Classification of Structures

It is important for a structural engineer to recognize the various types of elements composing a structure and to be able to classify structures as to their form and function. We will introduce some of these aspects now and expand on them at appropriate points throughout the text.

Structural Elements

Some of the more common elements from which structures are composed are as follows.

Tie Rods

Structural members subjected to a tensile force are often referred to as tie rods or bracing struts. Due to the nature of this load, these members are rather slender, and are often chosen from rods, bars, angles, or channels, Fig. 1.

tensile force / tie rod / bracing strut / slender / bar / angle / channel

Columns

Members that are generally vertical and resist axial compressive loads are referred to as columns, Fig. 3. Tubes and wide-flange cross sections are often used for metal columns, and circular and square cross sections with reinforcing rods are used for those made of concrete. Occasionally, columns are subjected to both an axial load and a bending moment as shown in the figure 3. Those members are referred to as beam columns.

The combination of structural elements and the materials from which they are composed is referred to as a structural system. Each system is constructed of one or more of four basic types of structures. Ranked in order of complexity of their force analysis, they are as follows.

column / wide-flange / beam column

Beams

Beams are usually straight horizontal members used primarily to carry vertical loads. Quite often they are classified according to the way they are supported, as indicated in Fig. 2. In particular, when the cross section varies the beam is referred to as tapered or haunched. Beams are primarily designed to resist bending moment; however if they are short and carry large loads, the internal shear force may become quite large and this force may govern their design.

Concrete beams generally have rectangular cross sections, since it is easy to construct this form directly in the field. Because concrete is rather weak in resisting tension, steel "reinforcing rods" are cast into the beam within regions of the cross section subjected to tension. Precast concrete beams or girders are fabricated at a shop or yard in the same manner and then transported to the job site.

straight / cross section / tapered / haunched / bending moment / shear force / construct / precast / girder / simply supported beam / cantilevered / fixed-supported

Trusses

When the span of a structure is required to be large and its depth is not an important criterion for design, a truss may be selected. Trusses consist of slender elements, usually arranged in triangular fashion. Planar trusses are composed of members that lie in the same plane and are frequently used for bridge and roof support, whereas space trusses have members extending in three dimensions and are suitable for derricks and towers. Due to the geometric arrangement of its members, loads that cause the entire truss to bend are converted into tensile or compressive forces in the members. Because of this, one of the primary advantages of a truss, compared to a beam, is that it uses less material to support a given load, Fig. 4.

span / truss / triangular fashion / planar / derrick / purlin / roof

Types of Structures and Loads

Introduction

A structure refers to a system of connected parts used to support a load. Important examples related to civil engineering include buildings, bridges, and towers. When designing a structure to serve a specified function for public use, the engineer must account for its safety, esthetics, and serviceability, while taking into consideration economic and environmental constraints. Once a preliminary design of a structure is proposed, the structure must then be analyzed to ensure that it has its required stiffness and strength. To analyze a structure properly, certain idealizations must be made as to how the members are supported and connected together. The loadings are determined from codes and local specifications, and the forces in the members and their displacements are found using the theory of structural analysis.

structure / safety / esthetics / serviceability / stiffness / strength

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straight / cross section / tapered / haunched / bending moment / shear force / construct / precast / girder / simply supported beam / cantilevered / fixed-supported
### Cables and Arches

Two other forms of structures used to span long distances are the cable and the arch. Cables are usually flexible and are used to support bridges, Fig. 6, and building roofs. When used for these purposes, the cable has an advantage over the beam and the truss, especially for spans that are greater than 40 m. Because they are always in tension, cables will not become unstable and suddenly collapse, as may happen with beams or trusses. Furthermore, the truss will require added costs for construction and increased depth as the span increases. Use of cables, on the other hand, is limited only by their sag, weight, and methods of anchorage.

The arch achieves its strength in compression, since it has a reverse curvature to that of the cable. The arch must be rigid, however, in order to maintain its shape, and this results in secondary loadings involving shear and moment, which must be considered in its design. Arches are frequently used in bridge structures, Fig. 7, dome roofs, and for openings in masonry walls.

cable / arch / flexible / unstable / collapse / sag / anchorage / reverse curvature / rigid / dome roof / openings in masonry walls

### Surface Structures

A surface structure is made from a material having a very small thickness compared to its other dimensions. Sometimes this material is very flexible and can take the form of a tent or air-inflated structure. In both cases, the material acts as a membrane that is subjected to pure tension. Surface structures may also be made of rigid material such as reinforced concrete. As such they may be shaped as folded plates, cylinders, or hyperbolic paraboloids, and are referred to as thin plates or shells. These structures act like cables or arches since they support loads primarily in tension or compression, with very little bending. In spite of this, plate or shell structures are generally very difficult to analyze, due to the three-dimensional geometry of their surface.

