arrangement and sizes of structural elements so that service loads may be safely carried.
The important steps in the design of separate members are shown in the form of a flow chart in Figure 1.1.

The complete design procedure for a whole structure requires iterations and the main steps are listed below:

1. The functions to be performed by the structure and the criteria for optimum solution of the resulting design must be established. This is referred to as the ***planning*** stage.
2. The general ***layout*** of the structure is decided.

Procedure for the Structural Design

3. Different arrangements of various elements to serve the functions in step 1 are considered.

   The possible structural forms that can be used are studied and an arrangement appearing to be best is selected for the first trial, called ***preliminary structural configuration***.

   Only in very rare cases, it has to be revised later on.
4. The ***Loading*** conditions are considered and the loads to be carried by the structure are estimated.
5. Based on the decisions of earlier steps, ***trial selection of member sizes*** is carried out depending on thumb rules or assumed calculations to satisfy an objective criterion, such as least weight or cost.

Procedure for the Structural Design

6. The ***Structural analysis*** involving modelling the loads and the structural framework to obtain internal forces stresses and deflections is carried out.

7. All strength and serviceability requirements along with the predetermined criteria for optimum are checked.

   If any check is not satisfied, the member sizes are revised.

   This stage is called ***evaluation*** of the trial member sizes.

8. Repetition of any part of the above sequence found necessary or desirable as a result of evaluation is performed in this stage called ***redesign***.

9. The rivets, bolts and welds along with other joining plates and elements are designed. The process is termed as the ***design of assembly and connections***.

Procedure for the Structural Design

10. It is determined whether or not an optimum design has been achieved, and the ***final decision*** is made.

11. Drawings are prepared to show all design details.

    An estimate for the required quantities is also made.

    This stage of design is called ***preparation of design documents***.

Load Factors and Load Combinations

It is almost impossible that all loads like live load, snow load, wind load and earthquake all occur together with their maximum intensity.

A load combination combines different types of loads depending on the probability of occurrence of these loads acting simultaneously, considering their expected intensity in the combination compared with the maximum load intensity.

The factors of safety are also included in the LRFD load combinations and hence the output of the expressions is a design load.

The alphabets used in the combinations mean different types of nominal service loads and the numerical values with them are the load factors.

When intermediate floors have full live load, any type of roof load may be considered equal to half of its normal service load intensity.

Similarly, in case of maximum intensity wind storm, live load may be half.

Load Factors and Load Combinations

The last combination, given afterwards, is very important for uplift of structure or reversal of forces.

The wind load on roof is upwards in majority of the cases and if the downward gravity load is less, the structure may be blown up or sagging bending may change into hogging bending.

A list of most commonly used combinations are as under:

LRFD Load Combinations

When the loads *S*, *R*, *H*, *F*, *E* and *T* are taken equal to zero and wind loads are taken from the previous codes, the load combinations are reduced to the following form:

1. **$1.4\,D$**
2. **$1.2\,D + 1.6\,L + 0.5L_r$**
3. **$1.2\,D + 1.6L_r + (L \text{ or } 0.8\,W)$**

Load Factors and Load Combinations

LRFD Load Combinations

4. $1.2\,D + 1.3\,W + L + 0.5\,L_r$
5. $0.9\,D + 1.3\,W$

ASD Load Combinations

The simplified ASD load combinations are as follows:

1. D
2. $D + L$
3. $D + L_r$
4. $D + 0.75L + 0.75L_r$
5. $D + 0.8W$
6. $D + 0.6W + 0.75L + 0.75L_r$
7. $0.6\,D + 0.8W$

Types of Structural Steel

Steels are divided into four categories depending on the carbon percentages (C) as follows:

1-	Low carbon steel	C < 0.15%
2-	Mild carbon steel	C = 0.15 – 0.29%
3-	Medium carbon steel	C = 0.30 – 0.59%
4-	High carbon steel	C = 0.60 –1.70%

E-value for steel = 185 GPa to 230 GPa (Average 200 GPa)

Unit weight = 7850 kg/m^3 = 77 kN/m^3

For comparison, the unit weight of concrete is 23.6 kN/m^3

Types of Structural Steel

Most of the structural steel falls into the mild carbon steel or simply mild steel (MS) category.

Hot rolled structural shapes may be made to conform to A36M, A529M, A572M, A588M, A709M, A913M and A992M.

Sheets are manufactured according to the standards ASTM A606, A1011MSS, HSLAS and HSLAS-F.

Bolts are made according to ASTM standards A307, A325M, A449, A40M and F1852.

Most commonly used structural steel is A36M having the following properties:

F_y = 250 MPa , F_u = 400 MPa, E = 200 GPa

Types of Structural Steel

Weld electrodes are classified as E60, E70, E80, E100 and E110. The letter *E* denotes electrode. The two digits indicate the ultimate tensile strength in ksi. The corresponding SI equivalents are E425, E495, E550, E690, E690 and E760.