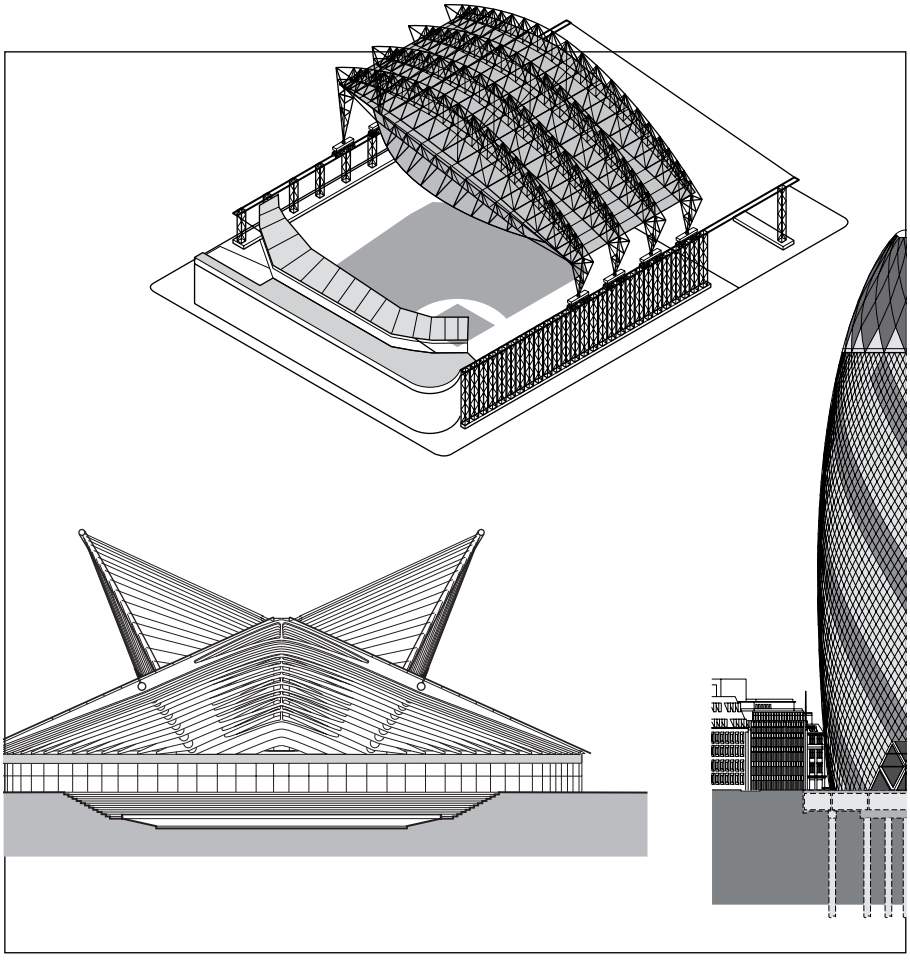
Building Structures
ILLUSTRATED

Second Edition



Francis D. K. Ching
Barry Onouye
Douglas Zuberbuhler

WILEY

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Preface

Many reputable books are available that cover the subject of building structures, from ones focusing on statics and strength of materials to others dealing with the design and analysis of structural elements, such as beams and columns, and still others covering specific structural materials. An understanding of the behavior of structural elements under different load conditions is critical to professionals, as is the ability to select, size, and shape appropriate structural materials and their connections. This book assumes the accessibility of these valuable resources and focuses instead on building structures as systems of interrelated parts for creating and supporting the habitable environments we call architecture.

A principal characteristic of this text is its holistic approach to building structures. Beginning with a concise review of how structural systems have evolved over time, the text discusses the idea of structural patterns and how these patterns of supports and spans can not only sustain but reinforce an architectural idea. The core of this book is an examination of the horizontal spanning and vertical support systems that house our activities and contribute to the vertical dimensions of form and space. The discussion then turns to a review of the critical aspects of lateral forces and stability, the unique properties of long-span structures, and current strategies for high-rise structures. The final chapter is a brief but important review of the integration of structural and other building systems.

While this text deliberately avoids a strictly mathematical approach to building structures, it does not neglect the fundamental principles that govern the behavior of structural elements, assemblies, and systems. To better serve as a guide during the preliminary design process, the discussion is accompanied by numerous drawings and diagrams that instruct and perhaps even inspire ideas about how a structural pattern might inform a design concept. The challenge in design is always how to translate principles into action. The major change in this second edition, therefore, is the addition of examples that illustrate the ways in which structural principles can be manifested in examples of real-world architecture.

The authors hope that this richly illustrated work will serve as a desktop resource for design students as well as young professionals and help them view structural systems as essential and integral to the design and building process.

Metric Equivalents

The International System of Units is an internationally accepted system of coherent physical units, using the meter, kilogram, second, ampere, kelvin, and candela as the base units of length, mass, time, electric current, temperature, and luminous intensity. To reinforce an understanding of the International System of Units, metric equivalents are provided throughout this book according to the following conventions:

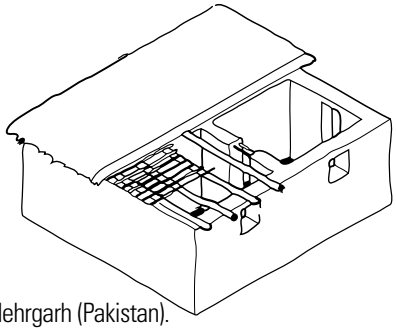
- All whole numbers in parentheses indicate millimeters unless otherwise noted.
- Dimensions 3 inches and greater are rounded to the nearest multiple of 5 millimeters.
- Note that 3487 mm = 3.487 m.
- In all other cases, the metric unit of measurement is specified.

BUILDING STRUCTURES

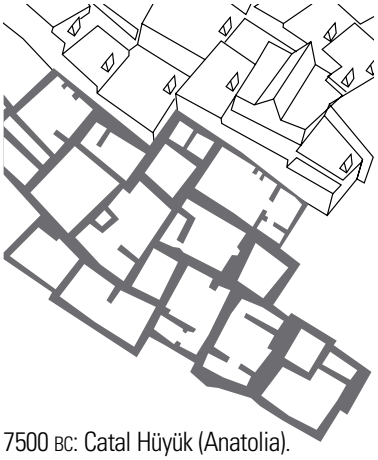
Buildings—the relatively permanent constructions we erect on a plot of land for habitable use—have developed over the course of history from simple shelters constructed of sticks, mud-brick, and stones to the more sophisticated constructions of concrete, steel, and glass of today. Throughout this evolution of building technology, what has remained constant is the enduring presence of some form of structural system capable of withstanding the forces of gravity, wind, and oftentimes, earthquakes.