surface structure / tent / air-inflated / membrane / folded plate / hyperbolic paraboloid / thin plate / shell
** Loads **

Once the dimensional requirements for a structure have been defined, it becomes necessary to determine the loads the structure must support. Often, it is the anticipation of the various loads that will be imposed on the structure that provides the basic type of structure that will be chosen for design. For example, high-rise structures must endure large lateral loadings caused by wind, and so shear walls and tubular frame systems are selected, whereas buildings located in areas prone to earthquakes must be designed having ductile frame and connections. Once the structural form has been determined, the actual design begins with those elements that are subjected to the primary loads the structure is intended to carry, and proceeds in sequence to the various supporting members until the foundation is reached.

![Evolution of Structural Systems](image1)

- High-rise structure / endure / shear wall / tubular frame / ductile frame
- Seismic / overturning / interact / restrain / storey / deformation

** Types of Some Loads **

** Dead Loads **

Dead loads consist of the weights of the various structural members and the weights of any objects that are permanently attached to the structure. Hence, for a building, the dead loads include the weights of the columns, beams, and girders, the floor slab, roofing, walls, windows, plumbing, electrical fixtures, and other miscellaneous attachments.

** Live Loads **

Live Loads can vary both in their magnitude and location. They may be caused by the weights of objects temporarily placed on a structure, moving vehicles, or natural forces. The minimum live loads specified in codes are determined from studying the history of their effects on existing structures. Usually, these loads include additional protection against excessive deflection or sudden overload.

![Dead loads / permanently attached / temporarily placed on / moving vehicles / excessive deflection / sudden overload](image2)

** Support Reactions **

The forces that develop at the supports or points of contact between bodies are called reactions. For two dimensional problems, i.e., bodies subjected to coplanar force systems, the supports most commonly encountered are shown in Table 1-1. Note carefully the symbol used to represent each support and the type of reactions it exerts on its contacting member. As a general rule, if the support prevents translation in a given direction, then a force must be developed on the member in that direction. Likewise, if rotation is prevented, a couple moment must be exerted on the member. For example, the roller support only prevents translation perpendicular or normal to the surface, hence, the roller exerts a normal force F on the member at its point of contact. Since the member can freely rotate about the roller, a couple moment cannot be developed on the member.

![Support reactions](image3)

- Building Loads
- Highway Bridge Loads
- Wind Loads
- Earthquake Loads
- Coplanar force system / translation / rotation / couple moment / be exerted on / span / roller support / normal force

** Wind Loads **

When structures block the flow of wind, the wind’s kinetic energy is converted into potential energy of pressure, which causes a wind loading. The effect of wind on a structure depends upon the density and velocity of the air, the angle of incidence of the wind, the shape and stiffness of the structure, and the roughness of its surface. For design purposes, wind loadings can be treated using either a static or a dynamic approach.

The above given loads are applied in structural analysis in terms of load combinations such as 1.4D + 1.6Q and G+D= E. Several such combinations are possible especially in bridge analysis.

![Wind loads](image4)

- Uniform / national code / be converted into / angle of incidence / roughness / be treated bridge span / LRFD Bridge Design Specification / ground acceleration
Statically Determinate Structures

An exact analysis of a structure can never be carried out, since estimates always have to be made of the loadings and the strength of the materials composing the structure. Furthermore, points of application for the loadings must also be estimated. It is important, therefore, that the structural engineer develop the ability to model or idealize a structure so that she or he can perform a practical force analysis of the members.

Support Connections

Structural members are joined together in various ways depending on the intent of the designer. The three types of joints most often specified are the pin connection, the roller support, and the fixed joint. A pin-connected joint and a roller support allow some freedom for slight rotation, whereas a fixed joint allows no relative rotation between the connected members and is consequently more expensive to fabricate. Examples of these joints, fashioned in metal and concrete, are shown in Figs 13 and 14, respectively. For most timber structures, the members are assumed to be pin connected, since bolting or nailing them will not sufficiently restrain them from rotating with respect to each other. Idealized models used in structural analysis that represent pinned and fixed supports and pin-connected and fixed-connected joints are shown in Figs 15a and 15b. In reality, however, all connections exhibit some stiffness toward joint rotations, owing to friction and material behavior.

