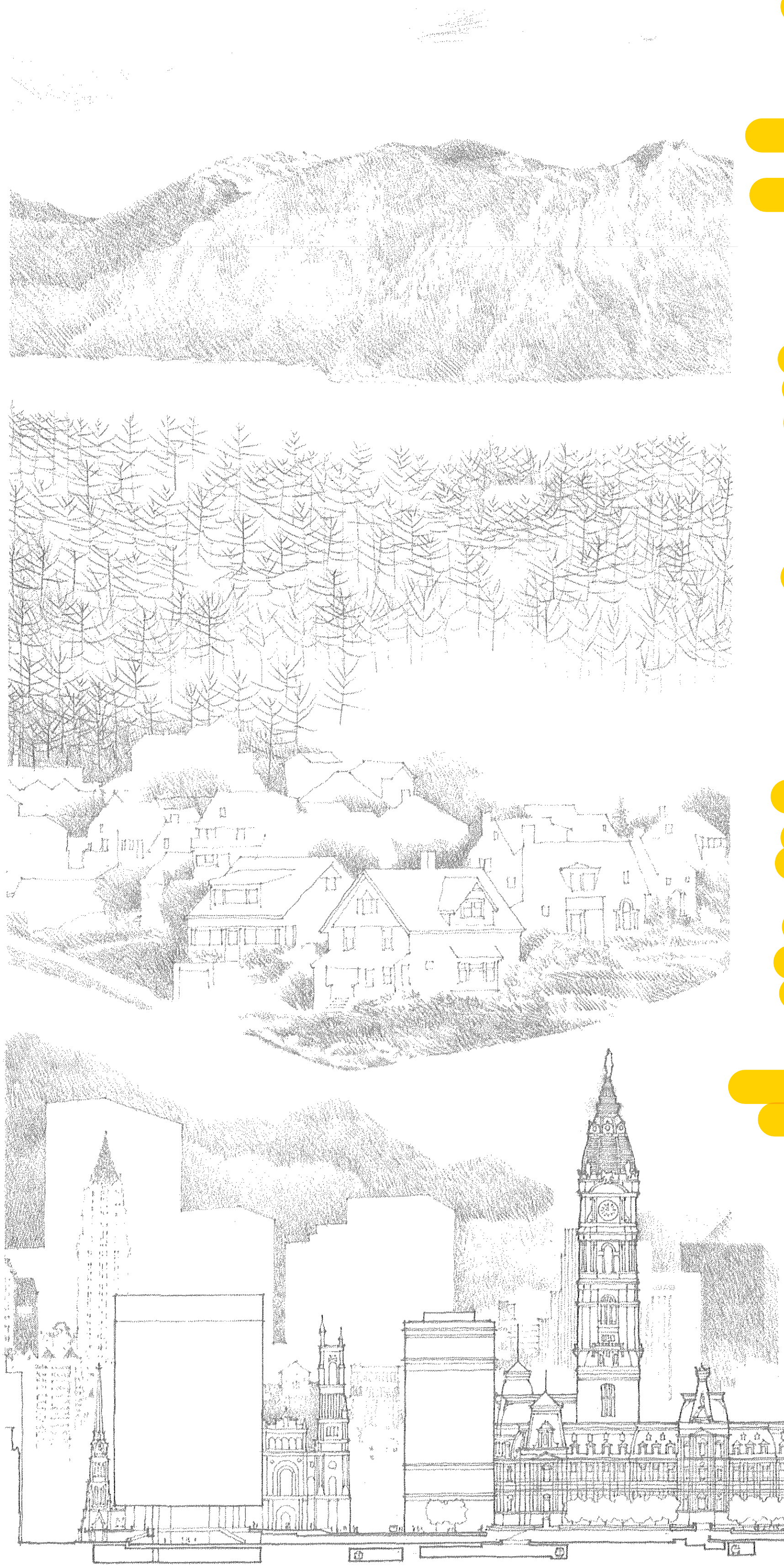


Buildings do not exist in isolation. They are conceived to house, support, and inspire a range of human activities in response to sociocultural, economic, and political needs, and are erected in natural and built environments that constrain as well as offer opportunities for development. We should therefore carefully consider the contextual forces that a site presents in planning the design and construction of buildings.

The microclimate, topography, and natural habitat of a site all influence design decisions at a very early stage in the design process. To enhance human comfort as well as conserve energy and material resources, responsive and sustainable design respects the indigenous qualities of a place, adapts the form and layout of a building to the landscape, and takes into account the path of the sun, the rush of the wind, and the flow of water on a site.

In addition to environmental forces, there exist the regulatory forces of zoning ordinances. These regulations take into account existing land-use patterns and prescribe the acceptable uses and activities for a site as well as limit the size and shape of the building mass and where it may be located on the site.

Ecological Design

Just as environmental and regulatory factors influence where and how development occurs, the construction, use, and maintenance of buildings inevitably place a demand on transportation systems, utilities, and other services. A fundamental question we face is how much development a site can sustain without exceeding the capacity of these service systems, consuming too much energy, or causing environmental damage.

Consideration of these contextual forces on site and building design cannot proceed without a brief discussion of sustainability.

In 1987, the United Nations World Commission on Environment and Development, chaired by Gro Harlem Brundtland, former Prime Minister of Norway, issued a report, *Our Common Future*. Among its findings, the report defined sustainable development as "a form of development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Increasing awareness of the environmental challenges presented by climate change and resource depletion has pushed sustainability into becoming a significant issue shaping how the building design industry operates. Sustainability is necessarily broad in scope, affecting how we manage resources as well as build communities, and the issue calls for a holistic approach that considers the social, economic, and environmental impacts of development and requires the full participation of planners, architects, developers, building owners, contractors, manufacturers, as well as governmental and non-governmental agencies.

In seeking to minimize the negative environmental impact of development, sustainability emphasizes efficiency and moderation in the use of materials, energy, and spatial resources. Building in a sustainable manner requires paying attention to the predictable and comprehensive outcomes of decisions, actions, and events throughout the life cycle of a building, from conception to the siting, design, construction, use, and maintenance of new buildings as well as the renovation process for existing buildings and the reshaping of communities and cities.

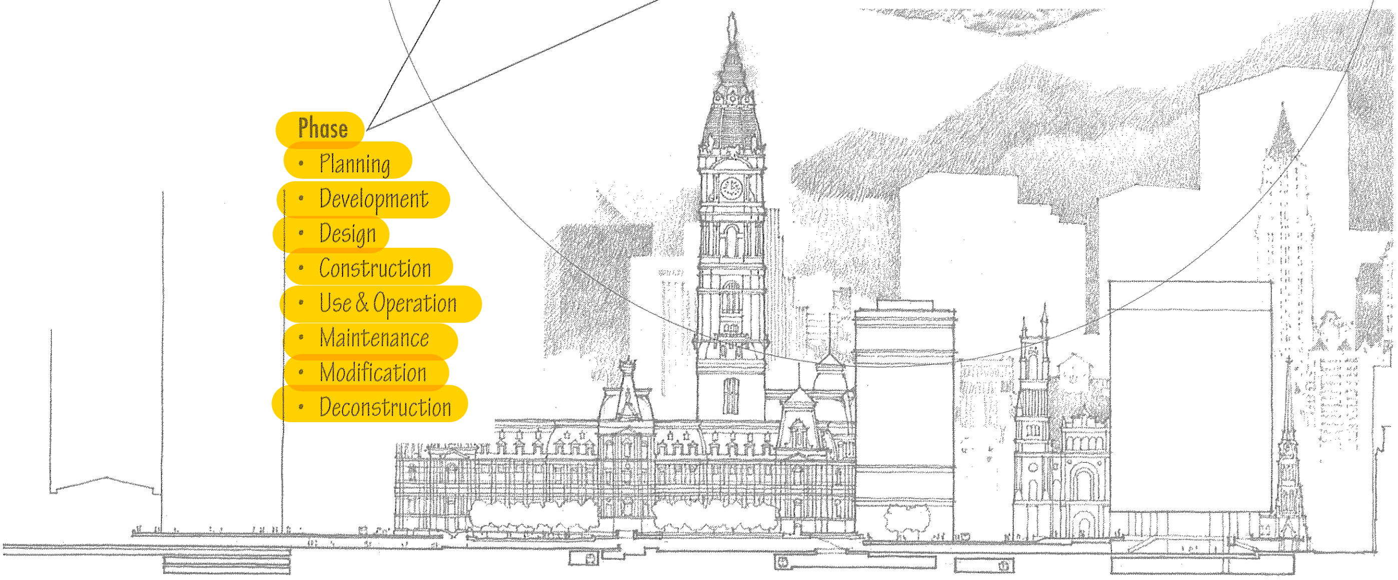
Principles
- Reduce resource consumption
- Reuse resources
- Recycle resources for reuse
- Protect nature
- Eliminate toxics
- Apply life-cycle costing
- Focus on quality

Framework for Sustainable Development

In 1994 Task Group 16 of the International Council for Research and Innovation in Building and Construction proposed a three-dimensional framework for sustainable development.

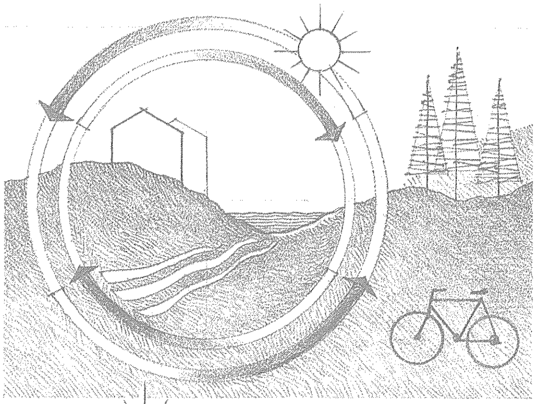
Resources
- Land
- Materials
- Water
- Energy
- Ecosystems

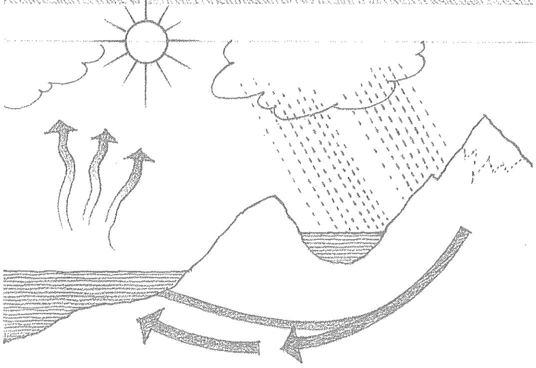
Phase
- Planning
- Development
- Design
- Construction
- Use & Operation
- Maintenance
- Modification
- Deconstruction



The terms "green building" and "sustainable design" are often used interchangeably to describe any building designed in an environmentally sensitive manner. However, sustainability calls for a whole-systems approach to development that encompasses the notion of green building but also addresses broader social, ethical, and economic issues, as well as the community context of buildings. As an essential component of sustainability, green building seeks to provide healthy environments in a resource-efficient manner using ecologically based principles.

Green building is increasingly governed by standards, such as the Leadership in Energy and Environmental Design (LEED®) Green Building Rating System™, which provides a set of measurable criteria that promote environmentally sustainable construction. The rating system was developed by the U.S. Green Building Council (USGBC) as a consensus among its members—federal/state/local agencies, suppliers, architects, engineers, contractors, and building owners—and is continually being evaluated and refined in response to new information and feedback. In July 2003 Canada obtained a license from the USGBC to adapt the LEED rating system to Canadian circumstances.





LEED®

To aid designers, builders, and owners achieve LEED certification for specific building types and phase of a building life cycle, the USGBC has developed a number of versions of the LEED rating system:

- LEED-NC: New Construction and Major Renovations
- LEED-CI: Commercial Interiors
- LEED-CS: Core/Shell
- LEED-EB: Existing Buildings
- LEED-Homes
- LEED-ND: Neighborhood Developments
- LEED for Schools
- LEED for Healthcare
- LEED for Labs
- LEED for Retail

The LEED rating system for new construction addresses six major areas of development.

1. Sustainable Sites

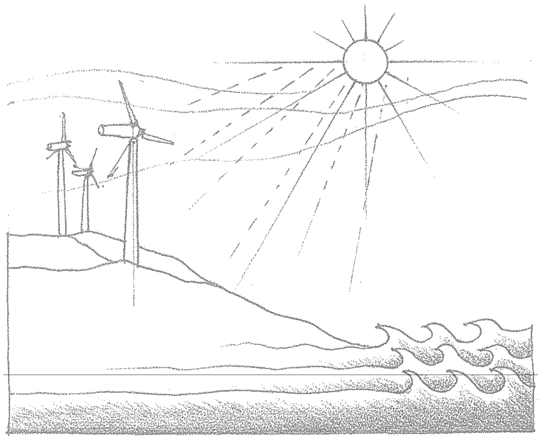
deals with reducing the pollution associated with construction activity, selecting sites appropriate for development, protecting environmentally sensitive areas and restoring damaged habitats, encouraging alternative modes of transportation to reduce the impact of automobile use, respecting the natural water hydrology of a site, and reducing the effects of heat islands.

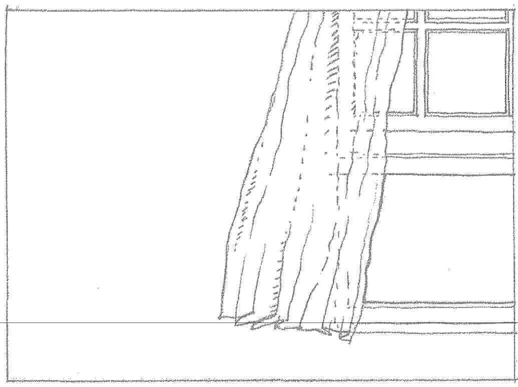
reduce pollution,the
impact automobile use
respect natural water
protect environment

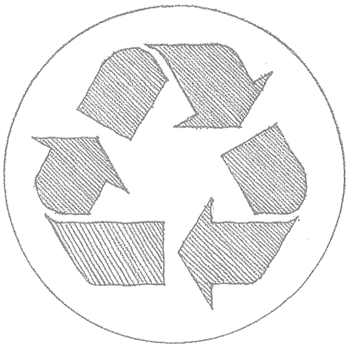
2. Water Efficiency

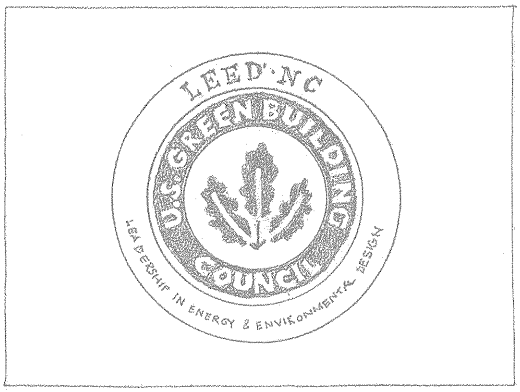
promotes reducing the demand for potable water and the generation of wastewater by using water-conserving fixtures, capturing rainwater or recycled graywater for conveying sewage, and treating wastewater with on-site systems.

water conserving reduces potable water and generation of wastewater
capture rainwater or recycled graywater









3. Energy & Atmosphere

renewable, nonpollutin g energy sources, onzone depletion, global warming

encourages increasing the efficiency with which buildings and their sites acquire and use energy, increasing renewable, nonpolluting energy sources to reduce the environmental and economic impacts associated with fossil fuel energy use, and minimizing the emissions that contribute to ozone depletion and global warming.

4. Materials & Resources

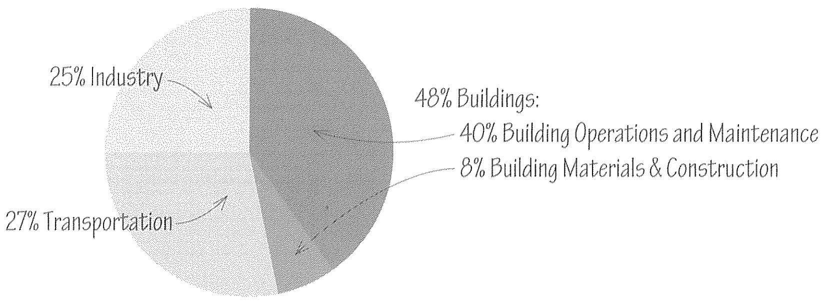
seeks to maximize the use of locally available, rapidly renewable and recycled materials, reduce waste and the demand for virgin materials, retain cultural resources, and minimize the environmental impacts of new buildings.

5. Indoor Environmental Quality

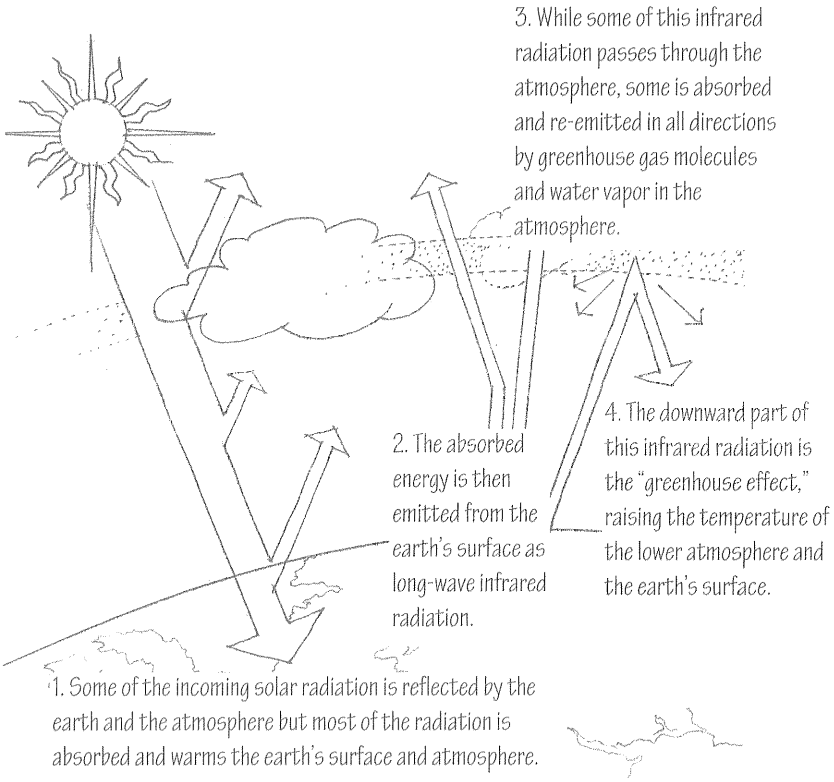
promotes the enhanced comfort, productivity, and well-being of building occupants by improving indoor air quality, maximizing daylighting of interior spaces, enabling user control of lighting and thermal comfort systems to suit task needs and preferences, and minimizing the exposure of building occupants to potentially hazardous particulates and chemical pollutants, such as the volatile organic compounds (VOC) contained in adhesives and coatings and the urea-formaldehyde resins in composite wood products.

6. Innovation & Design Process

rewards exceeding the requirements set by the LEED-NC Green Building Rating System and/or demonstrating innovative performance in Green Building categories not specifically addressed by the LEED-NC Green Building Rating System.



U.S. Energy Consumption by Sector



Climate Change & Global Warming

Greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, are emissions that rise into the atmosphere. CO^2 accounts for the largest share of U.S. greenhouse gas emissions. Fossil fuel combustion is the main source of CO^2 emissions.

Architecture 2030 is an environmental advocacy group whose mission is "to provide information and innovative solutions in the fields of architecture and planning, in an effort to address global climate change." Its founder, New Mexico architect Edward Mazria, points to data from the U.S. Energy Information Administration that indicates buildings are responsible for almost half the total U.S. energy consumption and greenhouse gas (GHG) emissions annually; globally, Mazria believes the percentage is even greater.

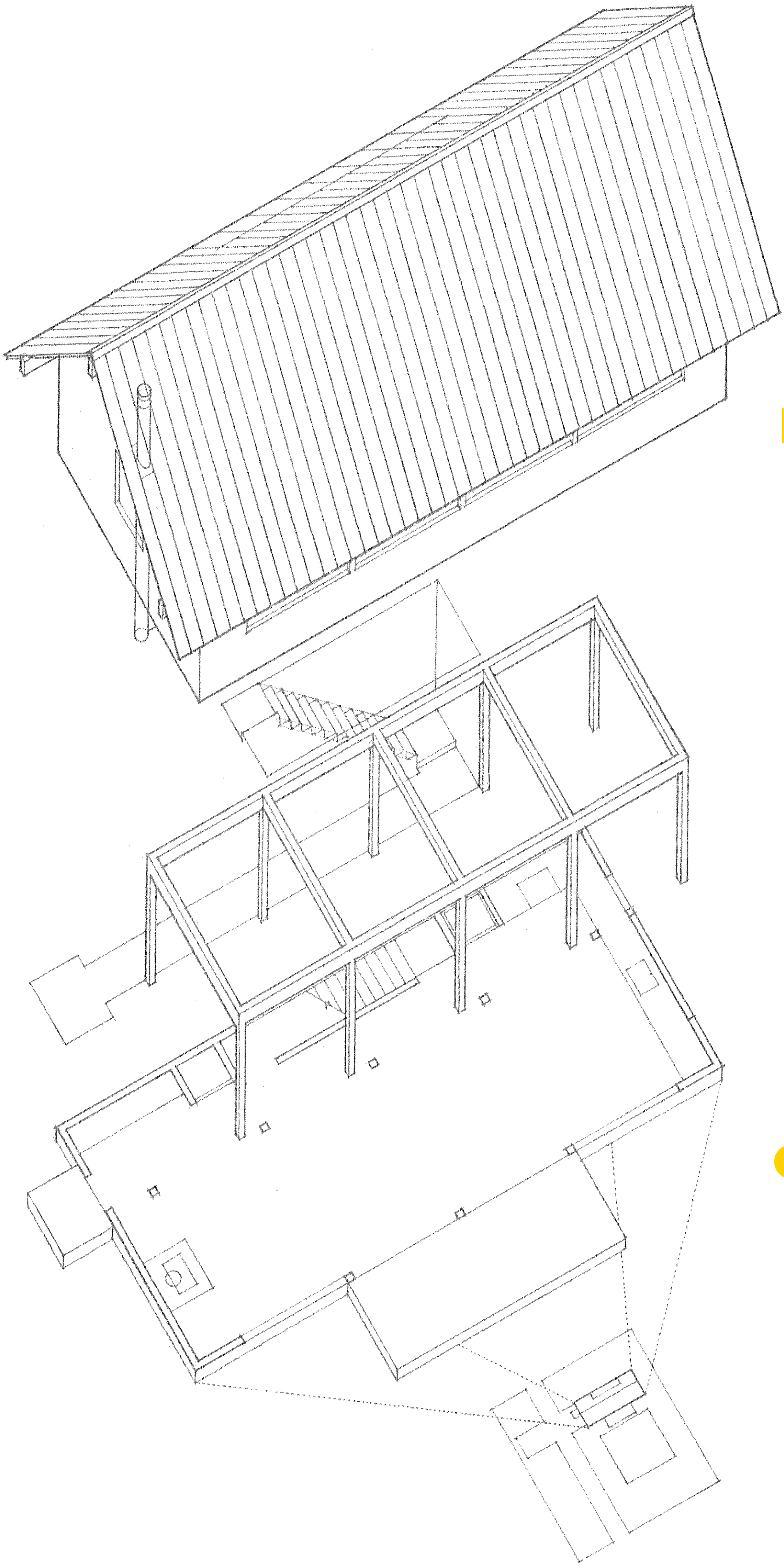
What is relevant to any discussion of sustainable design is that most of the building sector's energy consumption is not attributable to the production of materials or the process of construction, but rather to operational processes—the heating, cooling, and lighting of buildings. This means that to reduce the energy consumption and GHG emissions generated by the use and maintenance of buildings over their life span, it is necessary to properly design, site, and shape buildings and incorporate natural heating, cooling, ventilation, and daylighting strategies.