We can define a structural system as a stable assembly of elements designed and constructed to function as a whole in supporting and transmitting applied loads safely to the ground without exceeding the allowable stresses in the members. While the forms and materials of structural systems have evolved with advances in technology and culture, not to mention the lessons learned from numerous building failures, they remain essential to the existence of all buildings, no matter their scale, context, or use.

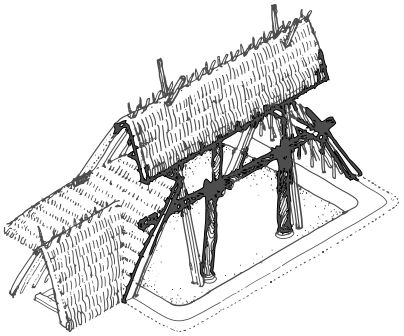
The brief historical survey that follows illustrates the development of structural systems over time, from the earliest attempts to satisfy the fundamental human need for shelter against sun, wind, and rain, to the longer spans, greater heights, and increasing complexity of modern architecture.



6500 BC: Mehrgarh (Pakistan). Compartmentalized mud-brick structures.



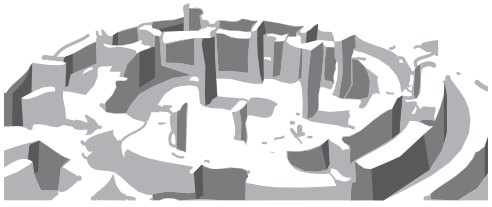
7500 BC: Catal Hüyük (Anatolia). Mud-brick houses with plastered interior walls.



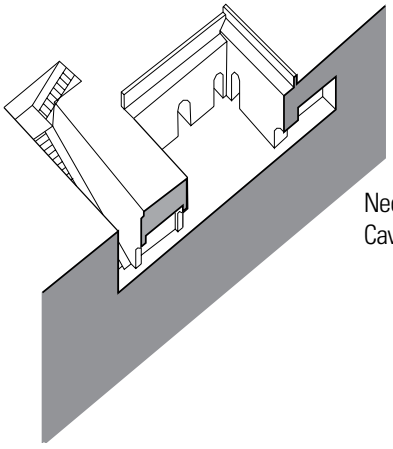
5000 BC: Banpo, China. Pit-style houses using thick pillars to support their roofs.

5000 BC Bronze Age

The Neolithic period dawned with the advent of farming c. 8500 BC and transitioned to the early Bronze Age with the development of metal tools c. 3500 BC. The practice of using caves for shelter and dwelling had already existed for millennia and continued to develop as an architectural form, ranging from simple extensions of natural caves to carved out temples and churches to entire towns carved into the sides of the mountains.

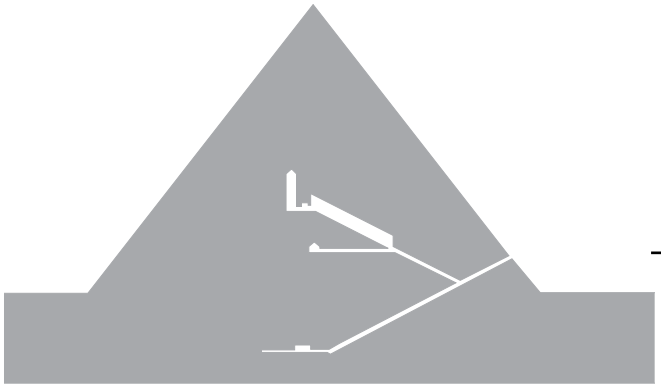


9000 BC: Göbekli Tepe (Turkey). The world's oldest known stone temples.

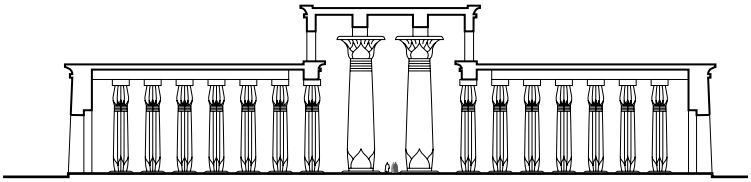


Neolithic Age: China, Northern Shaanxi province. Cave dwelling continues to the present day.

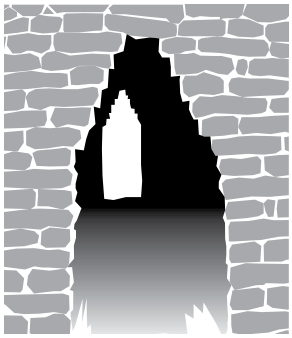
3400 BC: Sumerians introduce kilns.



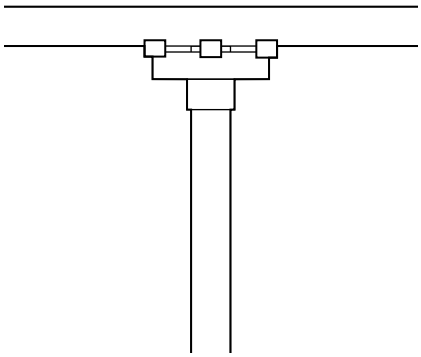
2500 BC: Great Pyramid of Khufu, Egypt. Until the 19th century, this stone pyramid was the tallest structure in the world.



1500 BC: Temple of Amun at Karnak, Egypt. Hypostyle Hall is a stellar example of trabeated (column-and-beam) stone construction.



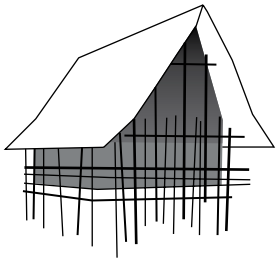
2600 BC: Harappa and Mohenjo-daro, Indus Valley, modern-day Pakistan and India. Fire-baked bricks and corbeled arches.



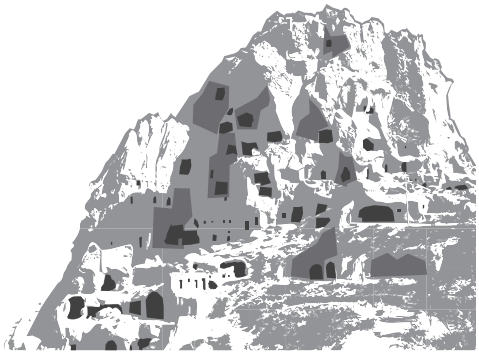
12th century BC: Zhou Dynasty architecture. Corbel brackets (dougong) on column heads help support projecting eaves.