Idealized Structure

Having stated the various ways in which the connections on a structure can be idealized, we are now ready to discuss some of the techniques used to represent various structural systems by idealized models. As a first example, consider the jib crane and trolley in Fig 16a. For the structural analysis we can neglect the thickness of the two main members and will assume that the joint at B is fabricated to be rigid. Furthermore, the support connection at A can be modeled as a fixed support and the details of the trolley excluded. Thus, the members of the idealized structure are represented by two connected lines, and the load on the hook is represented by a single concentrated force F. Fig 16b. Beams and girders are often used to support building floors. In particular, a girder is the main-load-carrying element of the floor, whereas the smaller elements having a shorter span and connected to the girders are called beams. Often the loads that are applied to a beam or girder are transmitted to it by the floor that is supported by the beam or girder. Again, it is important to be able to appropriately idealize the system as a series of models, which can be used to determine, to a close approximation, the forces acting in the members.

Determinacy and Stability

Determinacy

The equilibrium equations provide both the necessary and sufficient conditions for equilibrium. When all the forces in a structure can be determined strictly from these equations, the structure is referred to as statically determinate. Structures having more unknown forces than available equilibrium equations are called statically indeterminate. As a general rule, a structure can be identified as being either statically determinate or statically indeterminate by drawing free-body diagrams of all its members, or selected parts of its members, and then comparing the total number of unknown reactive force and moment components with the total number of available equilibrium equations. For a columnar structure there are at most three equilibrium equations for each part, so that if there is a total of n parts and r force and moment reaction components, we have

\[ r = 3n \text{, statically determinate } \]

\[ r > 3n \text{, statically indeterminate } \]

In particular, if a structure is statically indeterminate, the additional equations needed to solve for the unknown reactions are obtained by relating the applied loads and reactions to the displacement or slope at different points on the structure. These equations, which are referred to as compatibility equations, must be equal in number to the degree of indeterminacy of the structure.

necessary and sufficient conditions / equilibrium / statically indeterminate / free-body diagram / fixed-connected joint / compatibility equation
Stability
To ensure the equilibrium of a structure or its members, it is not only necessary to satisfy the equations of equilibrium, but the members must also be properly held or constrained by their supports.

Equations of Equilibrium
It may be recalled from statics that a structure or one of its members is in equilibrium when it maintains a balance of force and moment. In general this requires that the force and moment equations of equilibrium be satisfied along three independent axes, namely,

\[
\begin{align*}
\sum F_x &= 0 \\
\sum F_y &= 0 \\
\sum M_o &= 0
\end{align*}
\]

The principal load-carrying portions of most structures, however, lie in a single plane, and since the loads are also coplanar, the above requirements for equilibrium reduce to

\[
\begin{align*}
\sum F_x &= 0 \\
\sum F_y &= 0 \\
\sum M_o &= 0
\end{align*}
\]

Here \( F_x \) and \( F_y \) represent, respectively, the algebraic sums of the \( x \) and \( y \) components of all the forces acting on the structure or one of its members, and \( M_o \) represents the algebraic sum of the moments of those force components about an axis perpendicular to the \( x-y \) plane (the \( z \) axis) and passing through point \( O \).

Statically Indeterminate Structures
A structure of any type is classified as statically indeterminate when the number of unknown reactions or internal forces exceeds the number of equilibrium equations available for its analysis. Realize that most of the structures designed today are statically indeterminate. This indeterminacy may arise as a result of added supports or members, or by the general form of the structure. For example, reinforced concrete buildings are almost always statically indeterminate since the columns and beams are poured as continuous members through the joints and over supports.

Advantages and Disadvantages
Although the analysis of a statically indeterminate structure is more involved than that of a statically determinate one, there are usually several very important reasons for choosing this type of structure for design. Most important, for a given loading the maximum stress and deflection of an indeterminate structure are generally smaller than those of its statically determinate counterpart.

Methods of Analysis
When analyzing any indeterminate structure, it is necessary to satisfy equilibrium, compatibility, and force-displacement requirements for the structure. Equilibrium is satisfied when the reactive forces \( \text{hold the structure at rest} \), and compatibility is satisfied when the various segments of the structure fit together without intentional breaks or overlaps. The force-displacement requirements depend upon the way the material responds (i.e. linear or nonlinear). In general there are two different ways to satisfy those requirements when analyzing a statically indeterminate structure: the force or flexibility method, and the displacement or stiffness method.

Homework
1) Find out a training video on analysis of statically determinate structures and watch out.
2) Read a text about statically indeterminate structures (could be a page from any Statical Analysis text-book).