The 2030 Challenge issued by Architecture 2030 calls for all new buildings and developments to be designed to use half the fossil fuel energy they would typically consume, and that an equal amount of existing building area be renovated annually to meet a similar standard. Architecture 2030 is further advocating that the fossil fuel reduction standard be increased from to 60% in 2010, 70% in 2015, 80% in 2020, and 90% in 2025, and that by 2030, all new buildings be carbon-neutral (using no fossil-fuel GHG-emitting energy to build and operate).

There are two approaches to reducing a building's consumption of GHG-emitting fossil fuels. The passive approach is to work with the climate in designing, siting, and orienting a building and employ passive cooling and heating techniques to reduce its overall energy requirements. The active approach is to increase the ability of a building to capture or generate its own energy from renewable sources (solar, wind, geothermal, low-impact hydro, biomass and bio-gas) that are available locally and in abundance. While striking an appropriate, cost-effective balance between energy conservation and generating renewable energy is the goal, minimizing energy use is a necessary first step, irrespective of the fact that the energy may come from renewable resources.

Passive approach

active approach



Architecture and building construction are not necessarily one and the same thing. An understanding of the methods for assembling various materials, elements, and components is necessary during both the design and the construction of a building. This understanding, however, while it enables one to build architecture, does not guarantee it. A working knowledge of building construction is only one of several critical factors in the execution of architecture. When we speak of architecture as the art of building, we should consider the following conceptual systems of order in addition to the physical ones of construction:

- The definition, scale, proportion, and organization of the interior spaces of a building
- The ordering of human activities by their scale and dimension
- The functional zoning of the spaces of a building according to purpose and use
- Access to and the horizontal and vertical paths of movement through the interior of a building
- The sensible qualities of a building: form, space, light, color, texture, and pattern
- The building as an integrated component within the natural and built environment

Of primary interest to us in this book are the physical systems that define, organize, and reinforce the perceptual and conceptual ordering of a building.

A system can be defined as an assembly of interrelated or interdependent parts forming a more complex and unified whole and serving a common purpose. A building can be understood to be the physical embodiment of a number of systems and subsystems that must necessarily be related, coordinated, and integrated with each other as well as with the three-dimensional form and spatial organization of the building as a whole.

Structural System

The structural system of a building is designed and constructed to support and transmit applied gravity and lateral loads safely to the ground without exceeding the allowable stresses in its members.

- The superstructure is the vertical extension of a building above the foundation.
- Columns, beams, and loadbearing walls support floor and roof structures.
- The substructure is the underlying structure forming the foundation of a building.

Enclosure System

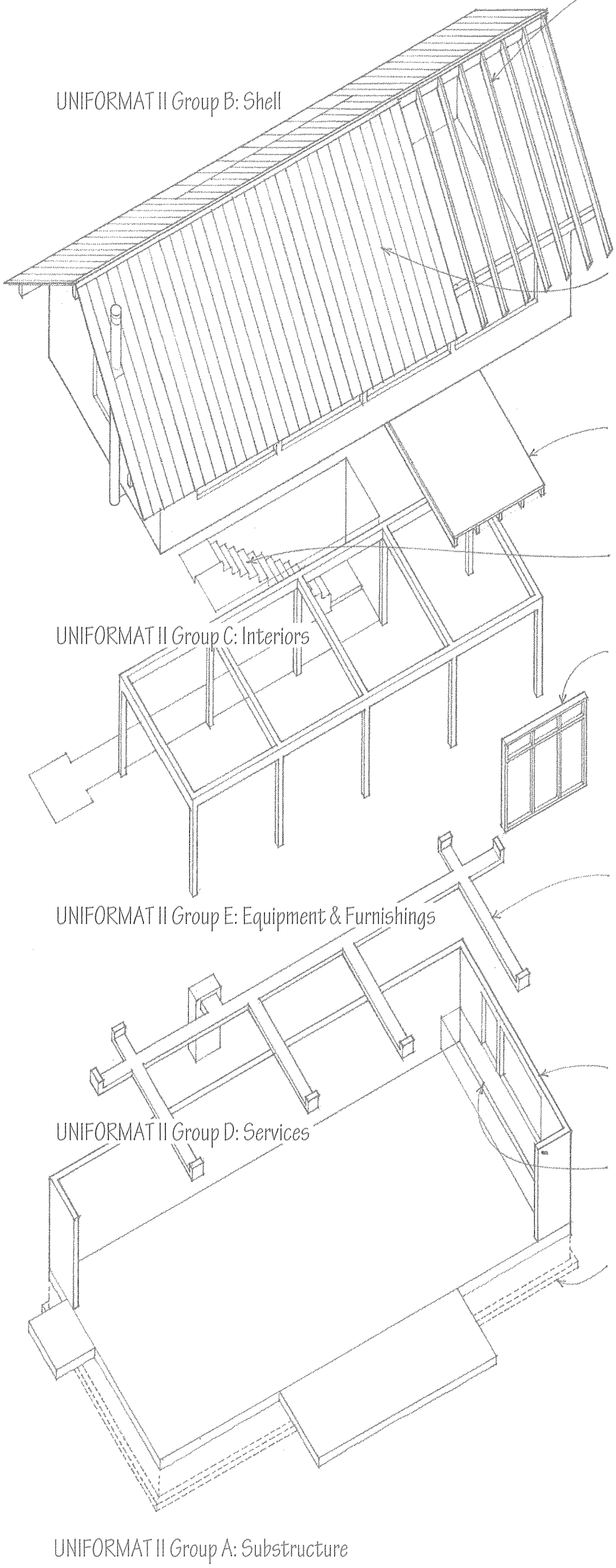
The enclosure system is the shell or envelope of a building, consisting of the roof, exterior walls, windows, and doors.

- The roof and exterior walls shelter interior spaces from inclement weather and control moisture, heat, and air flow through the layering of construction assemblies.
- Exterior walls and roofs also dampen noise and provide security and privacy for the occupants of a building.
- Doors provide physical access.
- Windows provide access to light, air, and views.
- Interior walls and partitions subdivide the interior of a building into spatial units.

Mechanical Systems

The mechanical systems of a building provide essential services to a building.

- The water supply system provides potable water for human consumption and sanitation.
- The sewage disposal system removes fluid waste and organic matter from a building.
- Heating, ventilating, and air-conditioning systems condition the interior spaces of a building for the environmental comfort of the occupants.
- The electrical system controls, meters, and protects the electric power supply to a building, and distributes it in a safe manner for power, lighting, security, and communication systems.
- Vertical transportation systems carry people and goods from one level to another in medium- and high-rise buildings.
- Fire-fighting systems detect and extinguish fires.
- Structures may also require waste disposal and recycling systems.



Roof Systems
Chapter 6

Moisture & Thermal Protection
Chapter 7

Floor Systems
Chapter 4

Special Construction
Chapter 9

Doors & Windows
Chapter 8

Mechanical & Electrical Systems
Chapter 11

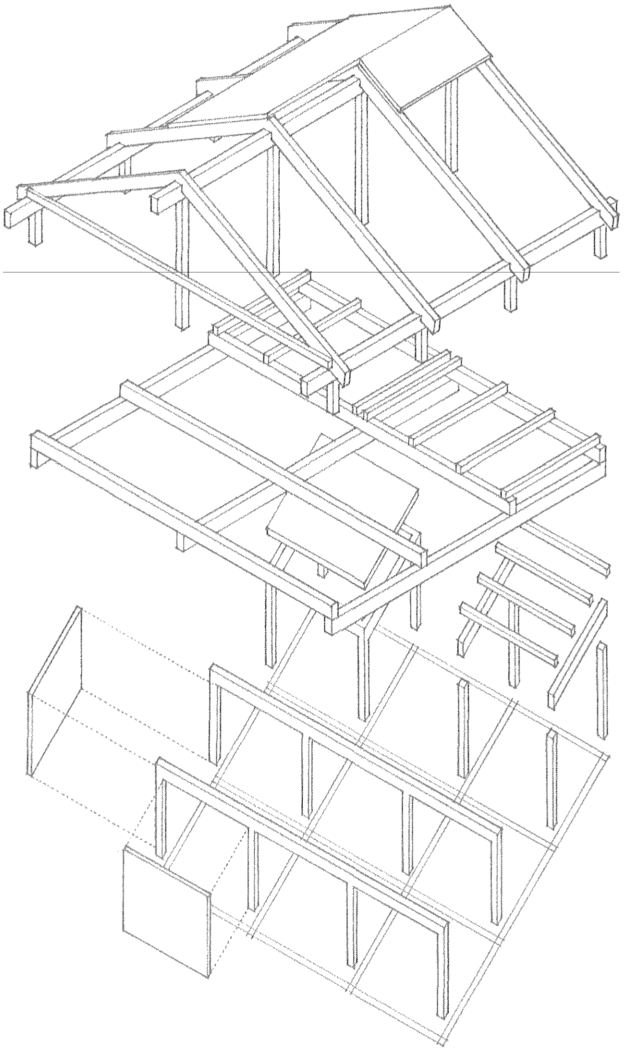
Wall Systems
Chapter 5

Finish Work
Chapter 10

Foundation Systems
Chapter 3

The Building Site
Chapter 1

Notes on Materials
Chapter 12



The manner in which we select, assemble, and integrate the various building systems in construction should take into account the following factors:

Performance Requirements
- Structural compatibility, integration, and safety
- Fire resistance, prevention, and safety
- Allowable or desirable thickness of construction assemblies
- Control of heat and air flow through building assemblies
- Control of migration and condensation of water vapor
- Accommodation of building movement due to settlement, structural deflection, and expansion or contraction with changes in temperature and humidity
- Noise reduction, sound isolation, and acoustical privacy
- Resistance to wear, corrosion, and weathering
- Finish, cleanliness, and maintenance requirements
- Safety in use

Aesthetic Qualities
- Desired relationship of building to its site, adjacent properties, and neighborhood
- Preferred qualities of form, massing, color, pattern, texture, and detail

Regulatory Constraints
- Compliance with zoning ordinances and building codes

Economic Considerations
- Initial cost comprising material, transportation, equipment, and labor costs
- Life-cycle costs, which include not only initial cost, but also maintenance and operating costs, energy consumption, useful lifetime, demolition and replacement costs, and interest on invested money

Environmental Impact
- Conservation of energy and resources through siting and building design
- Energy efficiency of mechanical systems
- Use of resource-efficient and nontoxic materials
- See 1.03–1.06

Construction Practices
- Safety requirements
- Allowable tolerances and appropriate fit
- Conformance to industry standards and assurance
- Division of work between the shop and the field
- Division of labor and coordination of building trades
- Budget constraints
- Construction equipment required
- Erection time required
- Provisions for inclement weather

- The U.S. Occupational Health and Safety Act (OSHA) regulates the design of workplaces and sets safety standards under which a building must be constructed.

Building codes are adopted and enforced by local government agencies to regulate the design, construction, alteration, and repair of buildings in order to protect the public safety, health, and welfare. The codes generally establish requirements based on the type of occupancy and construction of a building, minimum standards for materials and methods of construction, and specifications for structural and fire safety. While codes are primarily prescriptive in nature, they also contain performance criteria, stipulating how a particular component or system must function without necessarily giving the means to be employed to achieve the results. The codes often reference standards established by the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), and other technical societies and trade associations, to indicate the properties desired in a material or component and the methods of testing required to substantiate the performance of products.

Model Codes

Model codes are building codes developed by national organizations of code officials, materials and life safety experts, professional societies, and trade associations for adoption by local communities as legally enforceable regulations. If certain provisions need to be modified or added to address local requirements or concerns, a model code may be enacted by a municipality with amendments.

International Building Code®

Since the early part of the last century, three major model codes have been developed for use in various parts of the U.S. by the Building Officials and Code Administrators International, Inc. (BOCA), the International Conference of Building Officials (ICBO), and the Southern Building Code Conference (SBCC). In 1994, these model-code groups merged to form the International Code Council (ICC) with the goal of developing a comprehensive and coordinated set of national model codes. In 2000, the ICC published the first edition of the International Building Code® (IBC).

As with the model codes that preceded it, the IBC begins by defining categories of use or occupancy and setting height and area limitations in relation to the occupancy of a building and the type of construction employed, and then prescribes five types of construction according to degree of fire resistance and combustibility. The code also contains provisions for interior finishes, fire protection systems, emergency egress, accessibility, interior environment, energy efficiency, exterior walls and roofs, structural design, building materials, elevators and conveying systems, and existing structures.

Companion Codes

The International Residential Code® (IRC) regulates the construction of detached one- and two-family dwellings and townhouses not more than three stories in height and having a separate means of egress. The International Existing Building Code®, which regulates the alteration, repair, and renovation of existing facilities, emerged with the increasing importance of historic preservation and sustainable reuse of existing buildings. Other companion codes include the International Energy Conservation Code®, International Fire Code®, International Mechanical Code®, and International Plumbing Code®.

Other Important Codes

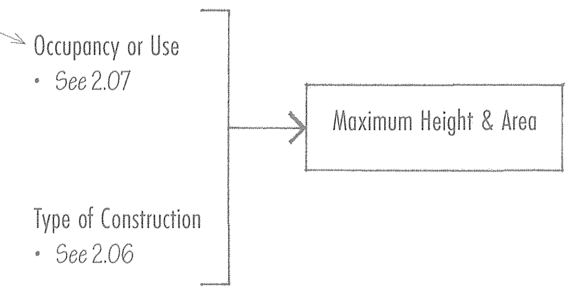
The National Fire Protection Association (NFPA) has developed a new model building code, NFPA 5000, as an alternative to the International Building Code. The NFPA also publishes other code documents.

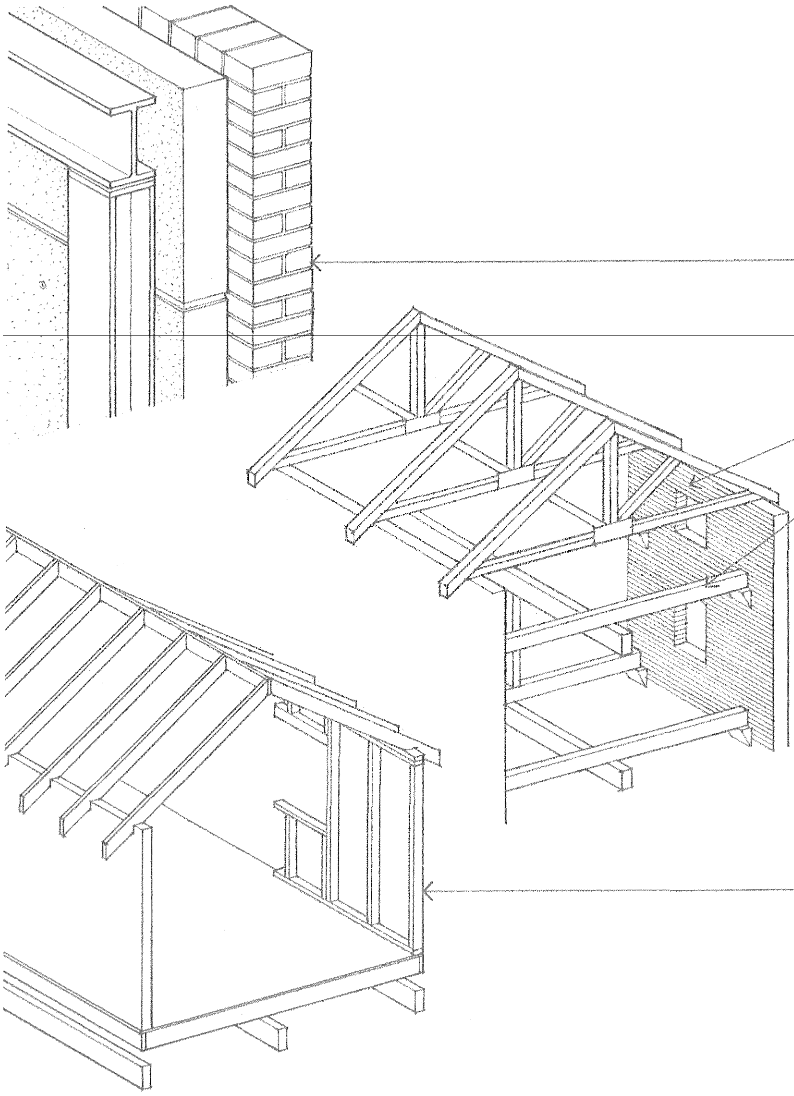
- NFPA-70, the National Electric Code, ensures the safety of persons and the safeguarding of buildings and their contents from hazards arising from the use of electricity for light, heat, and power.
- NFPA-101, the Life Safety Code, establishes minimum requirements for fire safety, the prevention of danger from fire, smoke and gases, fire detection and alarm systems, fire extinguishing systems, and emergency egress.
- NFPA-13 governs the installation of fire sprinklers.

Federal Requirements

In addition to the locally adopted version of the model codes, there are specific federal requirements that must be considered in the design and construction of facilities.

- The Americans with Disabilities Act (ADA) of 1990 is federal civil-rights legislation requiring that buildings be made accessible to persons with physical disabilities and certain defined mental disabilities. The ADA Accessibility Guidelines (ADAAG) are administered by the Architectural and Transportation Barriers Compliance Board (ATBCB), and the regulations are administered by the U.S. Department of Justice. The ADA applies to all new construction as well as to the alteration of existing buildings where such work is readily achievable.
- The Federal Fair Housing Act (FFHA) of 1988 includes Department of Housing and Urban Development (HUD) regulations requiring all residential complexes of four or more dwelling units constructed after March 13, 1991 to be adaptable for use by persons with disabilities.





The IBC classifies the construction of a building according to the fire resistance of its major elements: structural frame, exterior and interior bearing walls, nonbearing walls and partitions, and floor and roof assemblies.

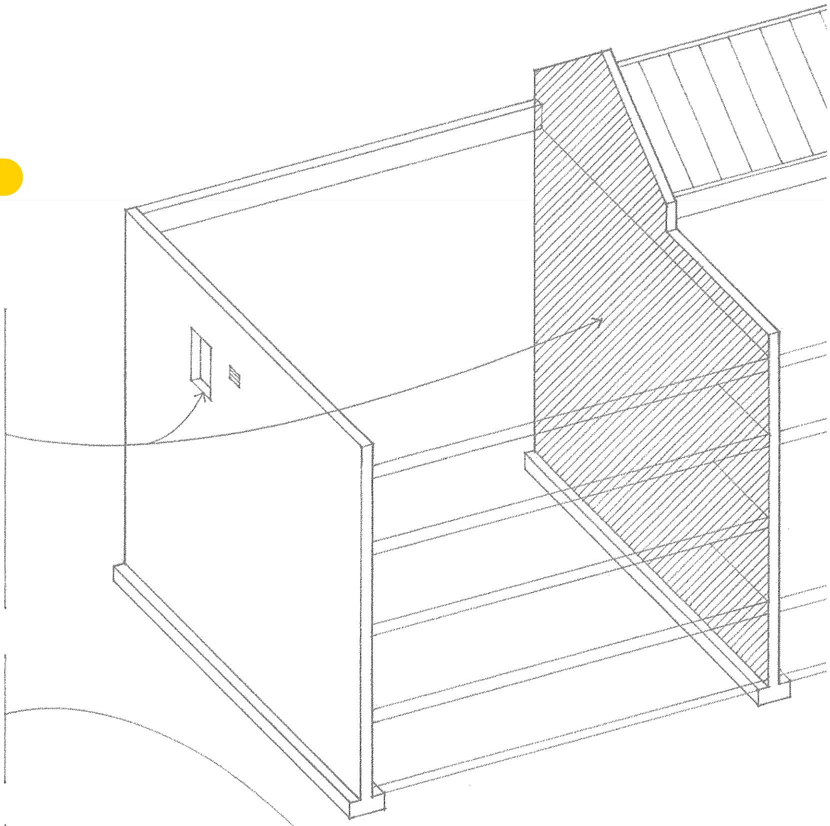
- Type I buildings have their major building elements constructed of noncombustible materials, such as concrete, masonry, or steel. Some combustible materials may be allowed if they are ancillary to the primary structure of the building. Type II buildings are similar to Type I buildings except for a reduction in the required fire-resistance ratings of the major building elements.
- Type III buildings have noncombustible exterior walls and major interior elements of any material permitted by the code.
- Type IV buildings (Heavy Timber, HT) have noncombustible exterior walls and major interior elements of solid or laminated wood of specified minimum sizes and without concealed spaces.
- Type V buildings have structural elements and exterior and interior walls of any material permitted by the code.
- Type V-Protected construction requires all major building elements, except for nonbearing interior walls and partitions, to be of one-hour fire-resistive construction.
- Type V-Unprotected construction has no requirements for fire-resistance except for when the code requires protection of exterior walls due their proximity to a property line.

- The table below outlines the required fire-resistive ratings of major building elements for the various types of construction. Consult Table 601 of the International Building Code for more specific requirements.
- See Appendix for the fire-resistance ratings of representative construction assemblies.

Fire-Resistance Rating Requirements (hours)

Construction Type	Type I		Type II		Type III		Type IV	Type V	
	A	B	A	B	A	B	HT	A	B
Building Element									
Structural frame	3	2	1	0	1	0	2	1	0
Bearing walls									
Exterior	3	2	1	0	2	2	2	1	0
Interior	3	2	1	0	1	0	1/HT	1	0
Nonbearing walls	Varies with occupancy, type of construction, location on property line, and distance to adjacent structures								
Floor construction	2	2	1	0	1	0	HT	1	0
Roof construction	1 1/2	1	1	0	1	0	HT	1	0

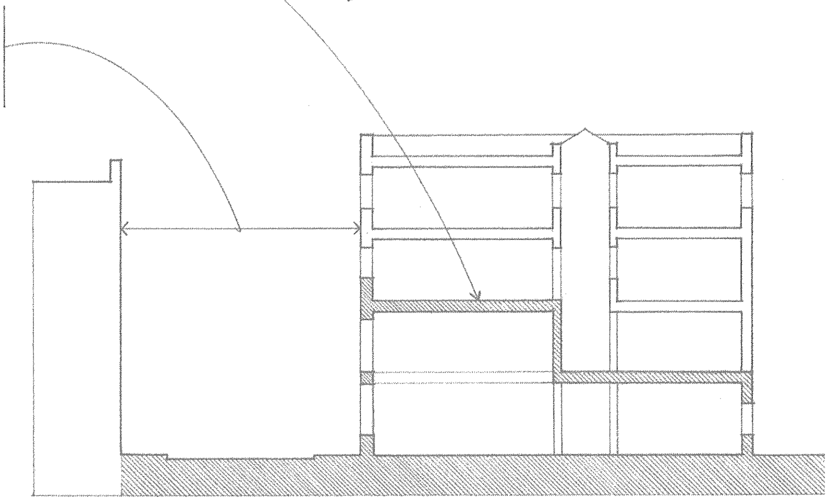
The IBC limits the maximum height and area per floor of a building according to construction type and occupancy group, expressing the intrinsic relationship between degree of fire resistance, size of a building, and nature of an occupancy. The larger a building, the greater the number of occupants, and the more hazardous the occupancy, the more fire-resistant the facility should be. The intent is to protect a building from fire and to contain a fire long enough for the safe evacuation of occupants and for a firefighting response to occur. The limitation on size may be exceeded if the building is equipped with an automatic fire sprinkler system, or if it is divided by fire walls into areas not exceeding the size limitation.