2500 BC **1000 BC** Iron Age

While cave dwelling endures in various forms in different parts of the world, most architecture is created by assembling materials to define the limits of space as well as to provide shelter, house activities, commemorate events, and signify meaning. Early houses consisted of rough timber frames with mud-brick walls and thatched roofing. Sometimes pits were dug in the earth to provide additional warmth and protection; at other times, dwellings were elevated on stilts for ventilation in warm, humid climates or to rise above the shores of rivers and lakes. The use of heavy timber for the structural framing of walls and roof spans continued to develop over time and was refined, especially in the architecture of China, Korea, and Japan.



3000 BC: Alvastra (Scandinavia). Houses raised on wood stilts.

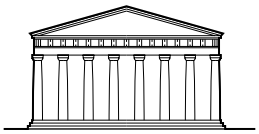


1000 BC: Cappadocia, Anatolia. Extensive excavations formed houses, churches, and monasteries.

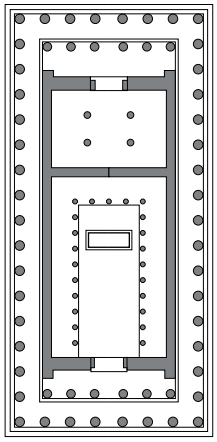
3000 BC: Egyptians mix straw with mud to bind dried bricks.

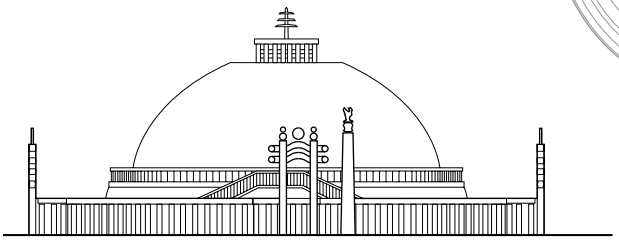
1500 BC: Egyptians work molten glass.

1350 BC: Shang Dynasty (China) develops advanced bronze casting.

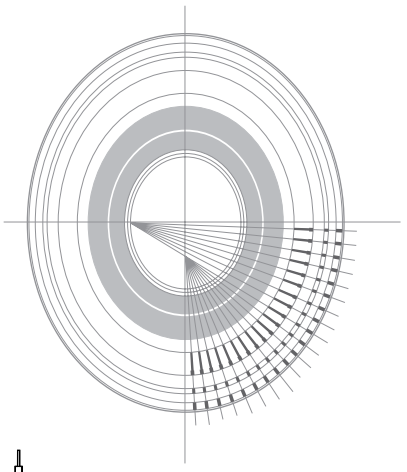


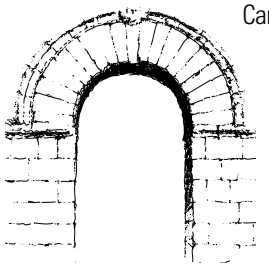
447 BC: Parthenon, Athens. This Temple of Athena is considered to be a paragon of the Doric order.



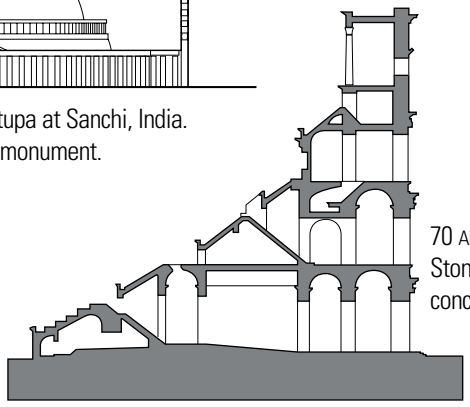


3rd century BC: Great Stupa at Sanchi, India. Carved stone Buddhist monument.



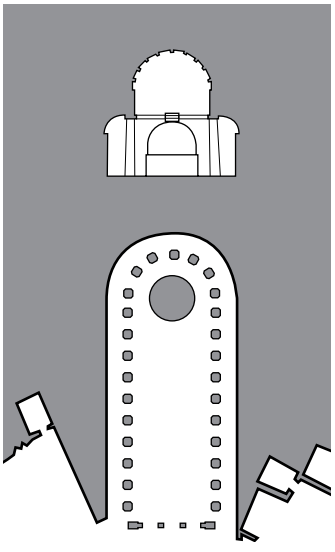


4th century BC: Etruscans develop the masonry arch and vault. Porta Pulchra, Perugia.



70 AD: Colosseum, Rome. Stone-faced brick and concrete amphitheater.

500 BC **1 AD**



200 BC: India. Numerous examples of Buddhist, Jain, and Hindu cave architecture.

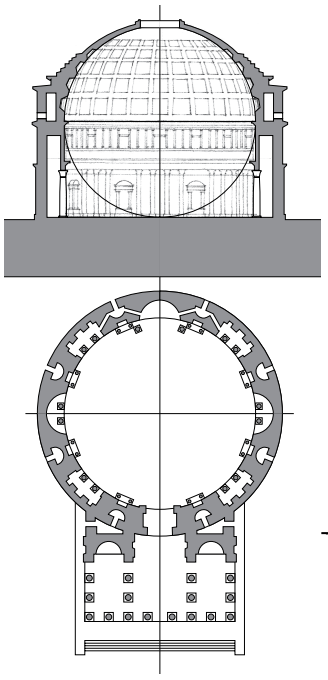


10 BC: Petra, Jordan. Palace tombs half-built, half-carved into the rock.

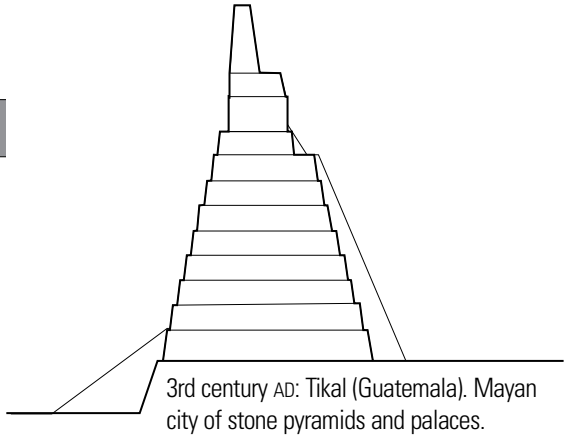
5th century BC: Chinese cast iron.

4th century BC: Babylonians and Assyrians use bitumen to bind bricks and stones.

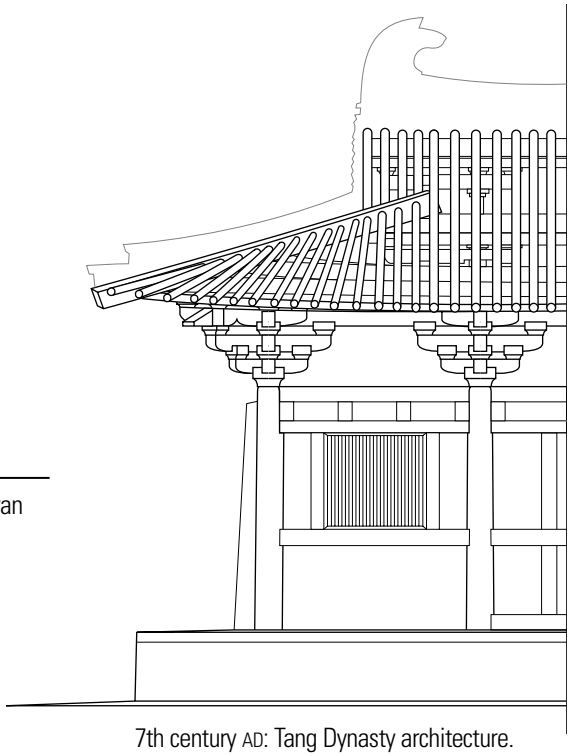
3rd century BC: Romans make concrete with pozzolanic cement.



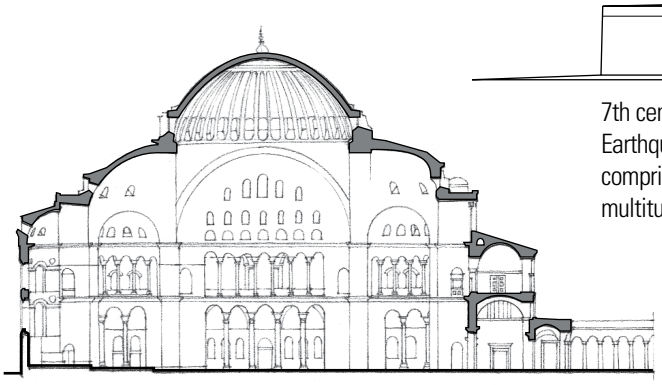
125 AD: The Pantheon, Rome.
Coffered concrete dome largest in the world until 18th century.



3rd century AD: Tikal (Guatemala). Mayan city of stone pyramids and palaces.



7th century AD: Tang Dynasty architecture. Earthquake-resistant timber framework comprised columns, beams, purlins, and a multitude of corbel brackets.



532–37 AD: Hagia Sophia, Istanbul. Central dome carried on pendentives that enable the transition from round dome to square plan. Concrete is used in the construction of the vaulting and arches of the lower levels.

800 AD

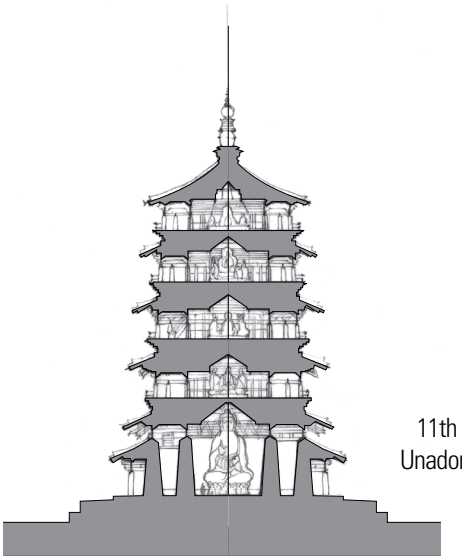


460 AD: Yungang Grottoes, China.
Buddhist temples carved into sandstone cliffs.

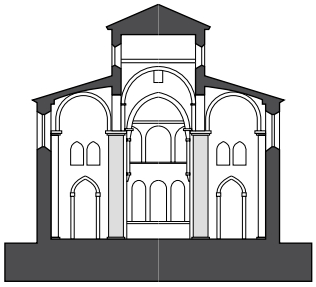


752 AD: Todaiji, Nara. Buddhist temple is world's largest wooden building; present reconstruction is two-thirds of the original temple's size.

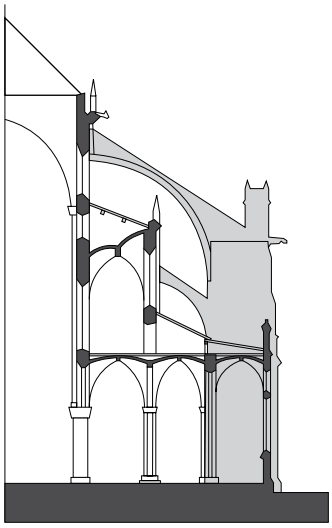
2nd century AD: Paper is invented in China.



1056: Sakyamuni Pagoda, China. Oldest surviving timber pagoda and tallest timber building in the world at a height of 220 feet (67.1 m).



11th century: Abbey church of St-Philibert, Tournus. Unadorned cylindrical pillars more than 4 feet (1.2 m) thick support the spacious and light nave.



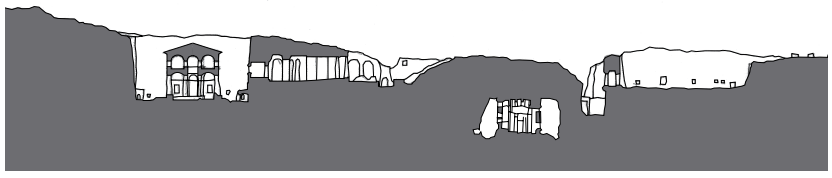
1163–1250: Notre Dame Cathedral, Paris. Cut stone structure utilizes external flying buttresses to transmit the outward and downward thrust from a roof or vault to a solid buttress.



1100: Chan Chan. Citadel walls of stucco-covered mud-brick.