- Fire walls are required to have a fire-resistance rating sufficient to prevent the spread of fire from one part of a building to another. They must extend in a continuous manner from the foundation to a parapet above the roof of a building, or to the underside of a noncombustible roof. All openings in fire walls are restricted to a certain percentage of the wall length and must be protected by self-closing fire doors, fire-rated window assemblies, and, in the case of air ducts, by fire and smoke dampers.

- Occupancy separations refer to fire-resistive vertical or horizontal constructions required to prevent the spread of fire from one occupancy to another in a mixed-occupancy building.

- Fire separation distance refers to the space required between a property line or adjacent building and an exterior wall having a specified fire-resistance rating.



Examples of Occupancy Classifications

A Assembly
Auditoriums, theaters, and stadiums

B Business
Offices, laboratories, and higher education facilities

E Educational
Child-care facilities and schools through the 12th grade

F Factories
Fabricating, assembling, or manufacturing facilities

H Hazardous uses
Facilities handling a certain nature and quantity of hazardous materials

I Institutional
Facilities for supervised occupants, such as hospitals, nursing homes, and reformatories

M Mercantile
Stores for the display and sale of merchandise

R Residential
Homes, apartment buildings, and hotels

S Storage
Warehousing facilities

In enclosing space for habitation, the structural system of a building must be able to support two types of loads—static and dynamic.

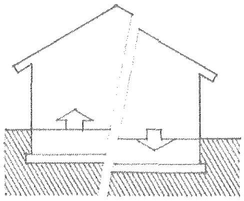
Static Loads

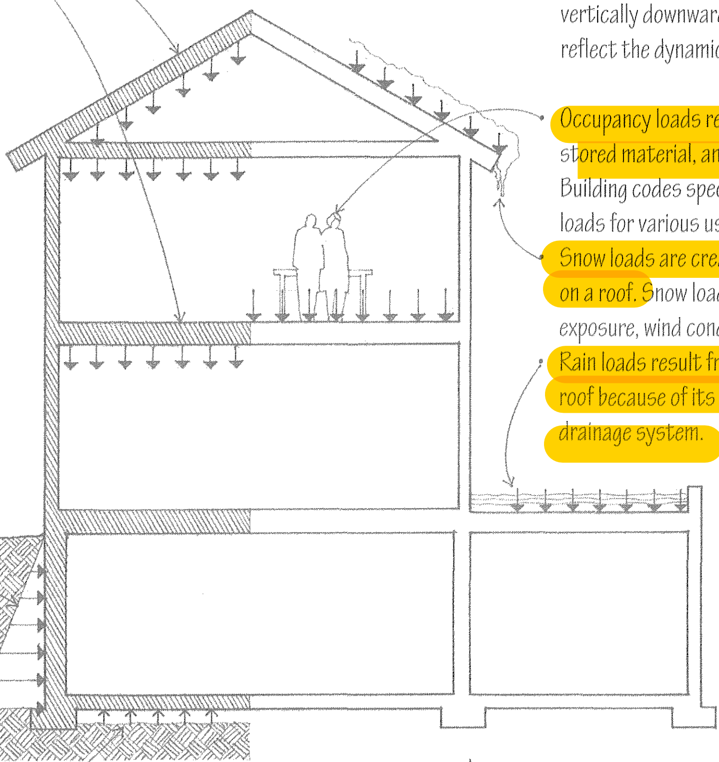
Static loads are assumed to be applied slowly to a structure until it reaches its peak value without fluctuating rapidly in magnitude or position. Under a static load, a structure responds slowly and its deformation reaches a peak when the static force is maximum.

- Dead loads are static loads acting vertically downward on a structure, comprising the self-weight of the structure and the weight of building elements, fixtures, and equipment permanently attached to it.

- Live loads comprise any moving or movable loads on a structure resulting from occupancy, collected snow and water, or moving equipment. A live load typically acts vertically downward but may act horizontally as well to reflect the dynamic nature of a moving load.

- Occupancy loads result from the weight of people, furniture, stored material, and other similar items in a building. Building codes specify minimum uniformly distributed unit loads for various uses and occupancies.
- Snow loads are created by the weight of snow accumulating on a roof. Snow loads vary with geographic location, site exposure, wind conditions, and roof geometry.
- Rain loads result from the accumulation of water on a roof because of its form, deflection, or the clogging of its drainage system.

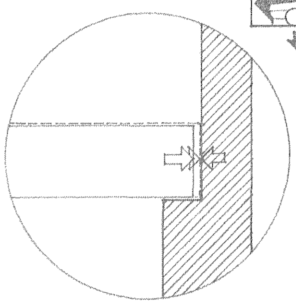




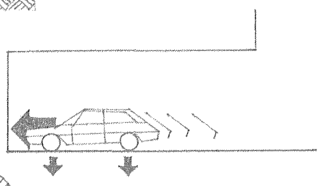
- Settlement loads are imposed on a structure by subsidence of a portion of the supporting soil and the resulting differential settlement of its foundation.

- Ground pressure is the horizontal force a soil mass exerts on a vertical retaining structure.

- Water pressure is the hydraulic force groundwater exerts on a foundation system.



- Thermal stresses are the compressive or tensile stresses developed in a material constrained against thermal expansion or contraction.



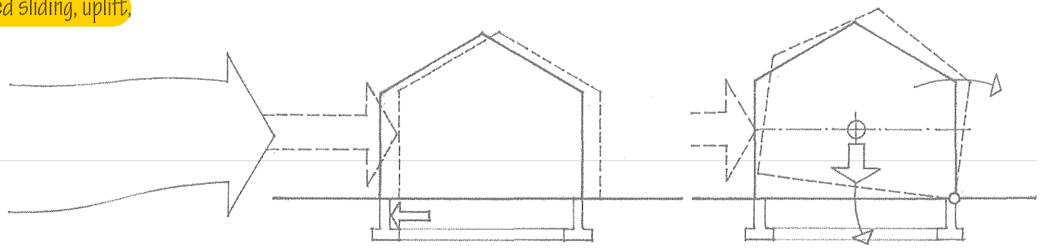
- Impact loads are kinetic loads of short duration due to moving vehicles, equipment, and machinery. Building codes treat this load as a static load, compensating for its dynamic nature by amplifying the static load.

Dynamic Loads

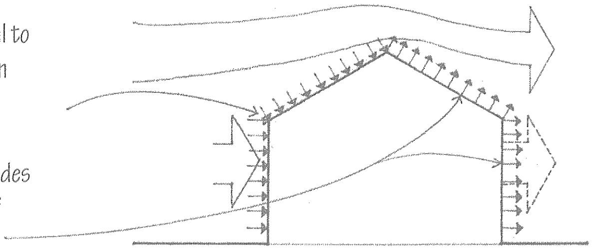
Dynamic loads are applied suddenly to a structure, often with rapid changes in magnitude and point of application. Under a dynamic load, a structure develops inertial forces in relation to its mass and its maximum deformation does not necessarily correspond to the maximum magnitude of the applied force. The two major types of dynamic loads are wind loads and earthquake loads.

Wind loads are the forces exerted by the kinetic energy of a moving mass of air, assumed to come from any horizontal direction.

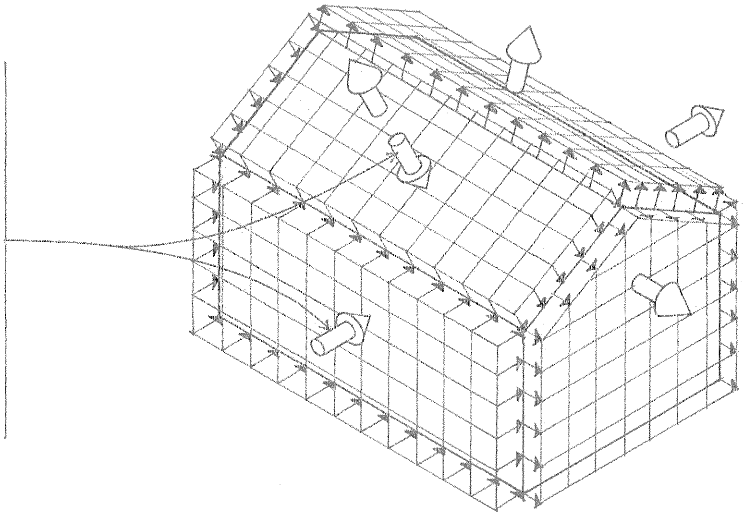
- The structure, components, and cladding of a building must be designed to resist wind-induced sliding, uplift, or overturning.

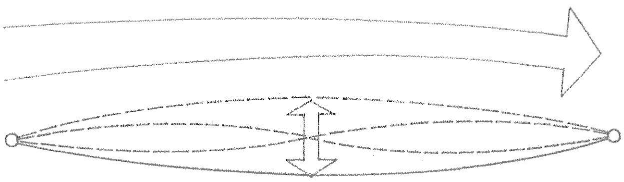


- Wind exerts positive pressure horizontally on the windward vertical surfaces of a building and normal to windward roof surfaces having a slope greater than 30°.
- Wind exerts negative pressure or suction on the sides and leeward surfaces and normal to windward roof surfaces having a slope less than 30°.



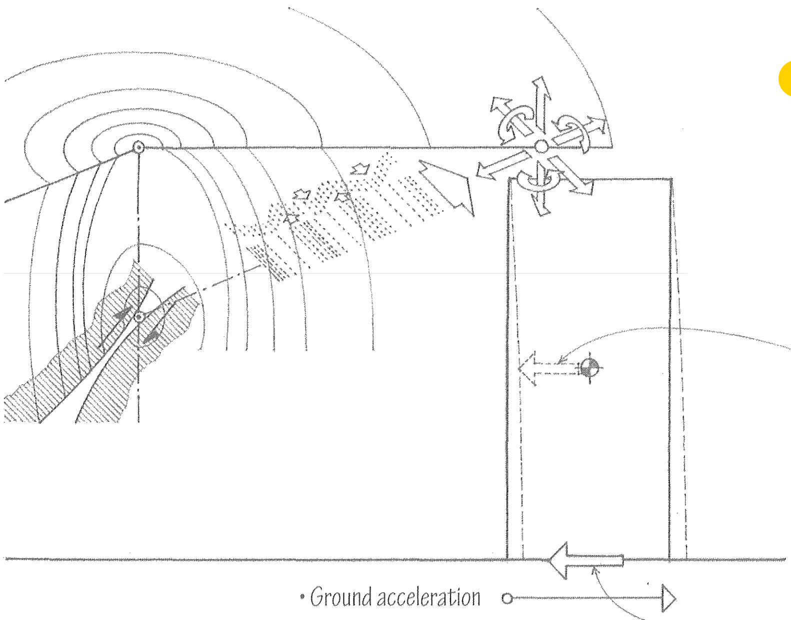
- Design wind pressure is a minimum design value for the equivalent static pressure on the exterior surfaces of a structure resulting from a critical wind velocity, equal to a reference wind pressure measured at a height of 33' (10 m), modified by a number of coefficients to account for the effects of exposure condition, building height, wind gusts, and the geometry and orientation of the structure to the impinging air flow.
- An importance factor may increase the design values for wind or seismic forces on a building because of its large occupancy, its potentially hazardous contents, or its essential nature in the wake of a hurricane or earthquake.





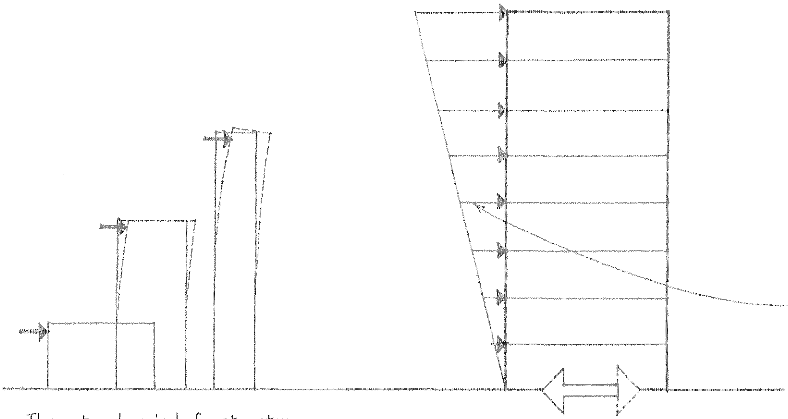
- Flutter refers to the rapid oscillations of a flexible cable or membrane structure caused by the aerodynamic effects of wind.
- Tall, slender buildings, structures with unusual or complex shapes, and lightweight, flexible structures subject to flutter require wind tunnel testing or computer modeling to investigate how they respond to the distribution of wind pressure.

2.10 EARTHQUAKE LOADS

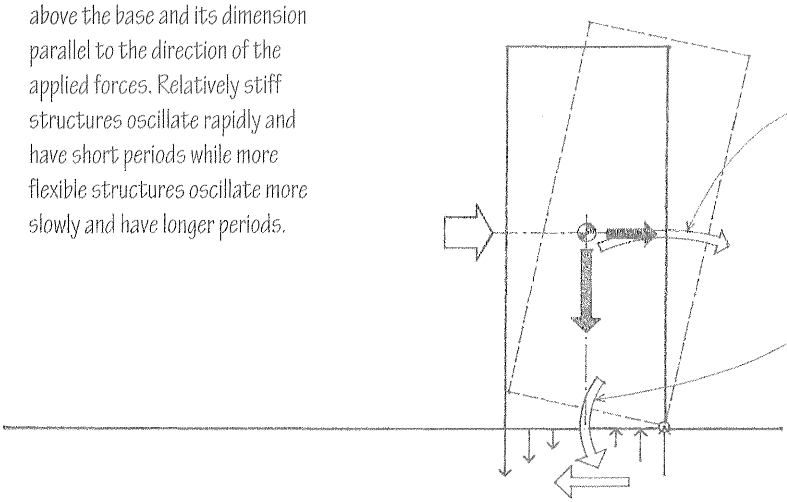


An earthquake consists of a series of longitudinal and transverse vibrations induced in the earth's crust by the abrupt movement of plates along fault lines. The shocks of an earthquake propagate along the earth's surface in the form of waves and attenuate logarithmically with distance from its source. While these ground motions are three-dimensional in nature, their horizontal components are considered to be the more critical in structural design; the vertical load-carrying elements of a structure usually have considerable reserve for resisting additional vertical loads.

- The upper mass of a structure develops an inertial force as it tends to remain at rest while the base is translated by the ground motions of an earthquake. From Newton's second law, this force is equal to the product of mass and acceleration.
- A statically equivalent lateral force, base shear, may be computed for regular structures less than 240' (73 m) in height, irregular structures not more than five stories high, and structures at low seismic risk.
- Base shear is the minimum design value for the total lateral seismic force on a structure assumed to act in any horizontal direction. It is computed by multiplying the total dead load of the structure by a number of coefficients to reflect the character and intensity of the ground motions in the seismic zone, the soil profile type underlying the foundation, the type of occupancy, the distribution of the mass and stiffness of the structure, and the natural period—the time required for one complete oscillation—of the structure.
- Base shear is distributed to each horizontal diaphragm above the base of regular structures in proportion to the floor weight at each level and its distance from the base.
- A more complex dynamic analysis is required for high-rise structures, structures with irregular shapes or framing systems, or for structures built on soft or plastic soils susceptible to failure or collapse under seismic loading.



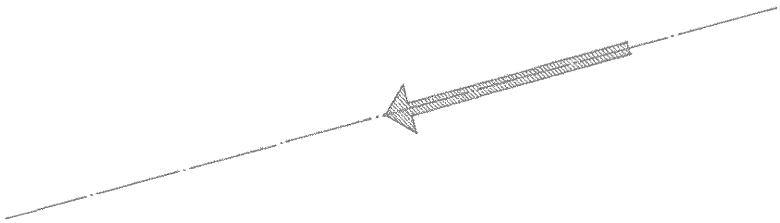
- The natural period of a structure varies according to its height above the base and its dimension parallel to the direction of the applied forces. Relatively stiff structures oscillate rapidly and have short periods while more flexible structures oscillate more slowly and have longer periods.



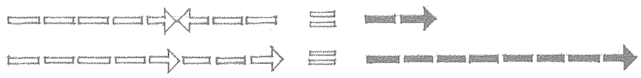
- Any lateral load applied at a distance above grade generates an overturning moment at the base of a structure. For equilibrium, the overturning moment must be counterbalanced by an external restoring moment and an internal resisting moment provided by forces developed in column members and shear walls.
- A restoring moment is provided by the dead load of a structure acting about the same point of rotation as the overturning movement. Building codes usually require that the restoring moment be at least 50% greater than the overturning moment.

The following is a brief introduction to the way a structural system must resolve all of the forces acting on a building and channel them to the ground. For more complete information on the structural design and analysis of buildings, see Bibliography.

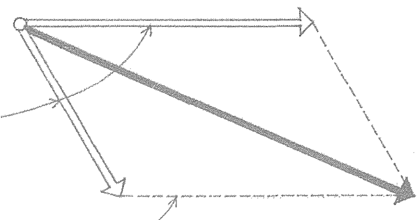
A force is any influence that produces a change in the shape or movement of a body. It is considered to be a vector quantity possessing both magnitude and direction, represented by an arrow whose length is proportional to the magnitude and whose orientation in space represents the direction. A single force acting on a rigid body may be regarded as acting anywhere along its line of action without altering the external effect of the force. Two or more forces may be related in the following ways:

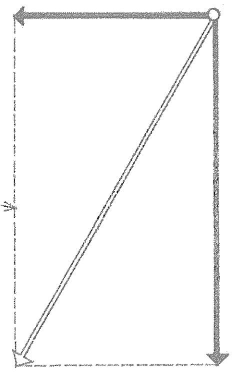


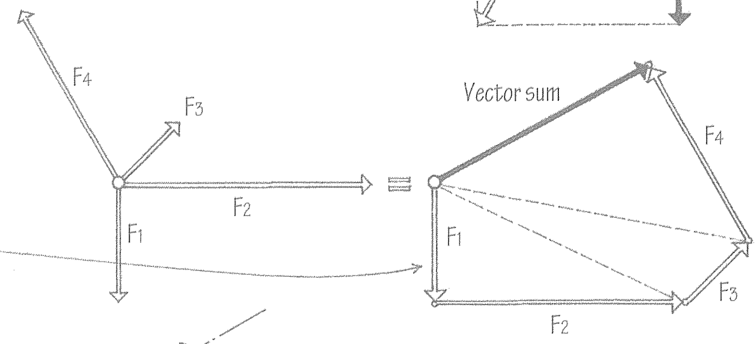
- Collinear forces occur along a straight line, the vector sum of which is the algebraic sum of the magnitudes of the forces, acting along the same line of action.



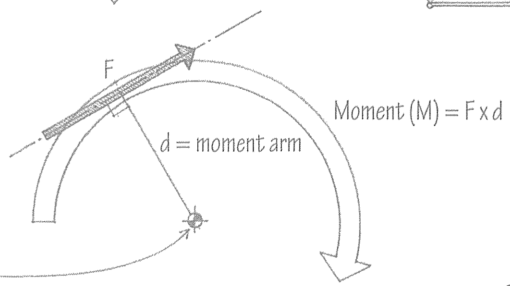
- Concurrent forces have lines of action intersecting at a common point, the vector sum of which is equivalent to and produces the same effect on a rigid body as the application of the vectors of the several forces.
- The parallelogram law states that the vector sum or resultant of two concurrent forces can be described by the diagonal of a parallelogram having adjacent sides that represent the two force vectors being added.
- In a similar manner, any single force can be resolved into two or more concurrent forces having a net effect on a rigid body equivalent to that of the initial force. For convenience in structural analysis, these are usually the rectangular or Cartesian components of the initial force.
- The polygon method is a graphic technique for finding the vector sum of a coplanar system of several concurrent forces by drawing to scale each force vector in succession, with the tail of each at the head of the one preceding it, and completing the polygon with a vector that represents the resultant force, extending from the tail of the first to the head of the last vector.

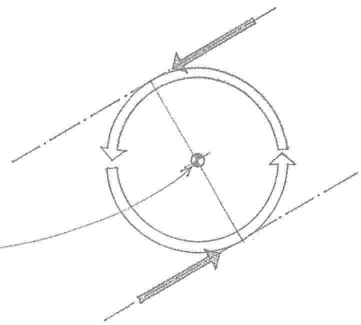




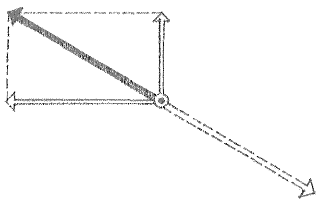


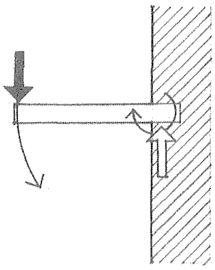
- Nonconcurrent forces have lines of action that do not intersect at a common point, the vector sum of which is a single force that would cause the same translation and rotation of a body as the set of original forces.
- A moment is the tendency of a force to produce rotation of a body about a point or line, equal in magnitude to the product of the force and the moment arm and acting in a clockwise or counterclockwise direction.
- A couple is a force system of two equal, parallel forces acting in opposite directions and tending to produce rotation but not translation. The moment of a couple is equal in magnitude to the product of one of the forces and the perpendicular distance between the two forces.



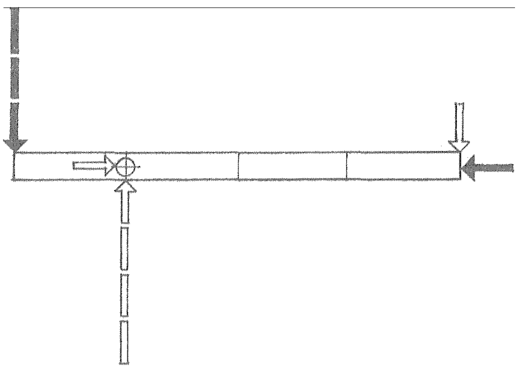


2.12 STRUCTURAL EQUILIBRIUM

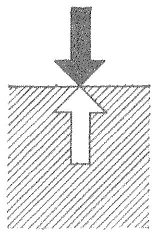




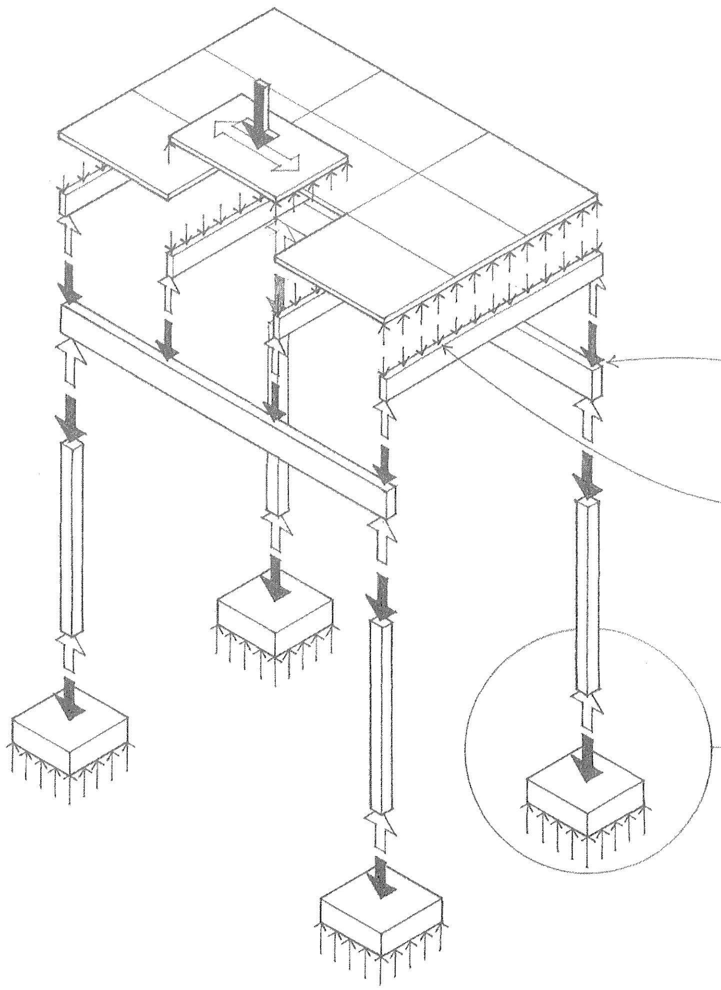
In both structural design and analysis, we are concerned first with the magnitude, direction, and point of application of forces, and their resolution to produce a state of equilibrium. Equilibrium is a state of balance or rest resulting from the equal action of opposing forces. In other words, as each structural element is loaded, its supporting elements must react with equal but opposite forces. For a rigid body to be in equilibrium, two conditions are necessary.