900 AD

Where stone was available, it was first used to establish defensive barriers and serve as bearing walls to support timber spans for floors and roofs. Masonry vaulting and domes led to higher elevations and greater spans, while the development of pointed arches, clustered columns, and flying buttresses enabled the creation of lighter, more open, skeletal stone structures.



1100: Lalibela, Ethiopia. Site of monolithic, rock-cut churches.

1170: Cast iron is produced in Europe.

15th century: Filippo Brunelleschi develops theory of linear perspective.

Formal Intent

There are three fundamental ways in which the structural system can relate to the form of an architectural design. These fundamental strategies are:

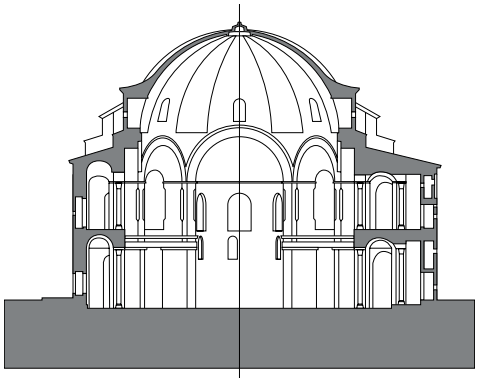
- Exposing the structural system
- Concealing the structure
- Celebrating the structure

Exposing the Structure

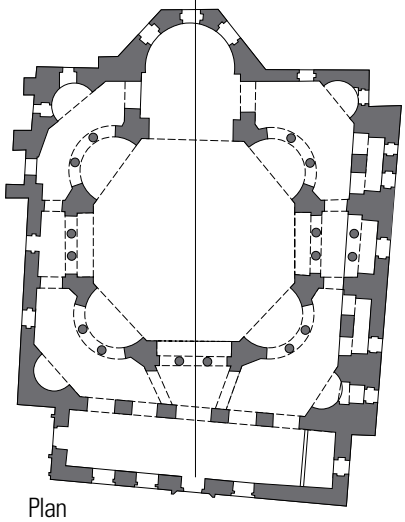
Historically, stone- and masonry-bearing wall systems dominated architecture until the advent of iron and steel construction in the late-18th century. These structural systems also functioned as the primary system of enclosure and therefore expressed the form of the architecture, typically in an honest and straightforward manner.

Whatever formal modifications were made were usually a result of molding or carving the structural material in such a way as to create additive elements, subtractive voids, or reliefs within the mass of the structure.

Even in the modern era, there are examples of buildings that exposed their structural systems—whether in timber, steel, or concrete—using them effectively as the primary architectonic form-givers.

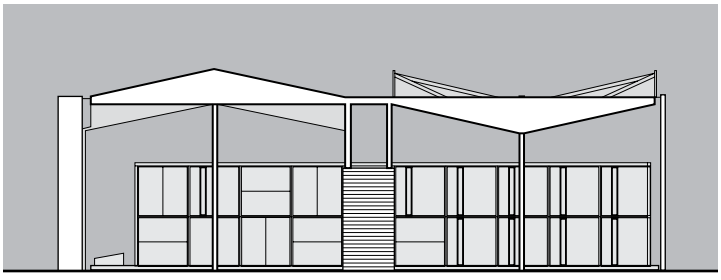


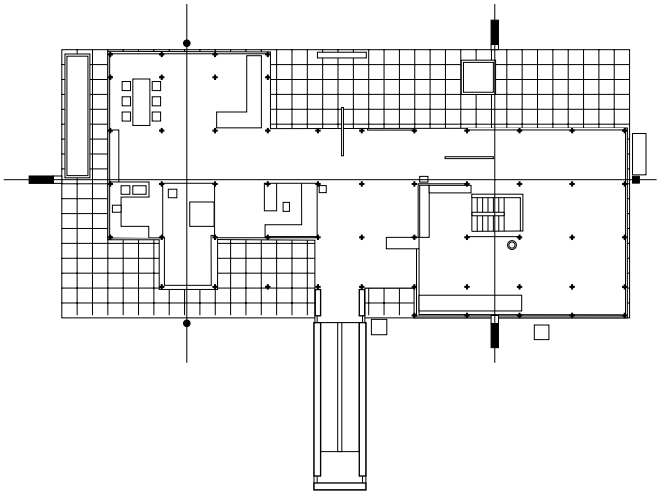
Section



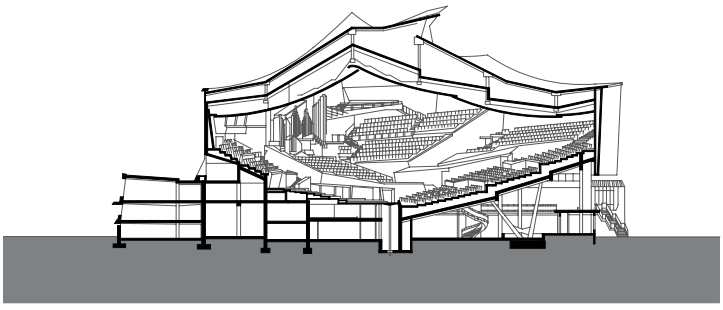
Plan

SS. Sergius and Bacchus, Istanbul, Turkey, 527–536 AD. The Ottomans converted this Eastern Orthodox church into a mosque. Featuring a central dome plan, it is believed by some to be a model for Hagia Sophia.

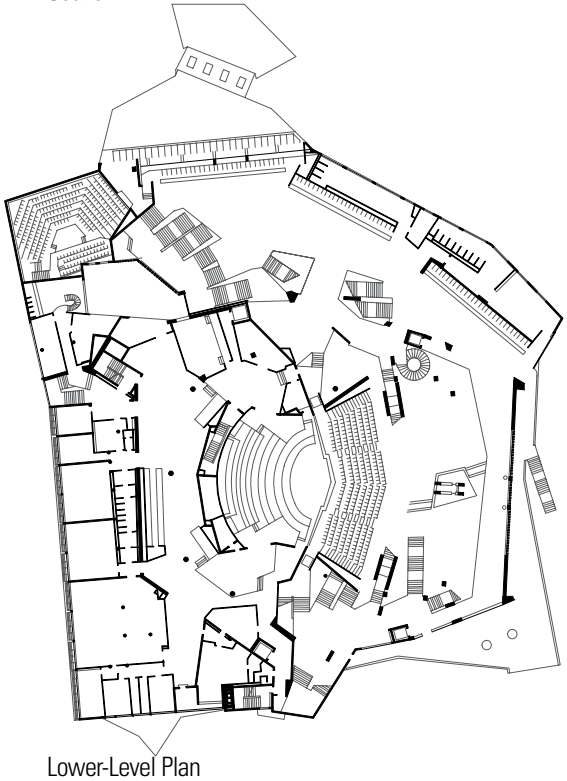




Centre Le Corbusier/Heidi Weber Pavilion, Zurich, 1965, Le Corbusier. A structural steel parasol hovers over a modular steel frame structure with sides of enameled steel panels and glass.



Section



Lower-Level Plan

Concealing the Structure

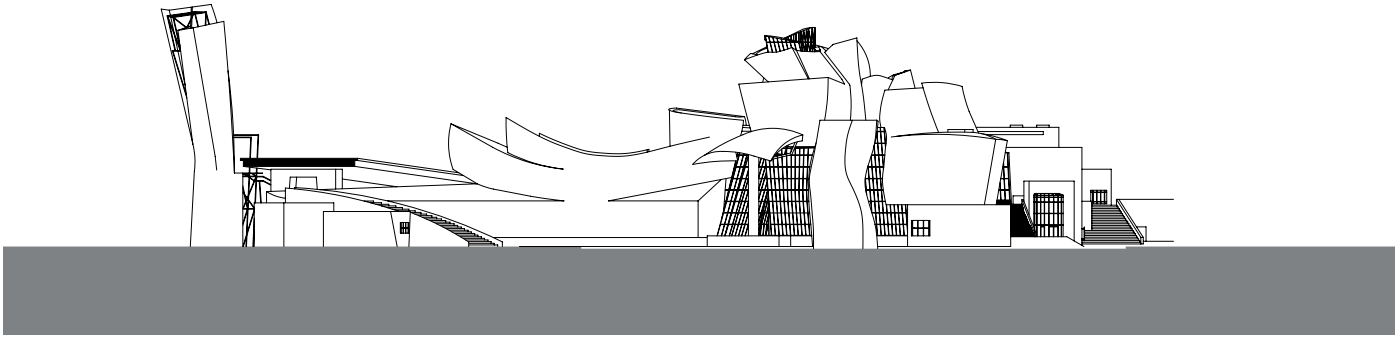
In this strategy, the structural system is concealed or obscured by the exterior cladding and roofing of the building. Some reasons for concealing the structure are practical, as when the structural elements must be clad to make them fire-resistant, or contextual, as when the desired exterior form is at odds with interior space requirements. In the latter case, the structure may organize the interior spaces while the form of the exterior shell responds to site conditions or constraints.

The designer may simply want freedom of expression for the shell without considering how the structural system might aid or hinder formal decisions. Or the structural system may be obscured through neglect rather than intent. In both of these cases, legitimate questions arise as to whether the resulting design is intentional or accidental, willful or, dare we say, careless.

◀ Philharmonic Hall, Berlin, Germany, 1960–63, Hans Scharoun. An example of the Expressionist movement, this concert hall has an asymmetric structure with a tent-like concrete roof and a stage in the middle of terraced seating. Its external appearance is subordinate to the functional and acoustic requirements of the concert hall.

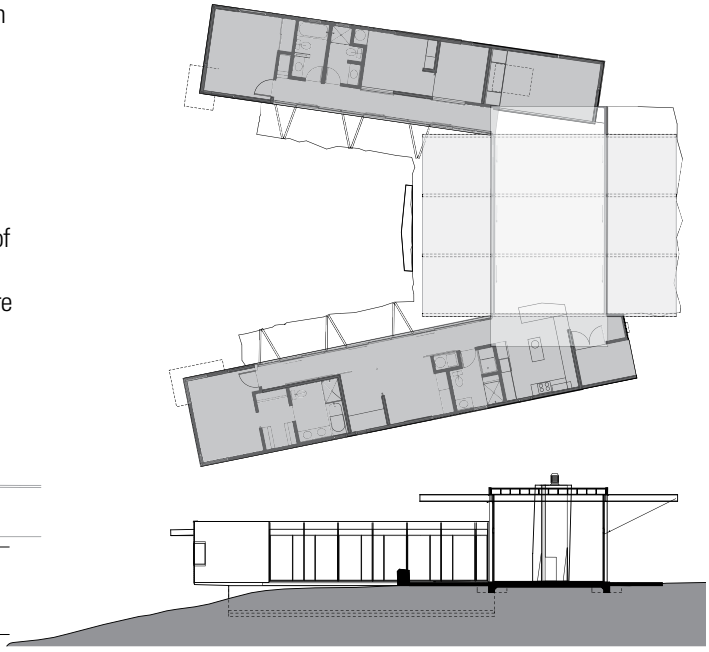
Guggenheim Museum, Bilbao, Spain, 1991–97, Frank Gehry. A novelty when completed, this contemporary art museum is known for its sculpted, titanium-clad forms. While difficult to understand in traditional architectural terms, the definition and constructibility of the apparently random forms were made possible through the use of CATIA, an integrated suite of Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM) applications.

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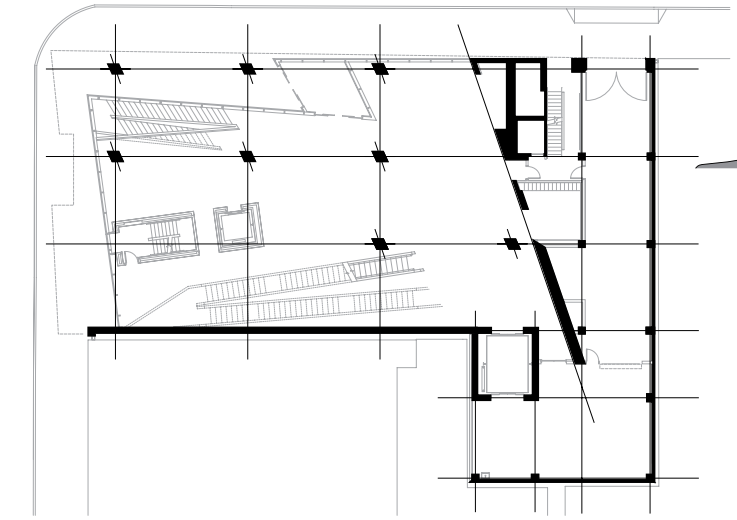