- First, the vector sum of all forces acting on it must equal zero, ensuring translational equilibrium: $\Sigma F_x = 0; \Sigma F_y = 0; \Sigma F_z = 0$.
- Second, the algebraic sum of all moments of the forces about any point or line must equal zero, ensuring rotational equilibrium: $\Sigma M = 0$.



- Newton's third law of motion, the law of action and reaction, states that for every force acting on a body, the body exerts a force having equal magnitude and the opposite direction along the same line of action as the original force.

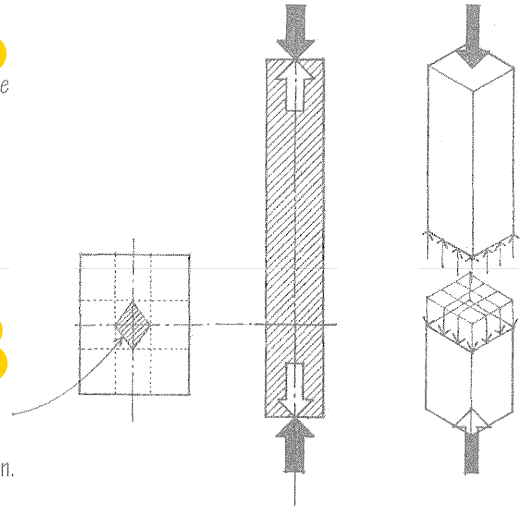


- A concentrated load acts on a very small area or particular point of a supporting structural element, as when a beam bears on a post or a column bears on its footing.
- A uniformly distributed load is a load of uniform magnitude extending over the length or area of the supporting structural element, as in the case of the live load on a floor deck or joist, or a wind load on a wall.

- A free-body diagram is a graphic representation of the complete system of applied and reactive forces acting on a body or an isolated part of a structure. Every elementary part of a structural system has reactions that are necessary for the equilibrium of the part, just as the larger system has reactions at its supports that serve to maintain the equilibrium of the whole.

Columns are rigid, relatively slender structural members designed primarily to support axial compressive loads applied to the ends of the members. Relatively short, thick columns are subject to failure by crushing rather than by buckling. Failure occurs when the direct stress from an axial load exceeds the compressive strength of the material available in the cross section. An eccentric load, however, can produce bending and result in an uneven stress distribution in the section.

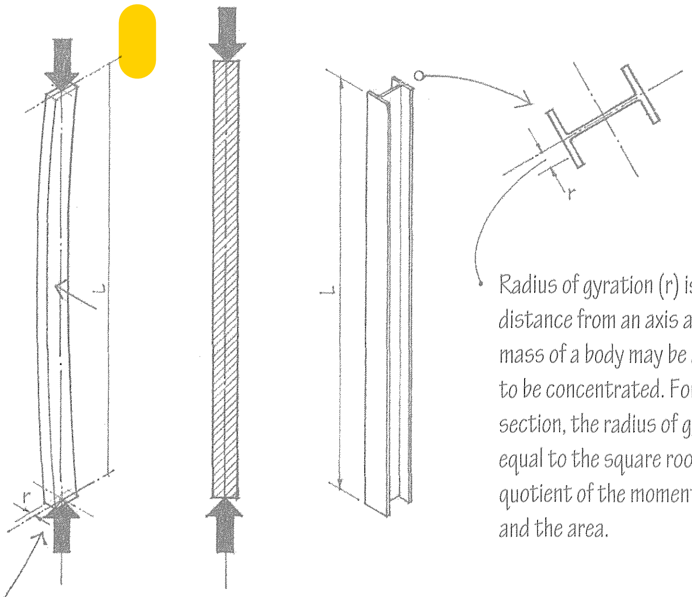
- Kern area is the central area of any horizontal section of a column or wall within which the resultant of all compressive loads must pass if only compressive stresses are to be present in the section. A compressive load applied beyond this area will cause tensile stresses to develop in the section.



- External forces create internal stresses within structural elements.

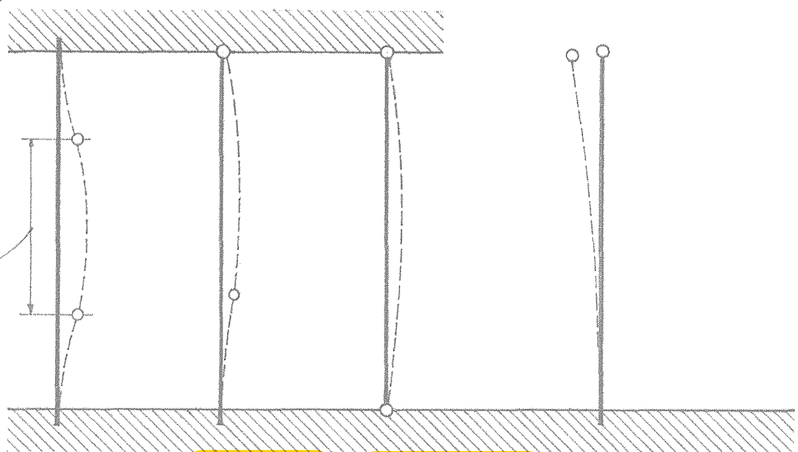
Long, slender columns are subject to failure by buckling rather than by crushing. Buckling is the sudden lateral or torsional instability of a slender structural member induced by the action of an axial load before the yield stress of the material is reached. Under a buckling load, a column begins to deflect laterally and cannot generate the internal forces necessary to restore its original linear condition. Any additional loading would cause the column to deflect further until collapse occurs in bending. The higher the slenderness ratio of a column, the lower is the critical stress that will cause it to buckle. A primary objective in the design of a column is to reduce its slenderness ratio by shortening its effective length or maximizing the radius of gyration of its cross section.

- The slenderness ratio of a column is the ratio of its effective length (L) to its least radius of gyration (r). For asymmetrical column sections, therefore, buckling will tend to occur about the weaker axis or in the direction of the least dimension.

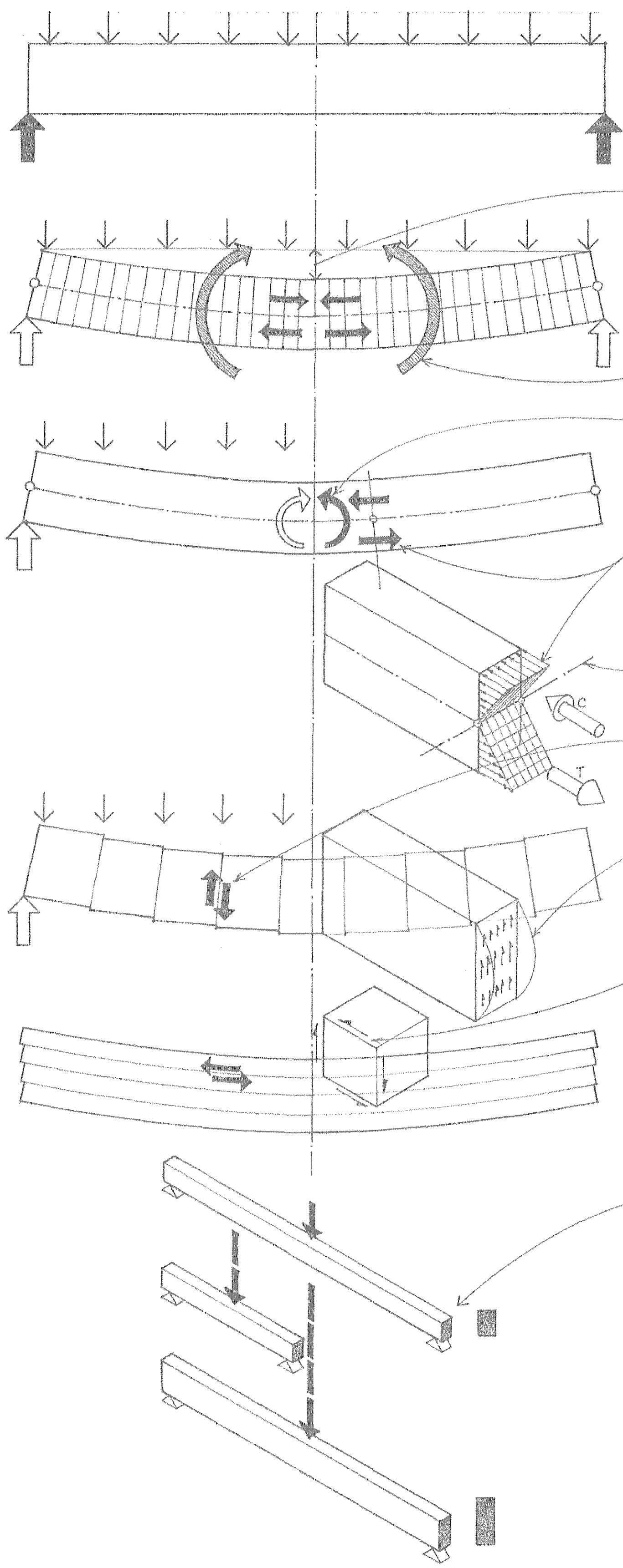


- Radius of gyration (r) is the distance from an axis at which the mass of a body may be assumed to be concentrated. For a column section, the radius of gyration is equal to the square root of the quotient of the moment of inertia and the area.

- Effective length is the distance between inflection points in a column subject to buckling. When this portion of a column buckles, the entire column fails.
- The effective length factor (k) is a coefficient for modifying the actual length of a column according to its end conditions in order to determine its effective length. For example, fixing both ends of a long column reduces its effective length by half and increases its load-carrying capacity by a factor of 4.



- Both ends fixed; k = 0.5
- One end pinned, one end fixed; k = 0.7
- Both ends pinned; k = 1.0
- One end free, one end fixed; k = 2.0



Beams are rigid structural members designed to carry and transfer transverse loads across space to supporting elements. The nonconcurrent pattern of forces subjects a beam to bending and deflection, which must be resisted by the internal strength of the material.

- Deflection is the perpendicular distance a spanning member deviates from a true course under transverse loading, increasing with load and span, and decreasing with an increase in the moment of inertia of the section or the modulus of elasticity of the material.
- Bending moment is an external moment tending to cause part of a structure to rotate or bend, equal to the algebraic sum of the moments about the neutral axis of the section under consideration.
- Resisting moment is an internal moment equal and opposite to a bending moment, generated by a force couple to maintain equilibrium of the section being considered.
- Bending stress is a combination of compressive and tension stresses developed at a cross section of a structural member to resist a transverse force, having a maximum value at the surface furthest from the neutral axis.
- The neutral axis is an imaginary line passing through the centroid of the cross section of a beam or other member subject to bending, along which no bending stresses occur.
- Transverse shear occurs at a cross section of a beam or other member subject to bending, equal to the algebraic sum of transverse forces on one side of the section.
- Vertical shearing stress develops to resist transverse shear, having a maximum value at the neutral axis and decreasing nonlinearly toward the outer faces.
- Horizontal or longitudinal shearing stress develops to prevent slippage along horizontal planes of a beam under transverse loading, equal at any point to the vertical shearing stress at that point.

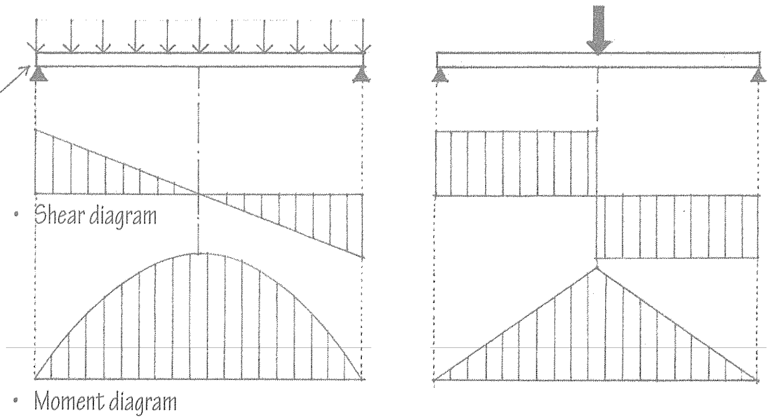
Vertical shearing

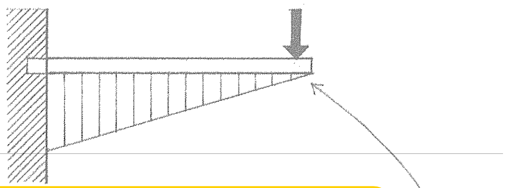
Horizontal shearing

The efficiency of a beam is increased by configuring the cross section to provide the required moment of inertia or section modulus with the smallest possible area, usually by making the section deep with most of the material at the extremities where the maximum bending stresses occur. For example, while halving a beam span or doubling its width reduces the bending stresses by a factor of 2, doubling the depth reduces the bending stresses by a factor of 4.

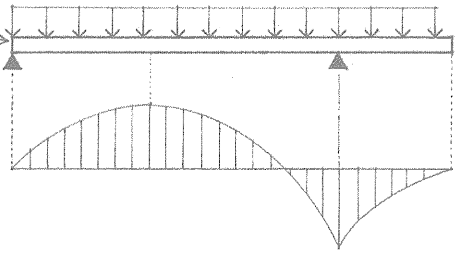
- Moment of inertia is the sum of the products of each element of an area and the square of its distance from a coplanar axis of rotation. It is a geometric property that indicates how the cross-sectional area of a structural member is distributed and does not reflect the intrinsic physical properties of a material.
- Section modulus is a geometric property of a cross section, defined as the moment of inertia of the section divided by the distance from the neutral axis to the most remote surface.

- A simple beam rests on supports at both ends, with the ends free to rotate and having no moment resistance. As with any statically determinate structure, the values of all reactions, shears, and moments for a simple beam are independent of its cross-sectional shape and material.

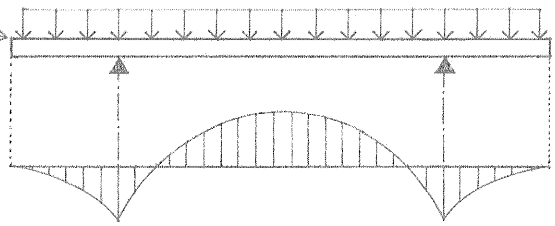




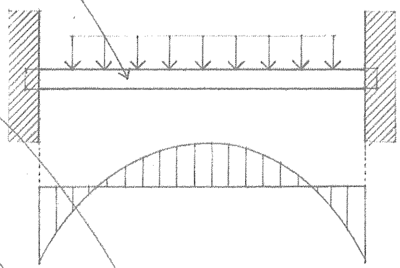
- A cantilever is a projecting beam or other rigid structural member supported at only one fixed end.
- An overhanging beam is a simple beam extending beyond one of its supports. The overhang reduces the positive moment at midspan while developing a negative moment at the base of the cantilever over the support. Assuming a uniformly distributed load, the projection for which the moment over the support is equal and opposite to the moment at midspan is approximately $^3/_8$ of the span.

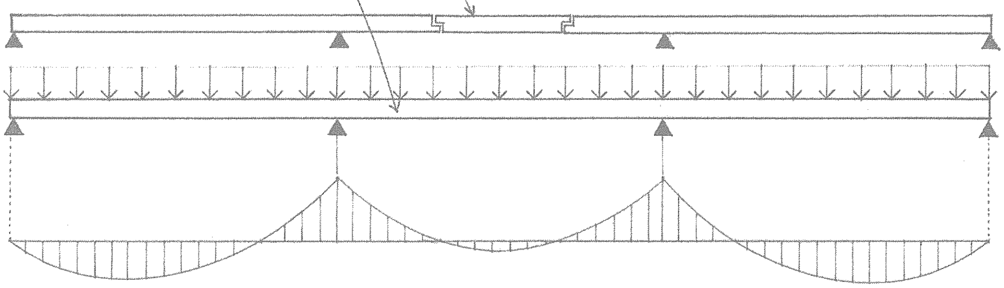


- A double overhanging beam is a simple beam extending beyond both of its supports. Assuming a uniformly distributed load, the projections for which the moments over the supports are equal and opposite to the moment at midspan are approximately $^1/_3$ of the span.

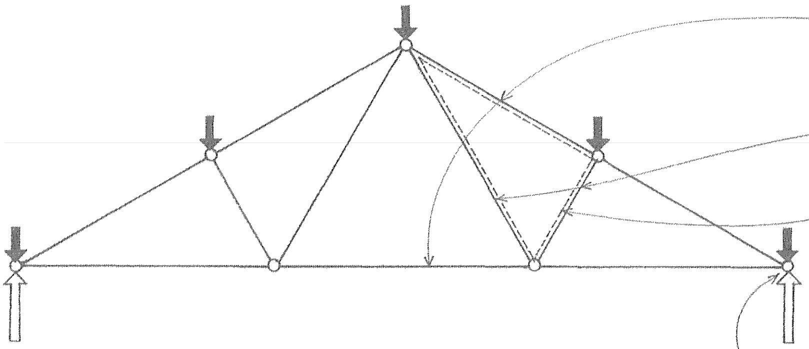


- A fixed-end beam has both ends restrained against translation and rotation. The fixed ends transfer bending stresses, increase the rigidity of the beam, and reduce its maximum deflection.
- A suspended-span is a simple beam supported by the overhangs of two adjoining spans with pinned construction joints at points of zero moment.
- A continuous beam extends over more than two supports in order to develop greater rigidity and smaller moments than a series of simple beams having similar spans and loading. Both fixed-end and continuous beams are indeterminate structures for which the values of all reactions, shears, and moments are dependent not only on span and loading but also on the cross-sectional shape and material of the beam.

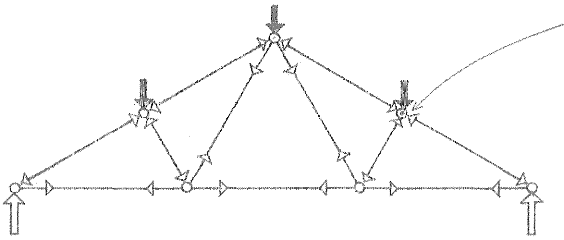




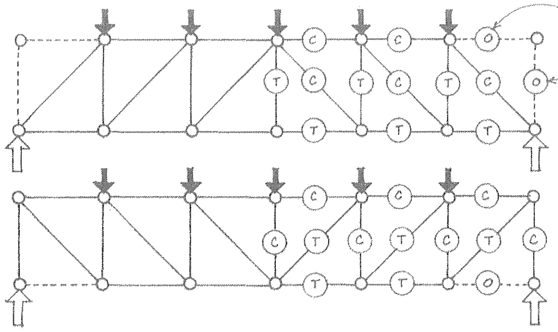
A truss is a structural frame based on the geometric rigidity of the triangle and composed of linear members subject only to axial tension or compression.



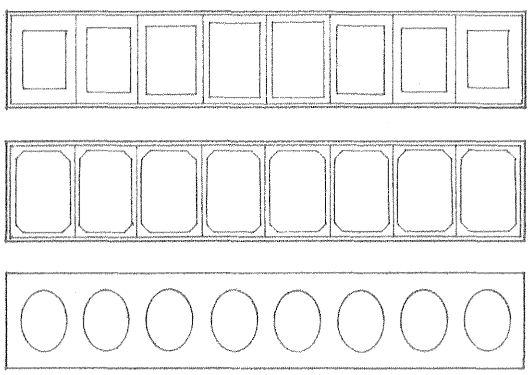
- Top and bottom chords are the principal members of a truss extending from end to end and connected by web members.
- Web is the integral system of members connecting the upper and lower chords of a truss.
- Panel refers to any of the spaces within the web of a truss between any two panel points on a chord and a corresponding joint or pair of joints on an opposite chord.
- Heel is the lower, supported end of a truss.



- Panel point is any of the joints between a principal web member and a chord. A truss must be loaded only at its panel points if its members are to be subject only to axial tension or compression. To prevent secondary stresses from developing, the centroidal axes of truss members and the load at a joint should pass through a common point.



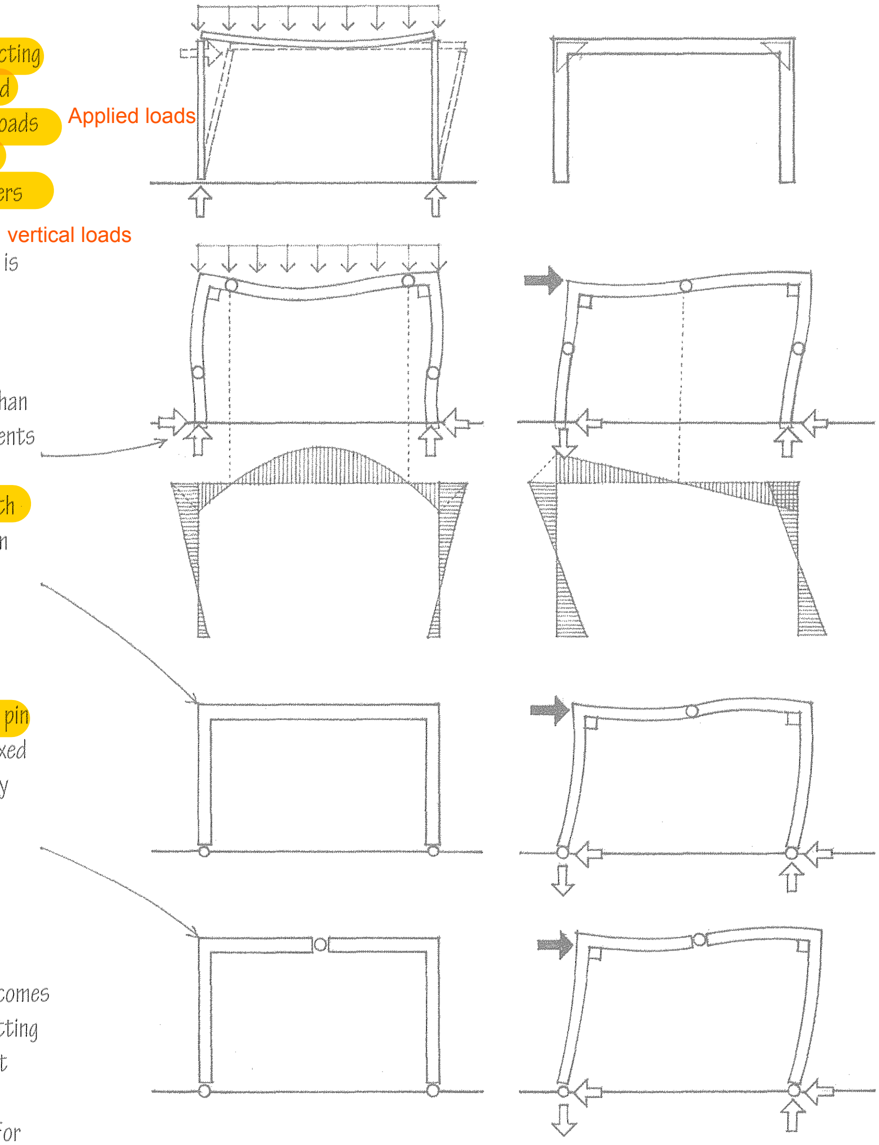
- Zero-force members theoretically carry no direct load; their omission would not alter the stability of the truss configuration.
- See 6.09 for types of trusses and truss configurations.



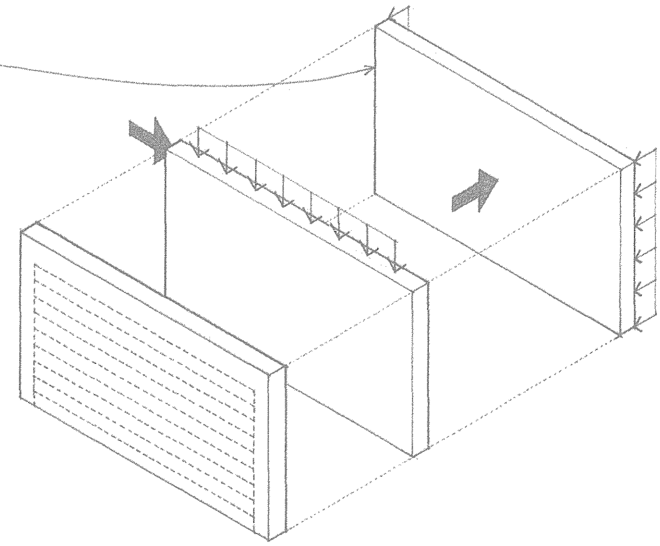
- Vierendeel trusses are framed beam structures having vertical web members rigidly connected to parallel top and bottom chords. Vierendeel trusses are not true trusses because their members are subject to nonaxial bending forces.

A beam simply supported by two columns is not capable of resisting lateral forces unless it is braced. If the joints connecting the columns and beam are capable of resisting both forces and moments, then the assembly becomes a rigid frame. Applied loads produce axial, bending, and shear forces in all members of the frame because the rigid joints restrain the ends of the members from rotating freely. In addition, vertical loads cause a rigid frame to develop horizontal thrusts at its base. A rigid frame is statically indeterminate and rigid only in its plane.

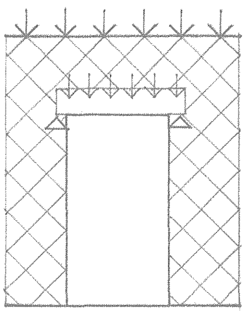
- Fixed frame is a rigid frame connected to its supports with fixed joints. A fixed frame is more resistant to deflection than a hinged frame but also more sensitive to support settlements and thermal expansion and contraction.
- Hinged frame is a rigid frame connected to its supports with pin joints. The pin joints prevent high bending stresses from developing by allowing the frame to rotate as a unit when strained by support settlements, and to flex slightly when stressed by changes in temperature.
- Three-hinged frame is a structural assembly of two rigid sections connected to each other and to its supports with pin joints. While more sensitive to deflection than either the fixed or hinged frame, the three-hinged frame is least affected by support settlements and thermal stresses. The three-pin joints also permit the frame to be analyzed as a statically determinate structure.



If we fill in the plane defined by two columns and a beam, it becomes a loadbearing wall that acts as a long, thin column in transmitting compressive forces to the ground. Loadbearing walls are most effective when carrying coplanar, uniformly distributed loads and most vulnerable to forces perpendicular to their planes. For lateral stability, loadbearing walls must rely on buttressing with pilasters, cross walls, transverse rigid frames, or horizontal slabs.



Any opening in a loadbearing wall weakens its structural integrity. A lintel or arch must support the load above a door or window opening and allow the compressive stresses to flow around the opening to adjacent sections of the wall.



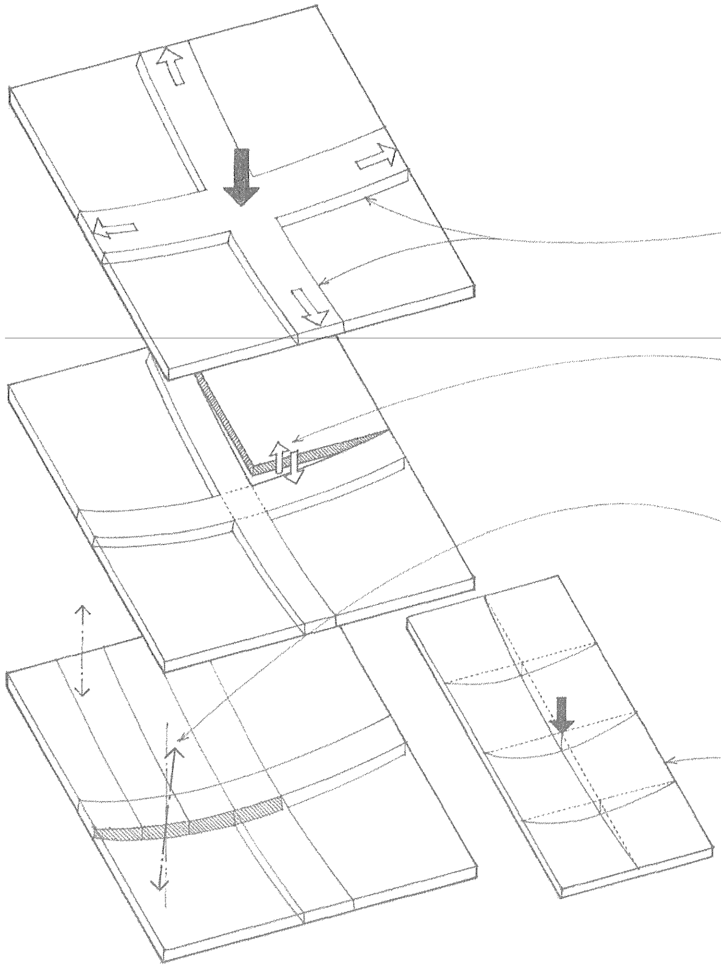
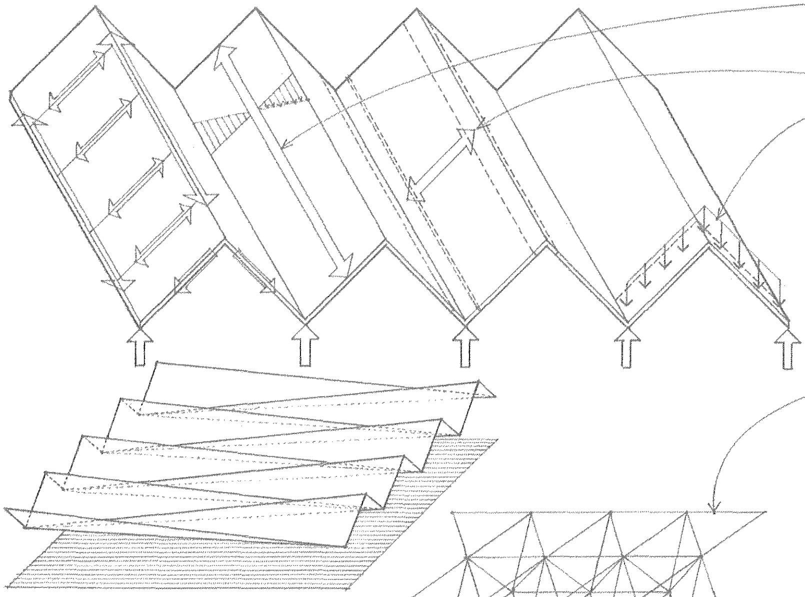


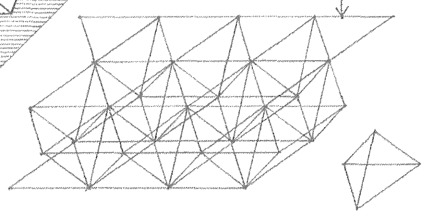
Plate structures are rigid, planar, usually monolithic structures that disperse applied loads in a multidirectional pattern, with the loads generally following the shortest and stiffest routes to the supports. A common example of a plate structure is a reinforced concrete slab.

A plate can be envisioned as a series of adjacent beam strips interconnected continuously along their lengths. As an applied load is transmitted to the supports through bending of one beam strip, the load is distributed over the entire plate by vertical shear transmitted from the deflected strip to adjacent strips. The bending of one beam strip also causes twisting of transverse strips, whose torsional resistance increases the overall stiffness of the plate. Therefore, while bending and shear transfer an applied load in the direction of the loaded beam strip, shear and twisting transfer the load at right angles to the loaded strip.

A plate should be square or nearly square to ensure that it behaves as a two-way structure. As a plate becomes more rectangular than square, the two-way action decreases and a one-way system spanning the shorter direction develops because the shorter plate strips are stiffer and carry a greater portion of the load.



Folded plate structures are composed of thin, deep elements joined rigidly along their boundaries and forming sharp angles to brace each other against lateral buckling. Each plane behaves as a beam in the longitudinal direction. In the short direction, the span is reduced by each fold acting as a rigid support. Transverse strips behave as a continuous beam supported at fold points. Vertical diaphragms or rigid frames stiffen a folded plate against deformation of the fold profile. The resulting stiffness of the cross section enables a folded plate to span relatively long distances.

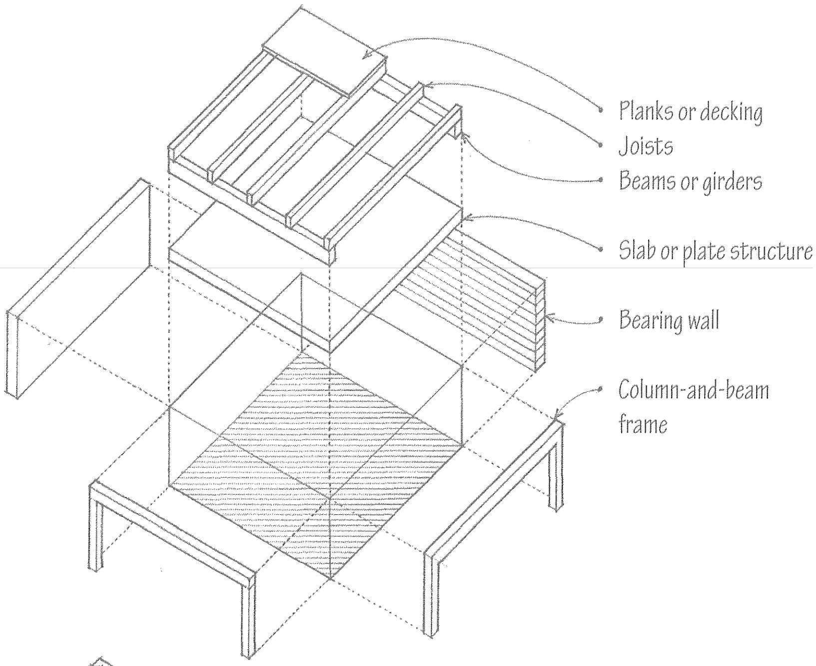


CSI MasterFormat 13 32 00 Space Frames

A space frame is composed of short rigid linear elements triangulated in three dimensions and subject only to axial tension or compression. The simplest spatial unit of a space frame is a tetrahedron having four joints and six structural members. Because the structural behavior of a space frame is analogous to that of a plate structure, its supporting bay should be square or nearly square to ensure that it acts as a two-way structure. Enlarging the bearing area of the supports increases the number of members into which shear is transferred and reduces the forces in the members. See 6.10 for more information on space frames.

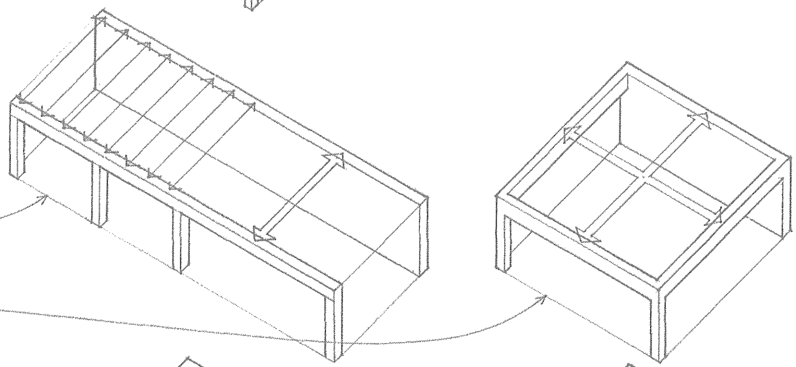
With the principal structural elements of column, beam, slab, and loadbearing wall, it is possible to form an elementary structural unit capable of defining and enclosing a volume of space for habitation. This structural unit is the basic building block for the structural system and spatial organization of a building.

- Horizontal spans may be traversed by reinforced concrete slabs or by a layered, hierarchical arrangement of girders, beams, and joists supporting planks or decking.
- The vertical support for a structural unit may be provided by loadbearing walls or by a framework of columns and beams.

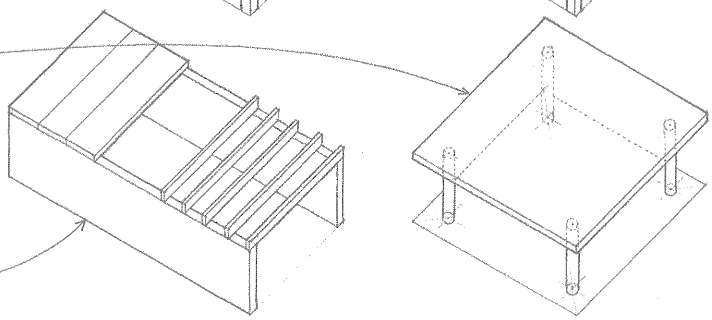


The dimensions and proportions of a structural unit or bay influence the selection of an appropriate spanning system.

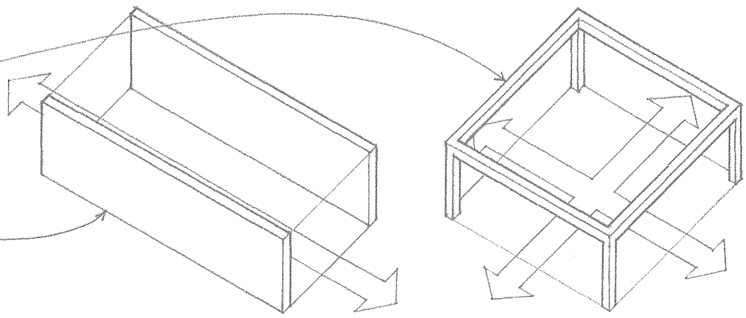
- One-way systems of joists, planks, or slabs are more efficient when structural bays are rectangular—that is, when the ratio of the long to the short dimensions is greater than 1.5:1—or when the structural grid generates a linear pattern of spaces.
- Two-way systems of beams and slabs are more effective for square or nearly square bays.



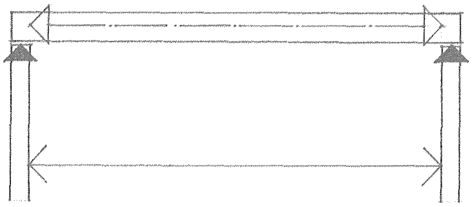
- A two-way slab supported by four columns defines a horizontal layer of space.
- The parallel nature of loadbearing walls leads naturally to the use of one-way spanning systems.
- Because loadbearing walls are most effective when supporting a uniformly distributed load, they typically support a series of joists, planks, or a one-way slab.



- A linear framework of columns and beams defines a three-dimensional module of space capable of being expanded both horizontally and vertically.
- Two loadbearing walls naturally define an axial, bidirectional space. Secondary axes can be developed perpendicular to the primary axis with openings within the loadbearing walls.

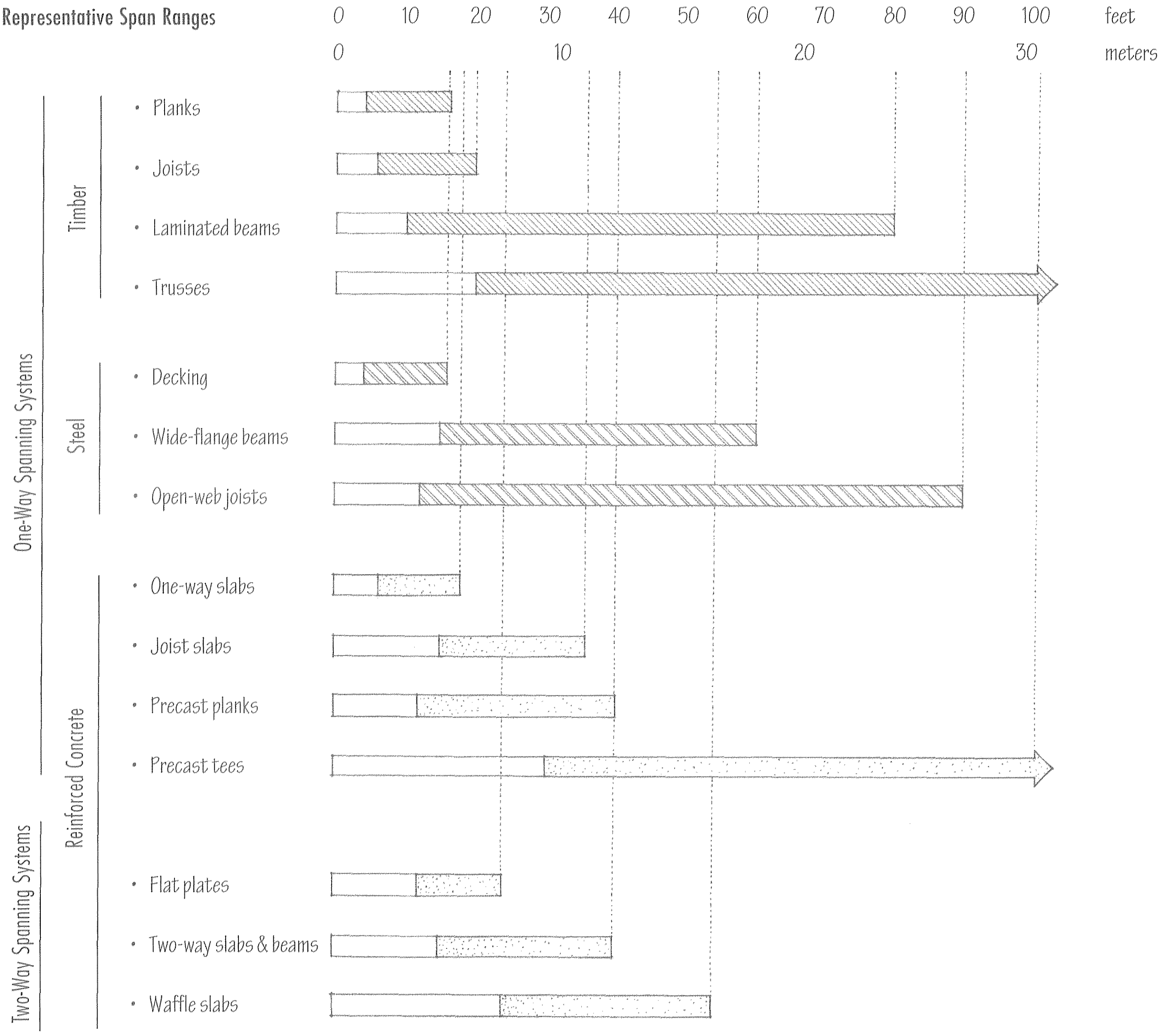


2.20 STRUCTURAL SPANS



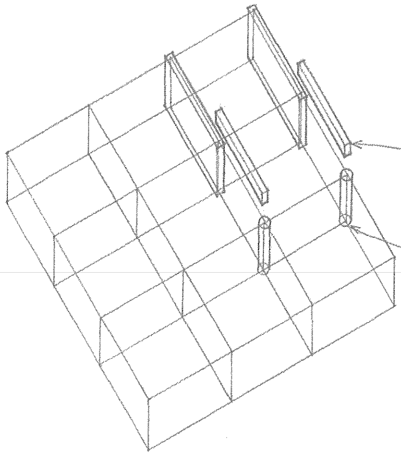
The spanning capability of horizontal elements determines the spacing of their vertical supports. This fundamental relationship between the span and spacing of structural elements influences the dimensions and scale of the spaces defined by the structural system of a building. The dimensions and proportions of structural bays, in turn, should be related to the programmatic requirements of the spaces.

Representative Span Ranges

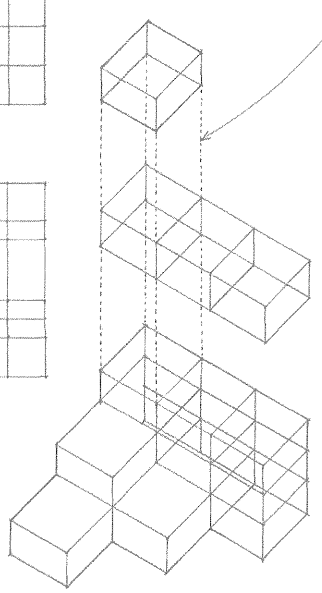


The arrangement of principal vertical supports not only regulates the selection of a spanning system, it also establishes the possibilities for the ordering of spaces and functions in a building.

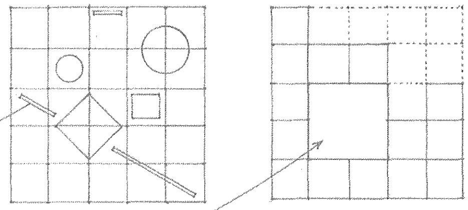
The principal points and lines of support for a structural system typically define a grid. The critical points of the grid are those at which columns and loadbearing walls collect loads from beams and other horizontal spanning elements and channel these loads vertically to the ground foundation.



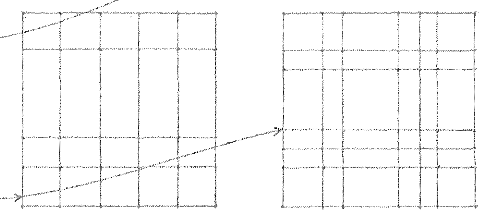
- Grid lines represent horizontal beams and loadbearing walls.
- Intersections of grid lines represent the locations of columns or concentrated gravity loads.
- A basic structural unit or bay can be logically extended vertically along the axes of columns and horizontally along the spans of beams and loadbearing walls.



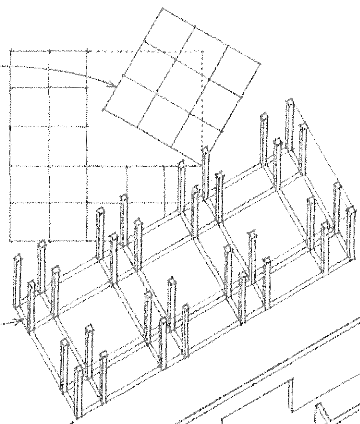
The inherent geometric order of a grid can be used in the design process to initiate and reinforce the functional and spatial organization of a building design.



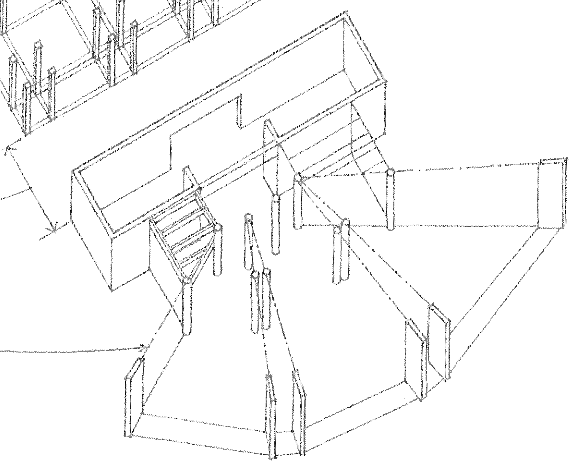
- Nonloadbearing walls may be placed to define a variety of spatial configurations and allow a building to be more flexible in responding to the programmatic requirements of its spaces.
- A structural grid can be modified by addition or subtraction to accommodate special needs such as large spaces or unusual site conditions.