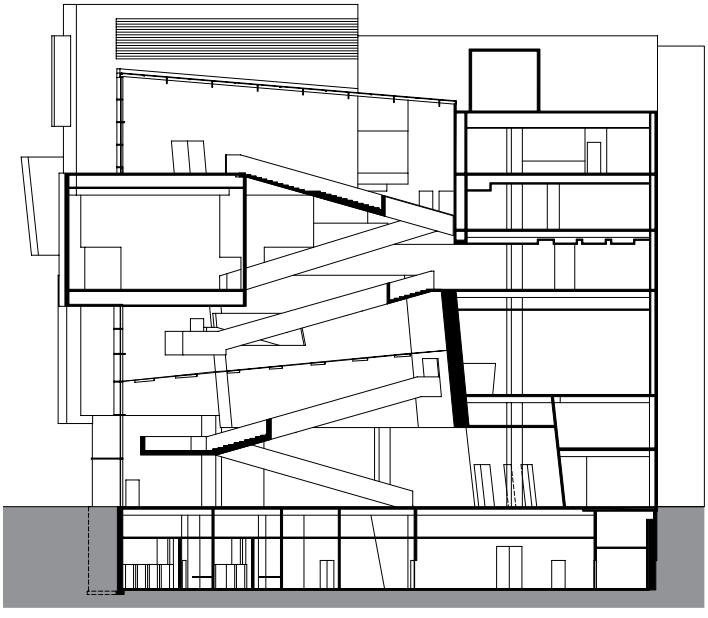
The examples on this and the previous page illustrate several ways in which contrasting orientations can be accommodated within a single composition.

The Palmach Museum of History consists of three parts, two of which are skewed to preserve an existing cluster of trees and rocks and define an irregularly shaped courtyard. The structure of the Lois & Richard Rosenthal Center for Contemporary Art is based on a regular rectilinear grid but the columns have the shape of parallelograms to reflect the skewed geometry of the full-height, skylit atrium space housing the vertical system of stairways. The Valley Center House uses the main living room as a transitional structure that rises above to visually link the contrasting orientations of two wings.



Plan and section: Valley Center House, San Diego County, California, 1999, Daly Genik Architects





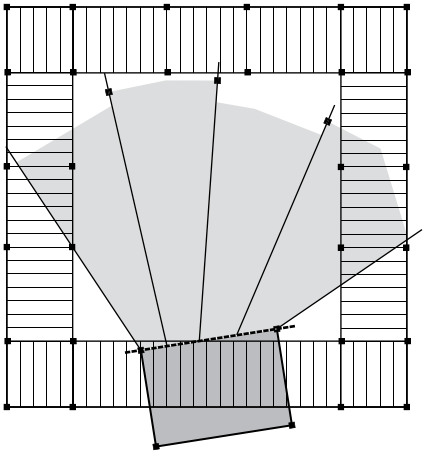
Plan and section: Lois & Richard Rosenthal Center for Contemporary Art, Cincinnati, Ohio, 2001–2003, Zaha Hadid Architects

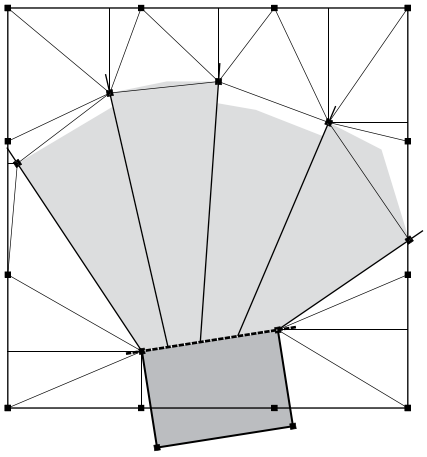
Accommodating Irregular Spaces

Design ideas are often generated not from the pattern of structural supports and spanning elements but rather from the desired ordering of program spaces and the formal qualities of the resulting composition. In a typical building program, there are usually requirements for various kinds of spaces. There may be requirements for spaces that are singular and unique in their function or significance to the building organization; others may be flexible in use and can be freely manipulated.



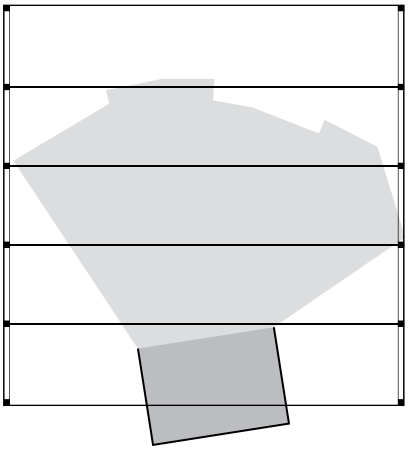
Discrete irregular spaces may be framed by the structure to conform with and reinforce the program requirements of the spatial volume.