- A grid may be irregular in one or two directions to accommodate the dimensional requirements of program spaces.
- A portion of the grid can be dislocated and rotated about a point in the basic pattern.



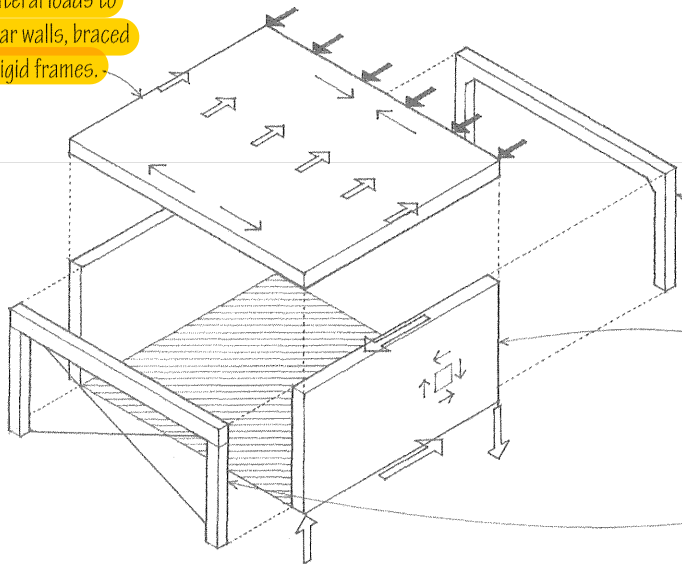
- Two parallel grids can be offset from each other to develop intervening or interstitial spaces that define patterns of movement, mediate between a series of larger spaces, or house mechanical services.
- When two structural patterns cannot be conveniently aligned, a third element, such as a loadbearing wall, a mediating space, or a finer-grained spanning system, can be used.



- Nonuniform or irregular grids can be employed to reflect the hierarchical or functional ordering of spaces within a building.

The structural elements of a building must be sized, configured, and joined to form a stable structure under any possible load conditions. Therefore, a structural system must be designed to not only carry vertical gravity loads, but also withstand lateral wind and seismic forces from any direction. The following are the basic mechanisms for ensuring lateral stability.

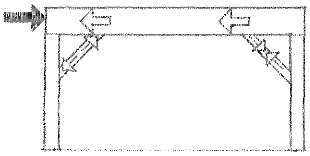
Horizontal diaphragm
- A rigid floor structure, acting as a flat, deep beam, transfers lateral loads to vertical shear walls, braced frames, or rigid frames.



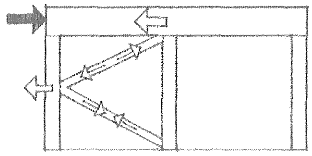
Rigid frame
- A steel or reinforced concrete frame with rigid joints capable of resisting changes in angular relationships

Shear wall
- A wood, concrete, or masonry wall capable of resisting changes in shape and transferring lateral loads to the ground foundation

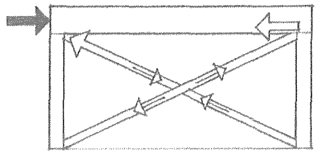
Braced Frame
- A timber or steel frame braced with diagonal members



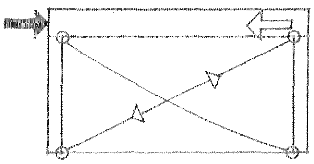
- Knee bracing

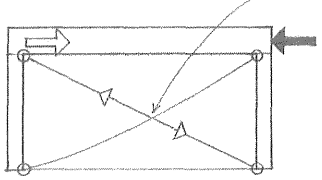


- K-brace

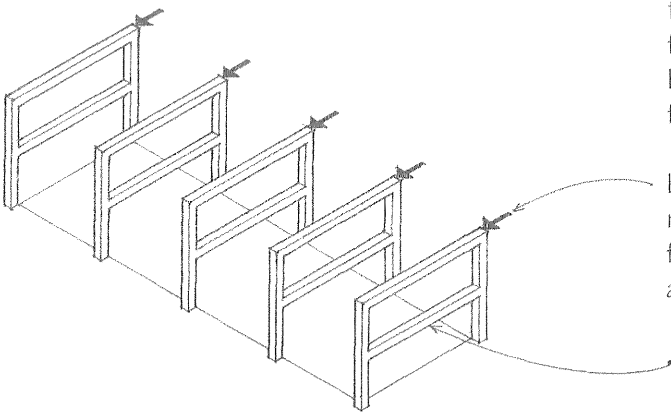


- Cross bracing
- When using cable bracing, two are necessary to stabilize the structure against lateral forces from either direction. For each direction, one cable will operate effectively in tension while the other would simply buckle. If rigid bracing is used, a certain degree of redundancy is involved because a single member is capable of stabilizing the structure.





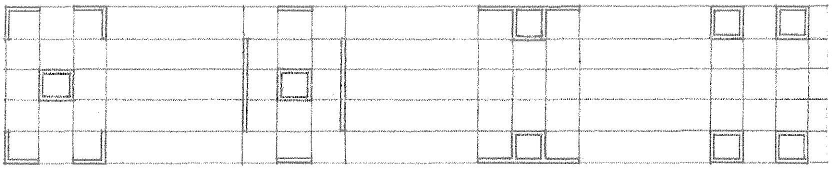
Any of these systems may be used singly or in combination to stabilize a structure. Of the three vertical systems, a rigid frame tends to be the least efficient. However, rigid frames can be useful when employing braced frames or shear walls would form undesired barriers between adjacent spaces.



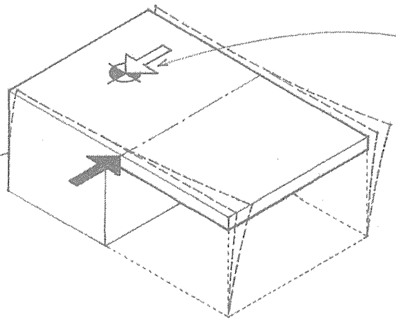
Lateral forces tend to be more critical in the short direction of rectangular buildings, and more efficient shear walls or braced frames are typically used in this direction. In the long direction, any of the lateral force-resisting elements may be used.

- Bents are braced or rigid frames designed to carry vertical and lateral loads transverse to the length of a framed structure.

To avoid destructive torsional effects, structures subject to lateral forces should be arranged and braced symmetrically with centers of mass and resistance as coincident as possible. The asymmetrical layout of irregular structures generally requires dynamic analysis in order to determine the torsional effects of lateral forces.

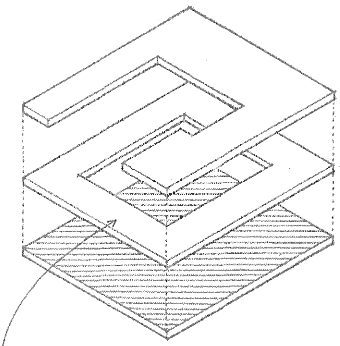


Irregular structures are characterized by any of various plan or vertical irregularities, such as the asymmetrical layout of mass or lateral-force resisting elements, a soft or weak story, or a discontinuous shear wall or diaphragm.

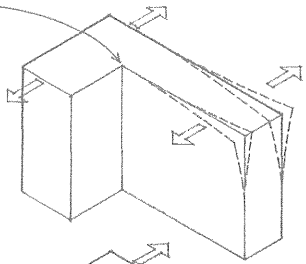


The center of resistance is the centroid of the vertical elements of a lateral force-resisting system, through which the shear reaction to lateral forces acts.

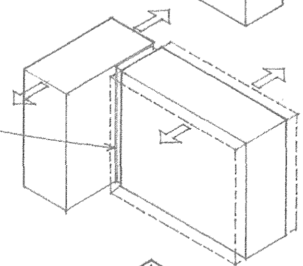
- Torsional irregularity refers to the asymmetrical layout of mass or lateral force-resisting elements, resulting in noncoincident centers of mass and resistance.

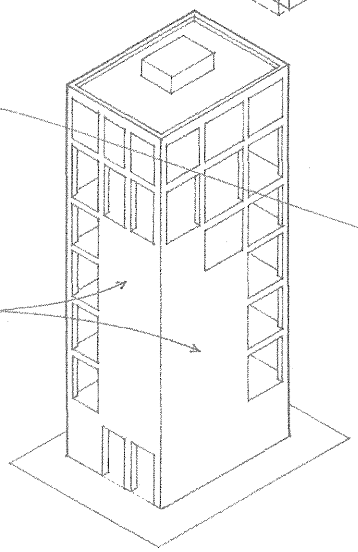


- A reentrant corner is a plan configuration of a structure having projections beyond a corner significantly greater than the plan dimension in the given direction. A reentrant corner tends to produce differential motions between different portions of the structure, resulting in local stress concentrations at the corner. Solutions include providing a seismic joint to separate the building into simpler shapes, tying the building together more strongly at the corner, or splaying the corner.

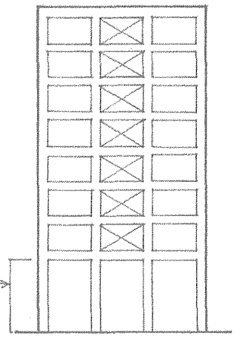


- Seismic joints physically separate adjacent building masses so that free vibratory movement in each can occur independently of the other.



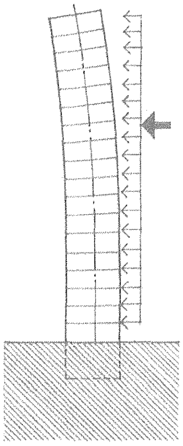


- A discontinuous diaphragm is a horizontal diaphragm having a large cutout or open area, or a stiffness significantly less than that of the story above or below.

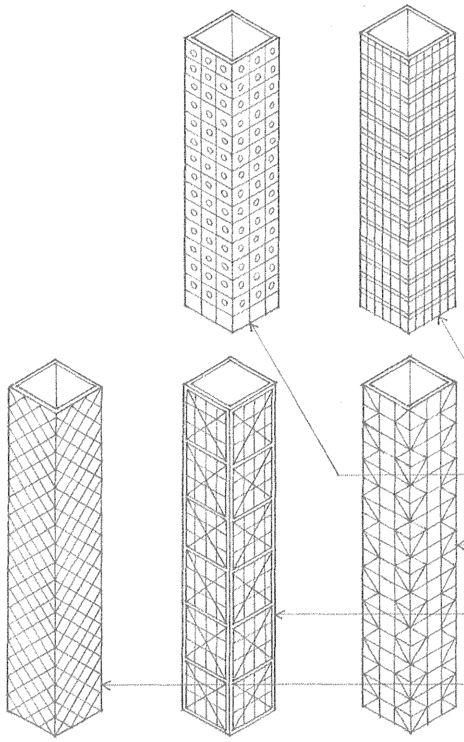


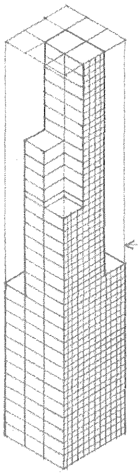
- A soft or weak story has lateral stiffness or strength significantly less than that of the stories above.
- A discontinuous shear wall has a large offset or a significant change in horizontal dimension.

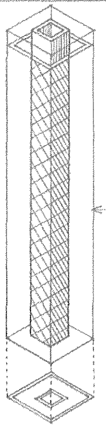
CSI MasterFormat 13 48 00 Sound, Vibration, and Seismic Control



Tall buildings are particularly susceptible to the effects of lateral forces. A rigid frame is the least efficient way to achieve lateral stability and is appropriate only for low- to medium-rise structures. As the height of a building increases, it becomes necessary to supplement a rigid frame with additional bracing mechanisms, such as diagonal bracing or a rigid core. An efficient type of high-rise structure is a tube structure that has perimeter lateral force-resisting systems internally braced by rigid floor diaphragms. The structure acts essentially as a cantilevered box beam in resisting lateral forces.

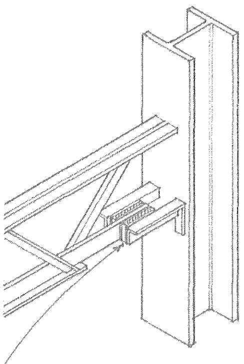


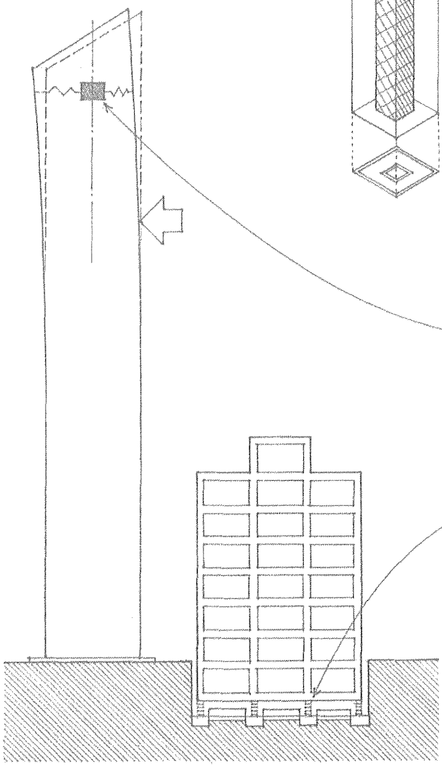




- A framed tube has closely spaced perimeter columns rigidly connected by deep spandrel beams.
- A perforated shell tube has perimeter shear walls with less than 30% of the surface area perforated by openings.
- A braced tube is a framed structure tied together by a system of diagonal braces.
- A trussed tube has trussed wall frames of widely spaced columns tied together by diagonal or cross bracing.
- A latticed truss tube has perimeter frames of closely spaced diagonals with no vertical columns.
- Bundled tubes is an assembly of narrow tubes tied directly to each other to form a modular structure that behaves like a multicellular box girder cantilevering out of the ground. More tubes are sometimes provided in the lower portion of a tall structure where greater lateral force resistance is needed.
- A tube-in-tube structure has an inner braced core added to the perimeter tube to improve its shear stiffness in resisting lateral forces.

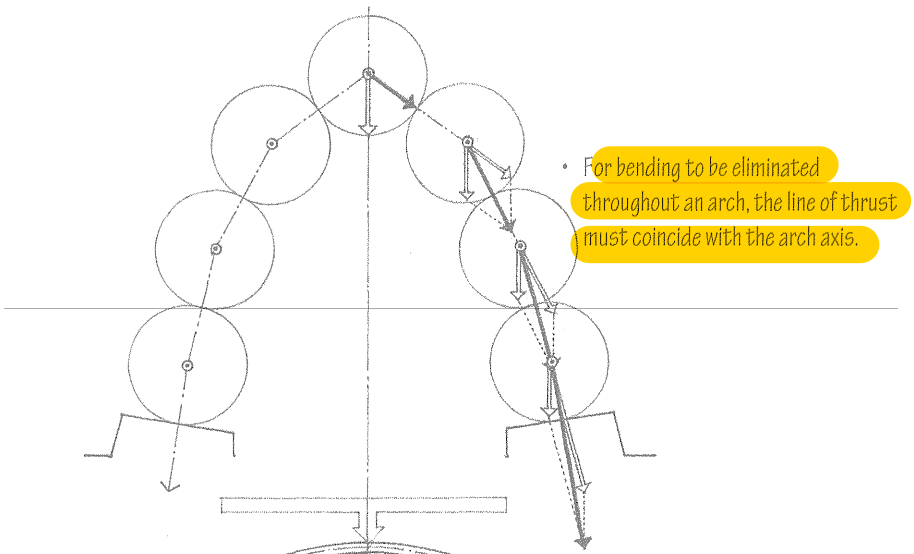
Damping mechanisms are viscoelastic devices that are typically installed at structural joints to absorb the energy generated by wind or earthquake forces, progressively diminish or eliminate vibratory or oscillatory motions, and prevent destructive resonances from occurring.





- A tuned mass damper is a heavy mass mounted on rollers and attached to the upper portion of a tall building with spring damping mechanisms, having an inertial tendency to remain at rest and thus counteracting and dissipating any building movements.
- Base isolation refers to isolating the base of a building from the ground with damping mechanisms to allow the superstructure to float as a rigid body and alter the natural period of vibration of the structure so that it is different from that of the ground, thus preventing destructive resonances from occurring.
- Internal damping is the damping that naturally occurs as a building undergoes elastic or plastic deformation, as from the internal friction of a stressed material (hysteresis damping), from the friction between two moving parts (frictional damping), or from the viscous resistance of a fluid such as air (viscous damping).

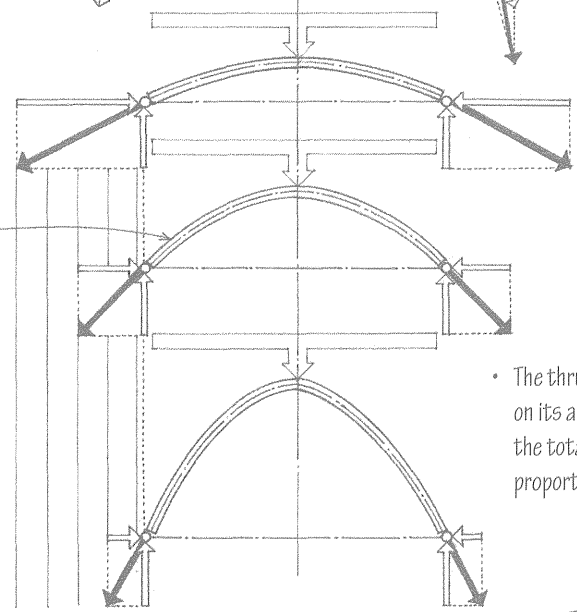
Columns, beams, slabs, and bearing walls are the most common structural elements because of the rectilinear building geometry they are capable of generating. There are, however, other means of spanning and enclosing space. These are generally form-active elements that, through their shape and geometry, make efficient use of their material for the distances spanned. While beyond the scope of this book, they are briefly described in the following section.



- For bending to be eliminated throughout an arch, the line of thrust must coincide with the arch axis.

Arches are curved structures for spanning an opening, designed to support a vertical load primarily by axial compression. They transform the vertical forces of a supported load into inclined components and transmit them to abutments on either side of the archway.

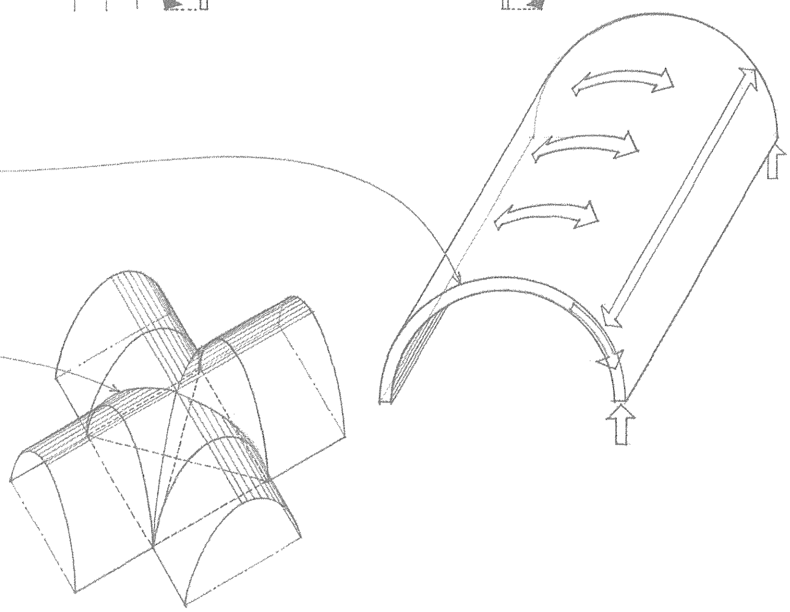
- Masonry arches are constructed of individual wedge-shaped stone or brick voussoirs; for more information on masonry arches, see 5.20.
- Rigid arches consist of curved, rigid structures of timber, steel, or reinforced concrete capable of carrying some bending stresses.



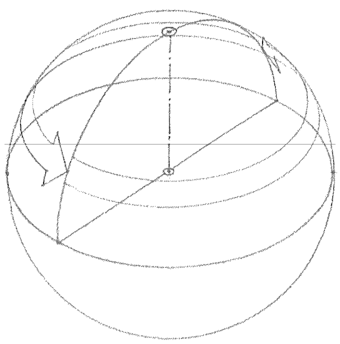
- The thrust of an arched structure on its abutments is proportional to the total load and span, and inversely proportional to the rise.

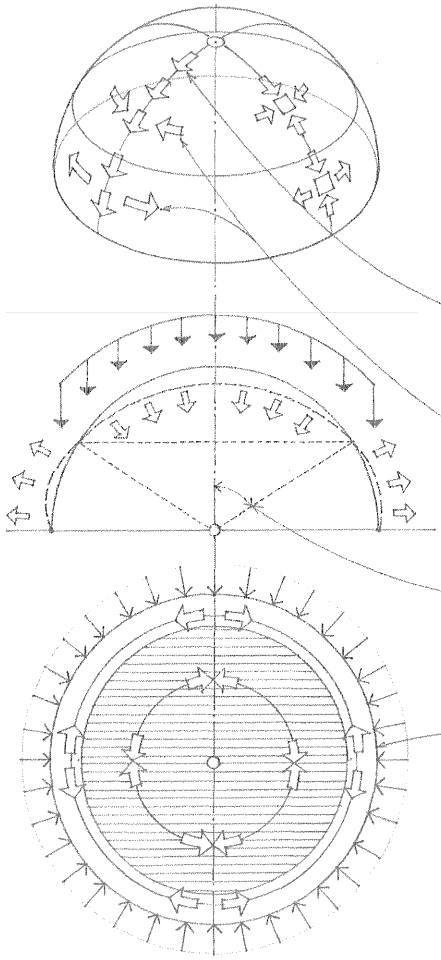
Vaults are arched structures of stone, brick, or reinforced concrete, forming a ceiling or roof over a hall, room, or other wholly or partially enclosed space. Because a vault behaves as an arch extended in a third dimension, the longitudinal supporting walls must be buttressed to counteract the outward thrusts of the arching action.

- Barrel vaults have semicircular cross sections.
- Groin or cross vaults are compound vaults formed by the perpendicular intersection of two vaults, forming arched diagonal arrises called groins.

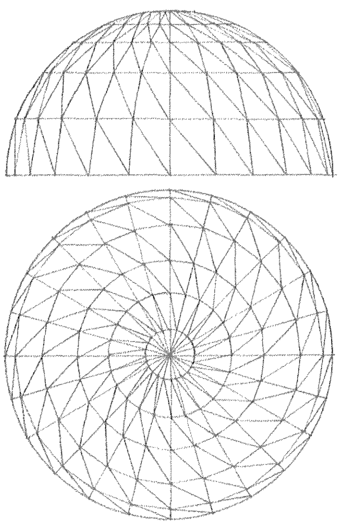


A dome is a spherical surface structure having a circular plan and constructed of stacked blocks, a continuous rigid material like reinforced concrete, or of short, linear elements, as in the case of a geodesic dome. A dome is similar to a rotated arch except that circumferential forces are developed that are compressive near the crown and tensile in the lower portion.

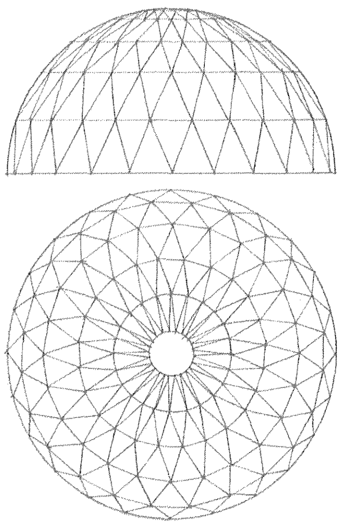




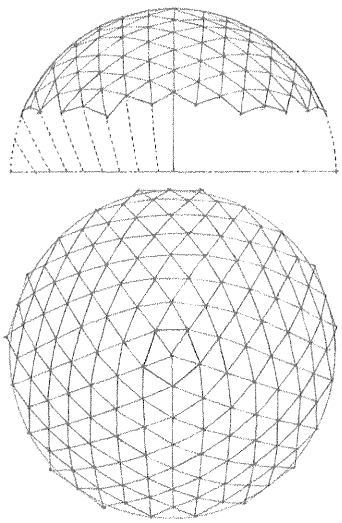
- Meridional forces acting along a vertical section cut through the surface of the dome are always compressive under full vertical loading.
- Hoop forces, restraining the out-of-plane movement of the meridional strips in the shell of a dome, are compressive in the upper zone and tensile in the lower zone.
- The transition from compressive hoop forces to tensile hoop forces occurs at an angle of from 45° to 60° from the vertical axis.
- A tension ring encircles the base of a dome to contain the outward components of the meridional forces. In a concrete dome, this ring is thickened and reinforced to handle the bending stresses caused by the differing elastic deformations of the ring and shell.



- Schwedler domes are steel dome structures having members that follow the lines of latitude and longitude, and a third set of diagonals completing the triangulation.



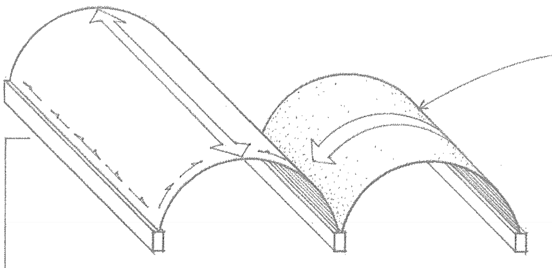
- Lattice domes are steel dome structures having members that follow the circles of latitude, and two sets of diagonals forming a series of isosceles triangles.



- Geodesic domes are steel dome structures having members that follow three principal sets of great circles intersecting at 60°, subdividing the dome surface into a series of equilateral spherical triangles.

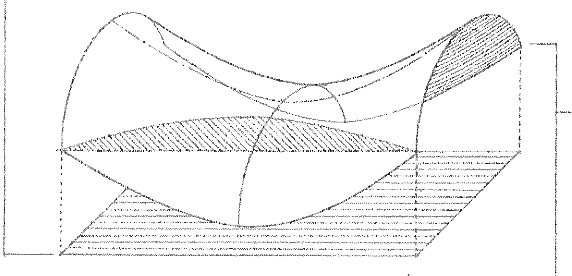
CSI MasterFormat 13 33 00 Geodesic Structures

Shells are thin, curved plate structures typically constructed of reinforced concrete. They are shaped to transmit applied forces by membrane stresses—the compressive, tensile, and shear stresses acting in the plane of their surfaces. A shell can sustain relatively large forces if uniformly applied. Because of its thinness, however, a shell has little bending resistance and is unsuitable for concentrated loads.

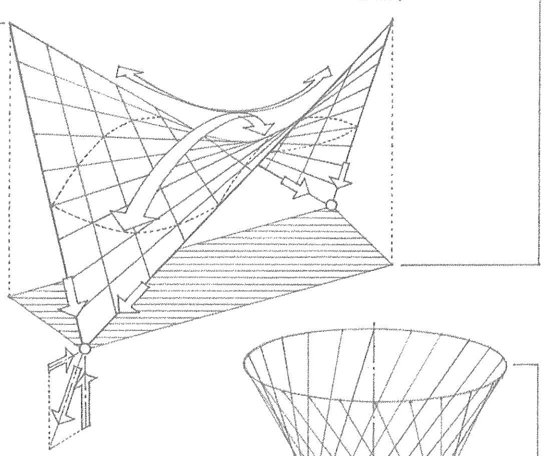


- Translational surfaces are generated by sliding a plane curve along a straight line or over another plane curve.

- Barrel shells are cylindrical shell structures. If the length of a barrel shell is three or more times its transverse span, it behaves as a deep beam with a curved section spanning in the longitudinal direction. If it is relatively short, it exhibits archlike action. Tie rods or transverse rigid frames are required to counteract the outward thrusts of the arching action.

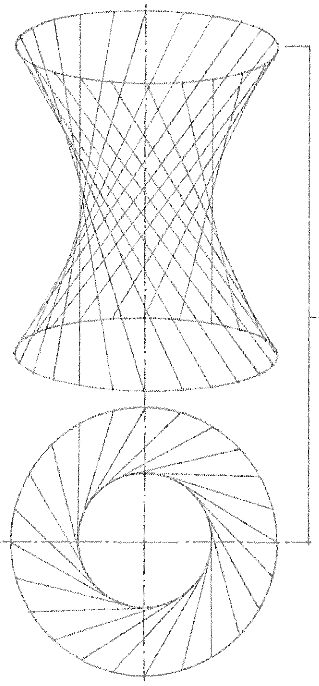


- A hyperbolic paraboloid is a surface generated by sliding a parabola with downward curvature along a parabola with upward curvature, or by sliding a straight line segment with its ends on two skew lines. It can be considered to be both a translational and a ruled surface.

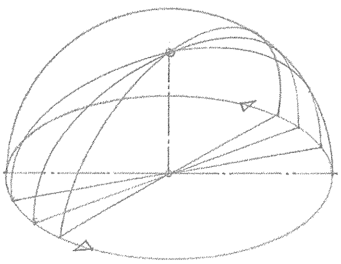


- Saddle surfaces have an upward curvature in one direction and a downward curvature in the perpendicular direction. In a saddle-surfaced shell structure, regions of downward curvature exhibit archlike action, while regions of upward curvature behave as a cable structure. If the edges of the surface are not supported, beam behavior may also be present.

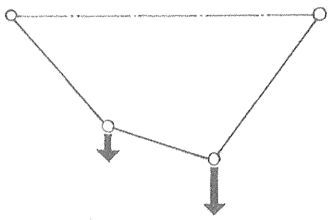
- Ruled surfaces are generated by the motion of a straight line. Because of its straight-line geometry, a ruled surface is generally easier to form and construct than a rotational or translational surface.

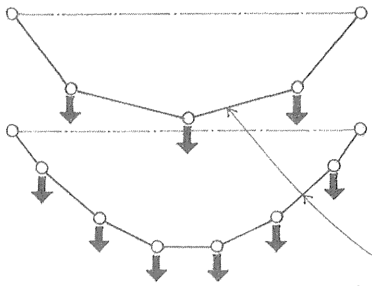


- A one-sheet hyperboloid is a ruled surface generated by sliding an inclined line segment on two horizontal circles. Its vertical sections are hyperbolas.

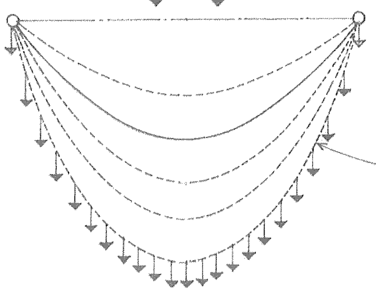


- Rotational surfaces are generated by rotating a plane curve about an axis. Spherical, elliptical, and parabolic dome surfaces are examples of rotational surfaces.





Cable structures utilize the cable as the principal means of support. Because cables have high tensile strength but offer no resistance to compression or bending, they must be used purely in tension. When subject to concentrated loads, the shape of a cable consists of straight-line segments. Under a uniformly distributed load, it will take on the shape of an inverted arch.

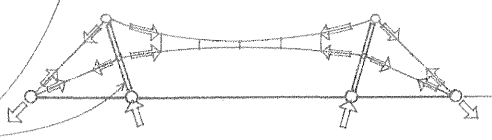


- A funicular shape is the shape assumed by a freely deforming cable in direct response to the magnitude and location of external forces. A cable always adapts its shape so that it is in pure tension under the action of an applied load.
- A catenary is the curve assumed by a perfectly flexible, uniform cable suspended freely from two points not in the same vertical line. For a load that is uniformly distributed in a horizontal projection, the curve approaches that of a parabola.

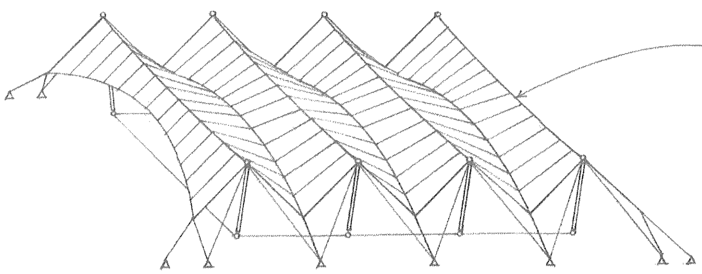
Suspension structures utilize a network of cables suspended and prestressed between compression members to directly support applied loads.

- Guy cables absorb the horizontal component of thrust in a suspension or cable-stayed structure and transfer the force to a ground foundation.
- The mast is a vertical or inclined compression member in a suspension or cable-stayed structure, supporting the sum of the vertical force components in the primary and guy cables. Inclining the mast enables it to pick up some of the horizontal cable thrust and reduces the force in the guy cables.

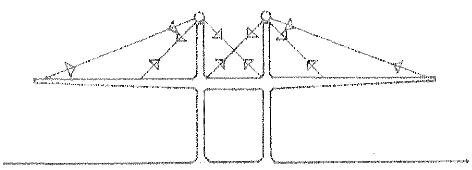
- Single-curvature structures utilize a parallel series of cables to support surface-forming beams or plates. They are susceptible to flutter induced by the aerodynamic effects of wind. This liability can be reduced by increasing the dead load on the structure or by anchoring the primary cables to the ground with transverse guy cables.



- Double-cable structures have upper and lower sets of cables of different curvatures, pretensioned by ties or compression struts to make the system more rigid and resistant to flutter.



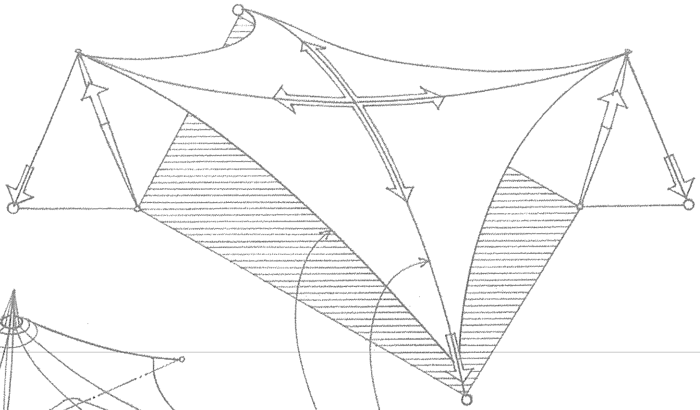
- Double-curvature structures consist of a field of crossed cables of different and often reverse curvatures. Each set of cables has a different natural period of vibration, thus forming a self-dampening system that is more resistant to flutter.

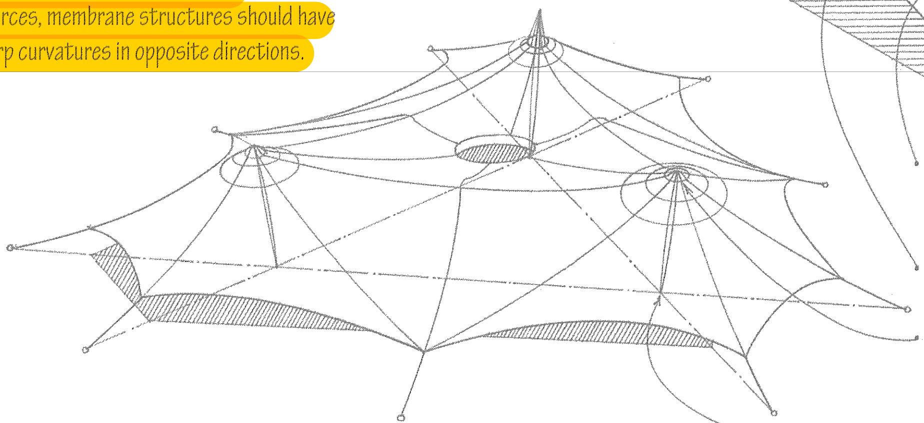


- Cable-stayed structures have vertical or inclined masts from which cables extend to support horizontally spanning members arranged in a parallel or radial pattern.

Membranes are thin, flexible surfaces that carry loads primarily through the development of tensile stresses. They may be suspended or stretched between posts, or be supported by air pressure.

Tent structures are membrane structures that are prestressed by externally applied forces and held completely taut under all anticipated load conditions. To avoid extremely high tensile forces, membrane structures should have relatively sharp curvatures in opposite directions.

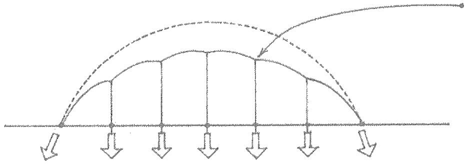




- Membrane and steel cables transmit external loads to masts and ground anchors by means of tensile forces.
- Reinforcing edge cables stiffen the free edges of a tent structure.
- The membrane may be tied to the mast supports by a reinforcing cable loop or be stretched over a distribution cap.
- The masts are designed to resist buckling under compressive loading.

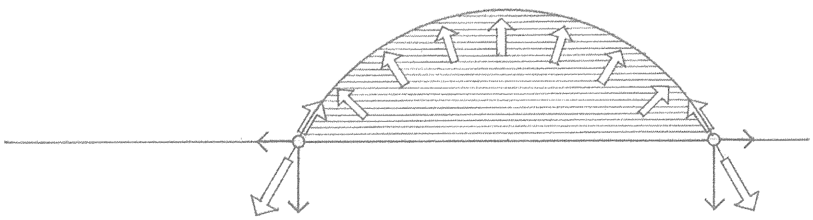
Pneumatic structures are membrane structures that are placed in tension and stabilized against wind and snow loads by the pressure of compressed air. The membrane is usually a woven textile or glass-fiber fabric coated with a synthetic material such as silicone. Translucent membranes provide natural illumination, gather solar radiation in the winter, and cool the interior space at night. Reflective membranes reduce solar heat gain. A fabric liner can capture air space to improve the thermal resistance of the structure.

There are two kinds of pneumatic structures: air-supported structures and air-inflated structures.

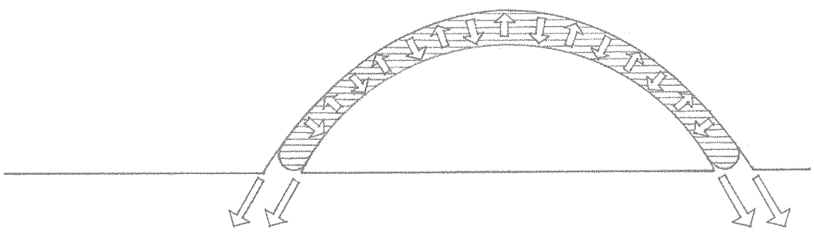


- Some air-supported structures use a net of cables placed in tension by the inflating force to restrain the membrane from developing its natural inflated profile.

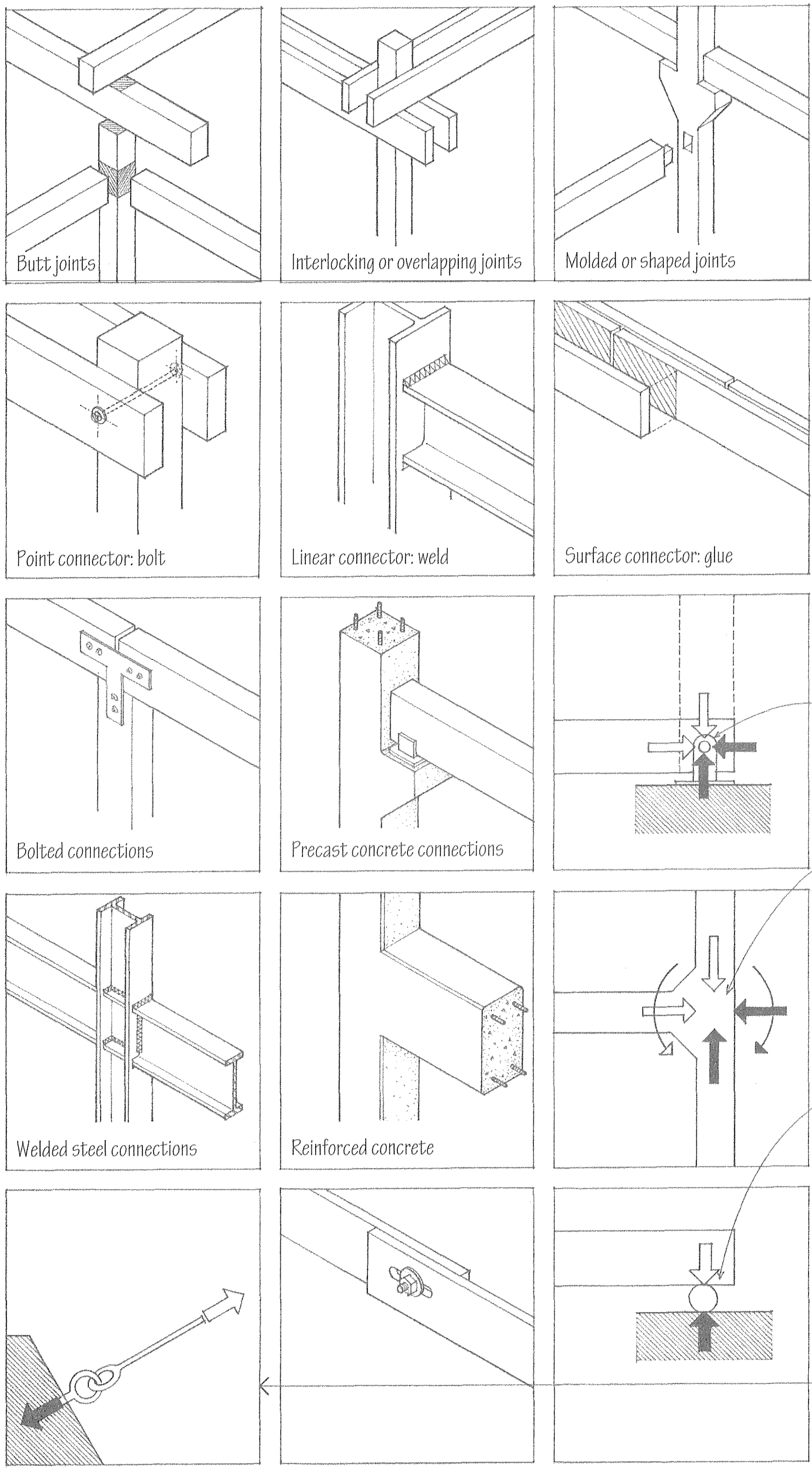
- Air-supported structures consist of a single membrane supported by an internal air pressure slightly higher than normal atmospheric pressure, and securely anchored and sealed along the perimeter to prevent leaking. Air locks are required at entrances to maintain the internal air pressure.



- Air-inflated structures are supported by pressurized air within inflated building elements. These elements are shaped to carry loads in a traditional manner, while the enclosed volume of building air remains at normal atmospheric pressure. The tendency for a double-membrane structure to bulge in the middle is restrained by a compression ring or by internal ties or diaphragms.



CSI MasterFormat 13 31 13 Air-Supported Fabric Structures



The manner in which forces are transferred from one structural element to the next and how a structural system performs as a whole depend to a great extent on the types of joints and connections used. Structural elements can be joined to each other in three ways. Butt joints allow one of the elements to be continuous and usually require a third mediating element to make the connection. Overlapping joints allow all of the connected elements to bypass each other and be continuous across the joint. The joining elements can also be molded or shaped to form a structural connection.

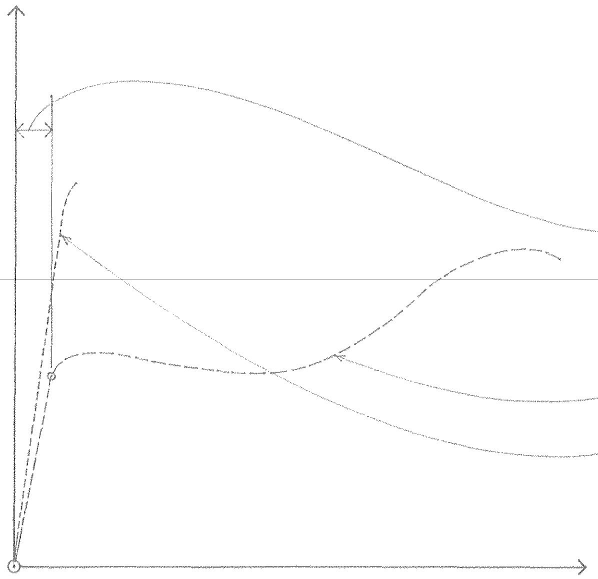
The connectors used to join the structural elements may be in the form of a point, a line, or a surface. While linear and surface types of connectors resist rotation, point connectors do not unless a series of them is distributed across a large surface area.

Pinned joints theoretically allow rotation but resist translation in any direction.

Rigid or fixed joints maintain the angular relationship between the joined elements, restrain rotation and translation in any direction, and provide both force and moment resistance.

Roller joints allow rotation but resist translation in a direction perpendicular into or away from their faces. They are not employed in building construction as often as pinned or fixed connections but they are useful when a joint must allow expansion and contraction of a structural element to occur.

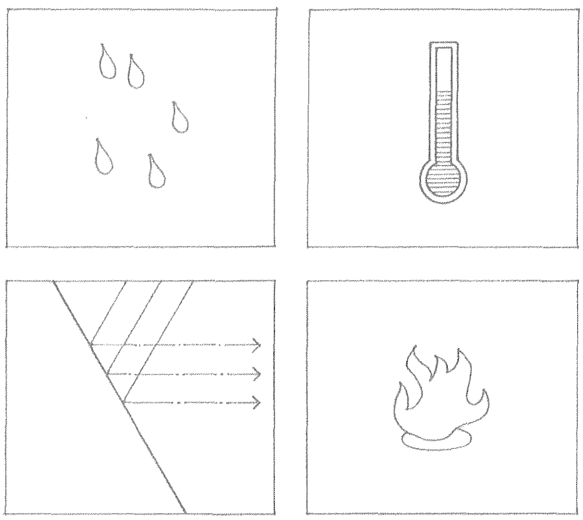
A cable anchorage allows rotation but resists translation only in the direction of the cable.



- Stress: the internal resistance or reaction of an elastic body to external forces applied to it, expressed in units of force per unit of cross-sectional area.
- Strain: the deformation of a body under the action of an applied force, equal to the ratio of the change in size or shape to the original size or shape of a stressed element

This chapter describes the major types of building materials, their physical properties, and their uses in building construction. The criteria for selecting and using a building material include those listed below.

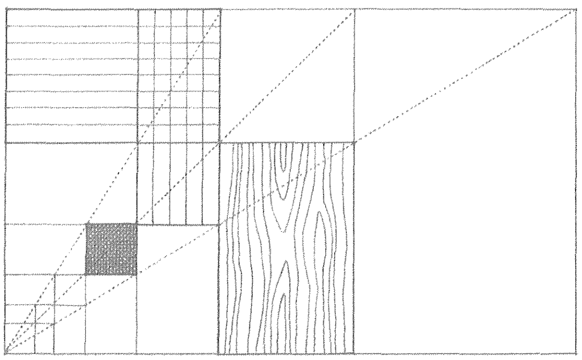
- Each material has distinct properties of strength, elasticity, and stiffness. The most effective structural materials are those that combine elasticity with stiffness.
- Elasticity is the ability of a material to deform under stress—bend, stretch or compress—and return to its original shape when the applied stress is removed. Every material has its elastic limit beyond which it will permanently deform or break.
- Materials that undergo plastic deformation before actually breaking are termed ductile.
- Brittle materials, on the other hand, have low elastic limits and rupture under loads with little visible deformation. Because brittle materials have less reserve strength than ductile materials, they are not as suitable for structural purposes.
- Stiffness is a measure of the force required to push or pull a material to its elastic limit. A material's stiffness, along with the stiffness of its cross-sectional shape, are important factors when considering the relationship between span and deflection under loading.



- The dimensional stability of a material as it responds to changes in temperature and moisture content affects the manner in which it is detailed and constructed to join with other materials.
- The resistance of a material to water and water vapor is an important consideration when it is exposed to weather or used in moist environments.
- The thermal conductivity or resistance of a material must be assessed when it is used in constructing the exterior envelope of a building.

- A material's transmission, reflection, or absorption of visible light and radiant heat should be evaluated when the material is used to finish the surfaces of a room.
- The density or hardness of a material determines its resistance to wear and abrasion, its durability in use, and the costs required to maintain it.

- The ability of a material to resist combustion, withstand exposure to fire, and not produce smoke and toxic gases, must be evaluated before using it as a structural member or an interior finish.



- The color, texture, and scale of a material are obvious considerations in evaluating how it fits within the overall design scheme.
- Many building materials are manufactured in standard shapes and sizes. These stock dimensions, however, may vary slightly from one manufacturer to the next. They should be verified in the planning and design phases of a building so that unnecessary cutting or wasting of material can be minimized during construction.

The evaluation of building materials should extend beyond their functional, economic, and aesthetic aspects and include assessing the environmental consequences associated with their selection and use. This examination, called a life-cycle assessment, encompasses the extraction and processing of raw materials, the manufacturing, packaging, and transportation of the finished product to the point of use, maintaining the material in use, the possible recycling and reuse of the material, and its final disposal. This assessment process consists of three components: inputs, life-cycle inventory, and outputs.

- Embodied energy includes all of the energy expended during the life cycle of a material.
- Refer to the *Environmental Resource Guide*, a project of the American Institute of Architects, for more information.

Embodied Energy in Building Materials

Material	Energy Content Btu/lb.*
Sand & gravel	18
Wood	185
Lightweight concrete	940
Gypsum board	1830
Brickwork	2200
Cement	4100
Glass	11,100
Plastic	18,500
Steel	19,200
Lead	25,900
Copper	29,600
Aluminum	103,500

*1 Btu/lb = 2. 326 kJ/kg

Inputs

- Raw materials
- Energy
- Water

Acquisition of Raw Materials

- What impact does the extraction, mining, or harvesting process have on health and the environment?
- Is the material renewable or nonrenewable?
- Nonrenewable resources include metals and other minerals.
- Renewable resources, such as timber, vary in their rate of renewal; their rate of harvest should not exceed their rate of growth.

Processing, Manufacturing, and Packaging

- How much energy and water is required to process, manufacture, and package the material or product?

Transportation and Distribution

- Is the material or product available regionally or locally, or does it have to be shipped a long distance?

Construction, Use, and Maintenance

- Does the material perform its intended function efficiently and effectively?
- How does the material affect the indoor air quality and energy consumption of a building?
- How durable is the material or product and how much maintenance is required for its upkeep?
- What is the material's useful life?

Disposal, Recycling, and Reuse

- Usable products

+

- How much waste and how many toxic by-products result from the manufacture and use of the material or product?

Life-Cycle Inventory

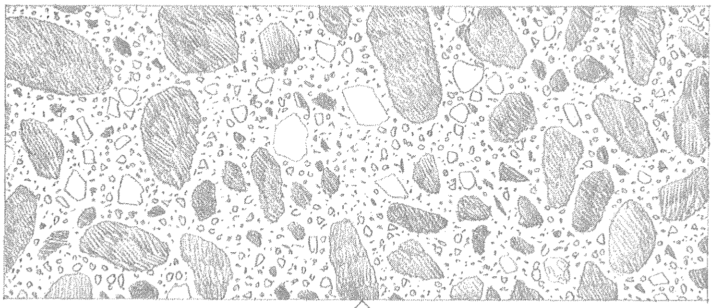
- Waterborne effluents
- Atmospheric emissions
- Solid wastes
- Other environmental releases

Outputs

Evaluating the choice of a building material is a complex matter that cannot be reduced to a simple formula yielding a precise and valid answer with certainty. For example, using less of a material with a high energy content may be more effective in conserving energy and resources than using more of a lower-energy material. Using a higher-energy material that will last longer and require less maintenance, or one that can be recycled and reused, may be more compelling than using a lower-energy material.

Reduce, reuse, and recycle best summarize the kinds of strategies that are effective in achieving the goal of sustainability.

- Reduce building size through more efficient layout and use of spaces.
- Reduce construction waste. LEED MR Credit 2: Construction Waste Management
- Specify products that use raw materials more efficiently. LEED MR Credit 5: Regional Materials
- Substitute plentiful resources for scarce resources. LEED MR Credit 6: Renewable Materials
- Reuse building materials from demolished buildings. LEED MR Credit 3: Materials Reuse
- Rehabilitate existing buildings for new uses. LEED MR Credit 1: Building Reuse
- Recycle new products from old. LEED MR Credit 3: Materials Reuse



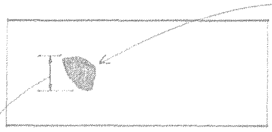
Concrete is made by mixing cement and various mineral aggregates with sufficient water to cause the cement to set and bind the entire mass. While concrete is inherently strong in compression, steel reinforcement is required to handle tensile and shear stresses. It is capable of being formed into almost any shape with a variety of surface finishes and textures. In addition, concrete structures are relatively low in cost and inherently fire-resistant. Concrete's liabilities include its weight—150 pcf (2400 kg/m^3) for normal reinforced concrete—and the forming or molding process that is required before it can placed to set and cure.

Cement

- Portland cement is a hydraulic cement made by burning a mixture of clay and limestone in a rotary kiln and pulverizing the resulting clinker into a very fine powder.
- Type I normal portland cement is used for general construction, having none of the distinguishing qualities of the other types.
- Type II moderate portland cement is used in general construction where resistance to moderate sulfate action is required or where heat buildup can be damaging, as in the construction of large piers and heavy retaining walls.
- Type III high-early-strength portland cement cures faster and gains strength earlier than normal portland cement; it is used when the early removal of formwork is desired, or in cold-weather construction to reduce the time required for protection from low temperatures.
- Type IV low-heat portland cement generates less heat of hydration than normal portland cement; it is used in the construction of massive concrete structures, as in gravity dams, where a large buildup in heat can be damaging.
- Type V sulfate-resisting portland cement is used where resistance to severe sulfate action is required.
- Air-entraining portland cement is a Type I, Type II, or Type III portland cement to which a small quantity of an air-entraining agent has been interground during manufacture; it is designated by the suffix A.

Water

- The water used in a concrete mix must be free of organic material, clay, and salts; a general criterion is that the water should be fit for drinking.
- Cement paste is a mixture of cement and water for coating, setting, and binding the aggregate particles together in a concrete mix.



- 1/3 the depth of a slab, 1/5 the thickness of a wall, or 3/4 of the clear space between reinforcing bars or between the bars and the formwork

Lightweight Concrete

- Structural lightweight concrete, made with expanded shale or slate aggregate, has a unit weight from 85 to 115 pcf (1362 to 1840 kg/m^3) and compressive strength comparable to that of normal concrete.
- Insulating concrete, made with perlite aggregate or a foaming agent, has a unit weight of less than 60 pcf (960 kg/ m^3) and low thermal conductivity.

Aggregate

- Aggregate refers to any of various inert mineral materials, as sand and gravel, added to a cement paste to make concrete. Because aggregate represents from 60% to 80% of the concrete volume, its properties are important to the strength, weight, and fire-resistance of the hardened concrete. Aggregate should be hard, dimensionally stable, and free of clay, silt, and organic matter that can prevent the cement matrix from binding the particles together.
- Fine aggregate consists of sand having a particle size smaller than 1/4" (6).
- Coarse aggregate consists of crushed stone, gravel, or blast-furnace slag having a particle size larger than 1/4" (6).
- The maximum size of coarse aggregate in reinforced concrete is limited by the size of the section and the spacing of the reinforcing bars.

Admixtures

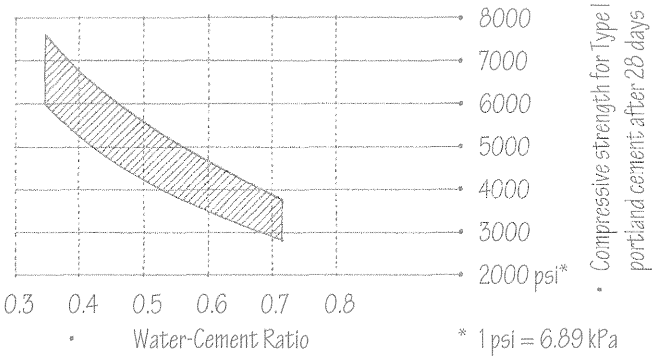
Admixtures may be added to a concrete mix to alter its properties or those of the hardened product.

- Air-entraining agents disperse microscopic, spherical air bubbles in a concrete mix to increase workability, improve resistance of the cured product to the cracking induced by free-thaw cycles or the scaling caused by deicing chemicals, and in larger amounts, to produce lightweight, insulating concrete.
- Accelerators hasten the setting and strength development of a concrete mix, while retarders slow the setting of a concrete mix in order to allow more time for placing and working the mix.
- Surface-active agents, or surfactants, reduce the surface tension of the mixing water in a concrete mix, thereby facilitating the wetting and penetrating action of the water or aiding in the emulsifying and dispersion of other additives in the mix.
- Water-reducing agents, or superplasticizers, reduce the amount of mixing water required for the desired workability of a concrete or mortar mix. Lowering the water-cement ratio in this manner generally results in increased strength.
- Coloring agents are pigments or dyes added to a concrete mix to alter or control its color.

CSI MasterFormat Division 03 – Concrete

Water-Cement Ratio

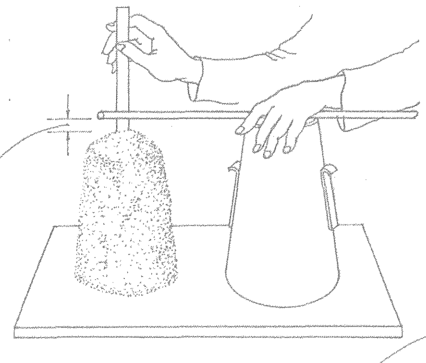
Water-cement ratio is the ratio of mixing water to cement in a unit volume of a concrete mix, expressed by weight as a decimal fraction or as gallons of water per sack of cement. The water-cement ratio controls the strength, durability, and watertightness of hardened concrete. According to Abrams' law, formulated by D. A. Abrams in 1919 from experiments at the Lewis Institute in Chicago, the compressive strength of concrete is inversely proportional to the ratio of water to cement. If too much water is used, the concrete mix will be weak and porous after curing. If too little water is used, the mix will be dense but difficult to place and work. For most applications, the water-cement ratio should range from 0.45 to 0.60.

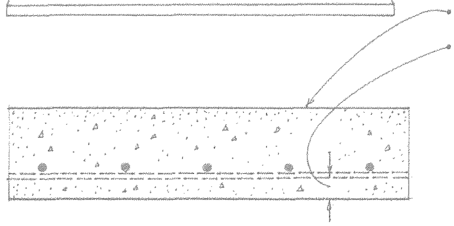


* 1 psi = 6.89 kPa

Concrete is normally specified according to the compressive strength it will develop within 28 days after placement (7 days for high-early-strength concrete).

- Slump test is a method for determining the consistency and workability of freshly mixed concrete by measuring the slump of a test specimen, expressed as the vertical settling, in inches, of a specimen after it has been placed in a slump cone, tamped in a prescribed manner, and the cone is lifted.
- Compression test for determining the compressive strength of a concrete batch uses a hydraulic press to measure the maximum load a test cylinder 6" (150) ø and 12" (305) high can support in axial compression before fracturing.





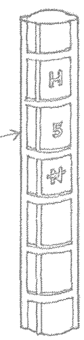
Reinforced concrete slab
$^3/_4$" (19) minimum for #5 bars and smaller;
1-$^1/_2$" (38) minimum when exposed to weather;
2" (51) minimum for #6 bars and larger

- Reinforcing steel must be protected by the surrounding concrete against corrosion and fire. Minimum requirements for cover and spacing are specified by the American Concrete Institute (ACI) *Building Code Requirements for Reinforced Concrete* according to the concrete's exposure, and the size of the coarse aggregate and steel used.
- For minimum coverage of steel reinforcement in other concrete members, see 3.08 for spread footings, 4.04 for concrete beams, 5.04 for concrete columns, and 5.06 for concrete walls.

Steel Reinforcement

Because concrete is relatively weak in tension, reinforcement consisting of steel bars, strands, or wires is required to absorb tensile, shearing, and sometimes the compressive stresses in a concrete member or structure. Steel reinforcement is also required to tie vertical and horizontal elements, reinforce the edges around openings, minimize shrinkage cracking, and control thermal expansion and contraction. All reinforcement should be designed by a qualified structural engineer.

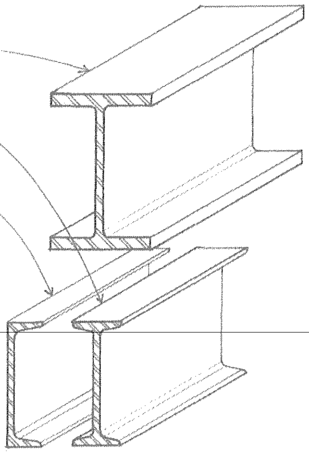
- Reinforcing bars are steel sections hot-rolled with ribs or other deformations for better mechanical bonding to concrete. The bar number refers to its diameter in eighths of an inch—for example, a #5 bar is $^5/_8$" (16) in diameter.
- Welded wire fabric consists of a grid of steel wires or bars welded together at all points of intersection. The fabric is typically used to provide temperature reinforcement for slabs but the heavier gauges can also be used to reinforce concrete walls. The fabric is designated by the size of the grid in inches followed by a number indicating the wire gauge or cross-sectional area; see 3.18 for typical sizes.

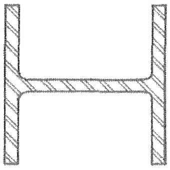


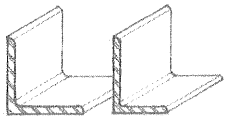
ASTM Standard Reinforcing Bars

Bar Size	Nominal Dimensions		
	Diameter inches (mm)	Cross-Sectional Area sq. in. (mm²)	Weight plf (N/m)
#3	0.375 (10)	0.11 (71)	0.38 (5.5)
#4	0.50 (13)	0.20 (129)	0.67 (9.7)
#5	0.625 (16)	0.31 (200)	1.04 (15.2)
#6	0.75 (19)	0.44 (284)	1.50 (21.9)
#7	0.875 (22)	0.60 (387)	2.04 (29.8)
#8	1.00 (25)	0.79 (510)	2.67 (39.0)
#9	1.125 (29)	1.00 (645)	3.40 (49.6)
#10	1.25 (32)	1.27 (819)	4.30 (62.8)

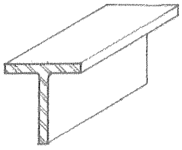
- W shape (wide flange)
- S shape (American standard)
- C shape (American standard channel)



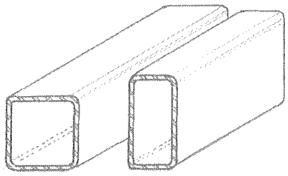




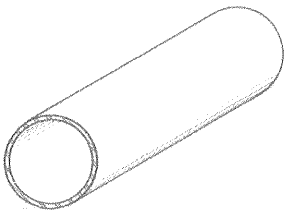
- L shapes (equal and unequal leg angles)



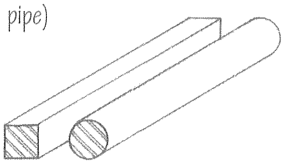
- WT shape (structural tee cut from W shape)



- Structural tubing (square or rectangular)



- Structural tubing (circular pipe)



- Bars (square, round, and flat)

Steel Shapes

- Refer to the American Institute of Steel Construction (AISC) *Manual of Steel Construction* for complete listing of sizes and weights.

Steel refers to any of various iron-based alloys having a carbon content less than that of cast iron and more than that of wrought iron, and having qualities of strength, hardness, and elasticity varying according to composition and heat treatment. Steel is used for light and heavy structural framing, as well as a wide range of building products such as windows, doors, hardware, and fastenings. As a structural material, steel combines high strength and stiffness with elasticity. Measured in terms of weight to volume, it is probably the strongest low-cost material available. Although classified as an incombustible material, steel becomes ductile and loses its strength when subject to temperatures over 1000°F (520°C). When used in buildings requiring fire-resistive construction, structural steel must be coated, covered, or enclosed with fire-resistant materials; see A.12. Because it is normally subject to corrosion, steel must be painted, galvanized, or chemically treated for protection against oxidation.

- Mild or soft steel is a low-carbon steel containing from 0.15% to 0.25% carbon.
- Medium steel is a carbon steel containing from 0.25% to 0.45% carbon; most structural steel is medium-carbon steel; ASTM A36 is the most common strength grade with a yield point of 36,000 psi (248,220 kPa).
- Hard steel is a high-carbon steel containing from 0.45% to 0.85% carbon.
- Spring steel is a high-carbon steel containing 0.85% to 1.8% carbon.

- Carbon steel is unalloyed steel in which the residual elements, such as carbon, manganese, phosphorus, sulfur and silicon, are controlled. Any increase in carbon content increases the strength and hardness of the steel but reduces its ductility and weldability.

- Stainless steel contains a minimum of 12% chromium, sometimes with nickel, manganese, or molybdenum as additional alloying elements, so as to be highly resistant to corrosion.
- High-strength low-alloy steel is a low-carbon steel containing less than 2% alloys in a chemical composition specifically developed for increased strength, ductility, and resistance to corrosion; ASTM A572 is the most common strength grade with a yield point of 50,000 psi (344750 kPa).
- Weathering steel is a high-strength, low-alloy steel that forms an oxide coating when exposed to rain or moisture in the atmosphere; this coating adheres firmly to the base metal and protects it from further corrosion. Structures using weathering steel should be detailed to prevent the small amounts of oxide carried off by rainwater from staining adjoining materials.
- Tungsten steel is an alloy steel containing 10% to 20% tungsten for increased hardness and heat retention at high temperatures.

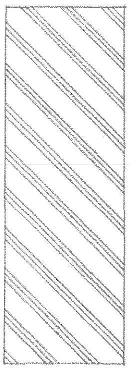
- Alloy steel refers to a carbon steel to which various elements, such as chromium, cobalt, copper, manganese, molybdenum, nickel, tungsten, or vanadium, have been added in a sufficient amount to obtain particular physical or chemical properties.

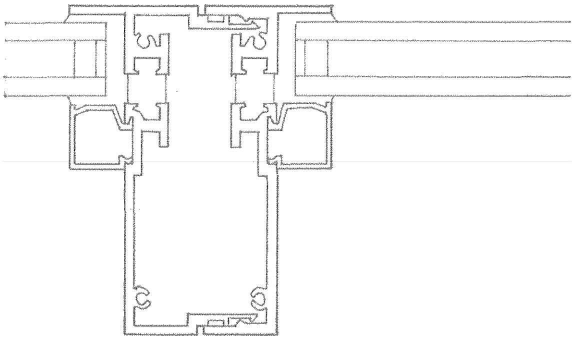
Other ferrous metals used in building construction include:

- Cast iron, a hard, brittle, nonmalleable iron-based alloy containing 2.0% to 4.5% carbon and 0.5% to 3% silicon, cast in a sand mold and machined to make many building products, such as piping, grating, and ornamental work
- Malleable cast iron, which has been annealed by transforming the carbon content into graphite or removing it completely
- Wrought iron, a tough, malleable, relatively soft iron that is readily forged and welded, having a fibrous structure containing approximately 0.2% carbon and a small amount of uniformly distributed slag
- Galvanized iron, which is coated with zinc to prevent rust

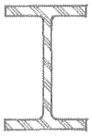
Nonferrous metals contain no iron. Aluminum, copper, and lead are nonferrous metals commonly used in building construction.

Aluminum is a ductile, malleable, silver-white metallic element that is used in forming many hard, light alloys. Its natural resistance to corrosion is due to the transparent film of oxide that forms on its surface; this oxide coating can be thickened to increase corrosion resistance by an electrical and chemical process known as anodizing. During the anodizing process, the naturally light, reflective surface of aluminum can be dyed a number of warm, bright colors. Care must be taken to insulate aluminum from contact with other metals to prevent galvanic action. It should also be isolated from alkaline materials such as wet concrete, mortar, and plaster.

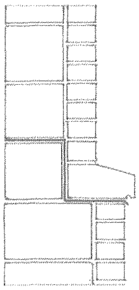




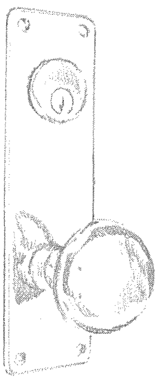
Aluminum is widely used in extruded and sheet forms for secondary building elements such as windows, doors, roofing, flashing, trim, and hardware. For use in structural framing, high-strength aluminum alloys are available in shapes similar to those of structural steel. Aluminum sections may be welded, bonded with adhesives, or mechanically fastened.



Copper is a ductile, malleable metallic element that is widely used for electrical wiring, water piping, and in the manufacture of alloys, as bronze and brass. Its color and resistance to corrosion also make it an excellent roofing and flashing material. However, copper will corrode aluminum, steel, stainless steel, and zinc. It should be fastened, attached, or supported only with copper or carefully selected brass fittings. Contact with red cedar in the presence of moisture will cause premature deterioration of the copper.



Brass refers to any of various alloys consisting essentially of copper and zinc, used for windows, railings, trim, and finish hardware. Alloys that are brass by definition may have names that include the word bronze, as architectural bronze.



Lead is a heavy, soft, malleable, bluish-gray metallic element used for flashing, sound isolation, and radiation shielding. Although lead is the heaviest of the common metals, its pliability makes it desirable for application over uneven surfaces. Lead dust and vapors are toxic.

Galvanic Action

Galvanic action can occur between two dissimilar metals when enough moisture is present for electric current to flow. This electric current will tend to corrode one metal while plating the other. The severity of the galvanic action depends on how far apart the two metals are on the galvanic series table.

• Gold, platinum	Most noble	
• Titanium	Cathode	(+)
• Silver		
• Stainless steel		
• Bronze		
• Copper		
• Brass		
• Nickel		
• Tin		
• Lead		
• Cast iron		
• Mild steel		
• Aluminum, 2024 T4		
• Cadmium		
• Aluminum, 1100		
• Zinc	Anode	(−)
• Magnesium	Least noble	

• Current flows from positive to negative.

Galvanic Series

- The galvanic series lists metals in order from most noble to least noble.
- Noble metals, such as gold and silver, resist oxidation when heated in air and solution by inorganic acids.
- The metal that is lower in the list is sacrificial and corrodes when enough moisture is present for electric current to flow.
- The farther apart two metals are on the list, the more susceptible the least noble one is to corrosive deterioration.