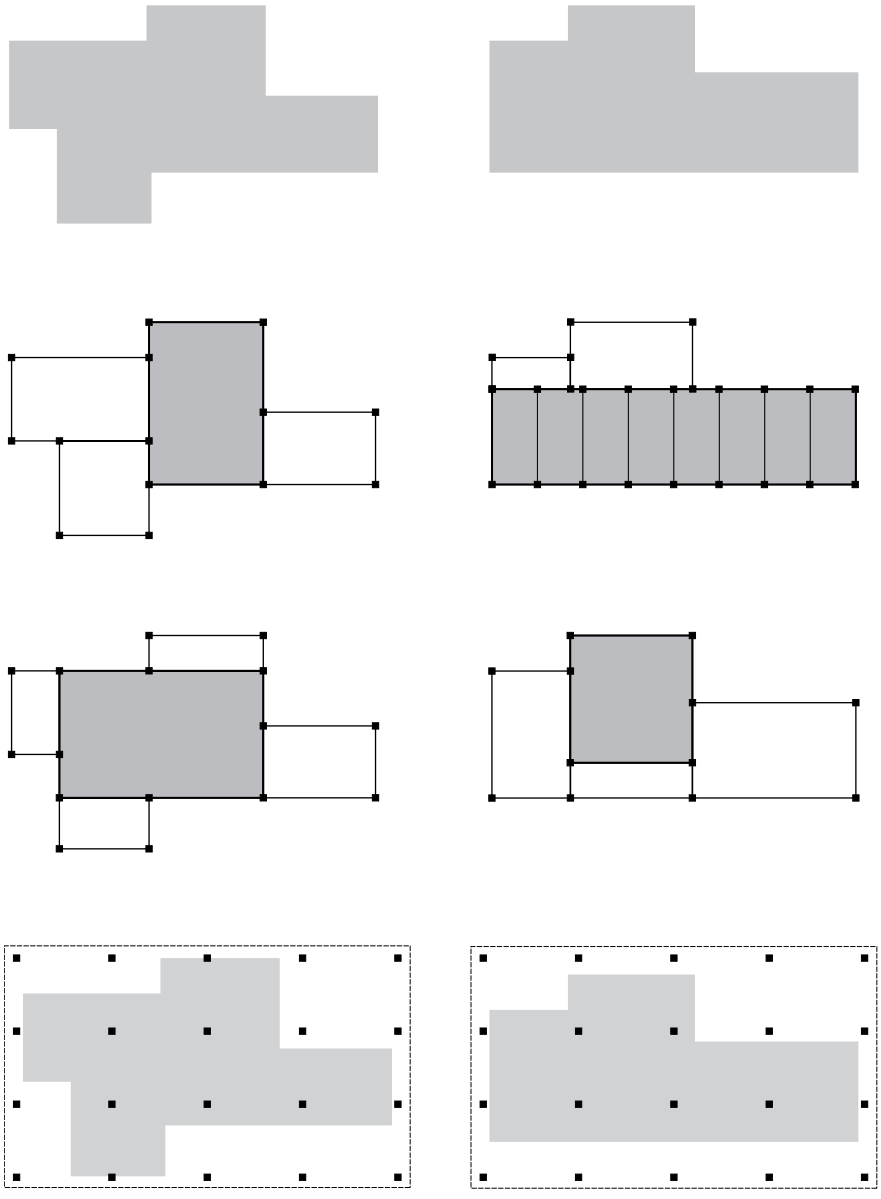


This usually involves working back and forth between a structural concept and the program requirements for the space, searching for an appropriate fit between the structural strategy and the vision for the formal, aesthetic and performance qualities of the resulting spatial environment.

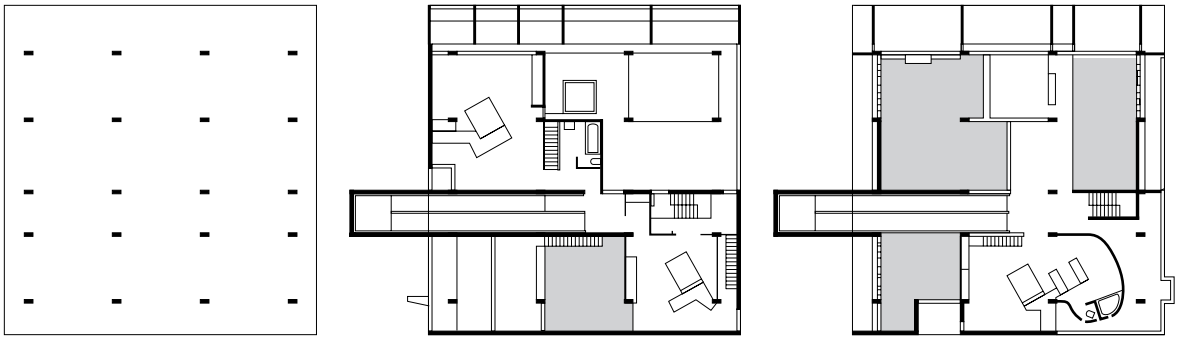
A discrete irregular space may also be developed as an independent structure with a separate structural system and geometry superimposed over the building as a whole. Although appropriate to accommodate the spatial requirements of such spaces as theaters, concert halls, and large galleries, this strategy typically requires long-span spanning systems. For a discussion of long-span structures, see Chapter 6.



Accommodating Irregular Shapes



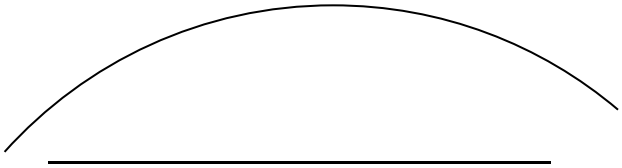
See plan and section of Centre Le Corbusier, pg. 16.



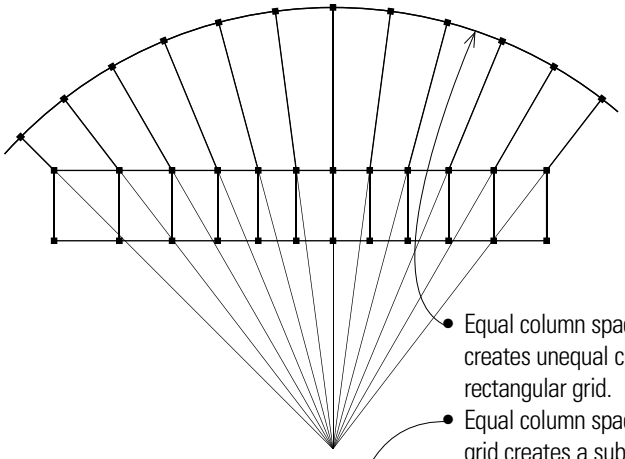
Plan diagrams: Mill Owners' Association Building, Ahmedabad, India, 1952–1954, Le Corbusier.

Accommodating Irregular Shapes

It is advisable to try to recognize the inherent geometry embedded in irregular plan shapes when attempting to develop a strategy for its structural system. Even the most irregular of plan shapes can often be dissected into parts which can be seen to be transformations of regular geometric shapes.

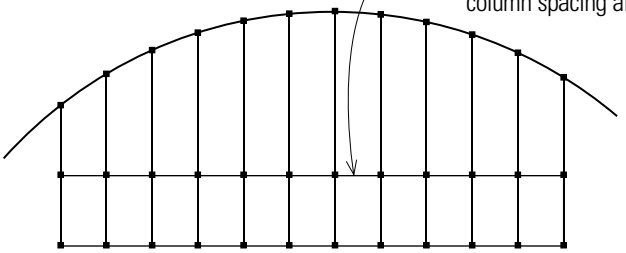


The manner in which an irregular shape or form might be constructed will often suggest logical options for a framing strategy. This may be as simple as using the center of an arc for a radial framing system or framing parallel or perpendicular to a significant wall or plane within an irregular geometry. Curves, especially, possess a number of properties for establishing the basis for a framing strategy. One might use the radius or center of an arc, a point that is tangent to the arc, or in the case of double curvatures, the inflection point where a change in curvature occurs. The approach one takes will depend on the design intent and how the structural strategy might reinforce the concept.

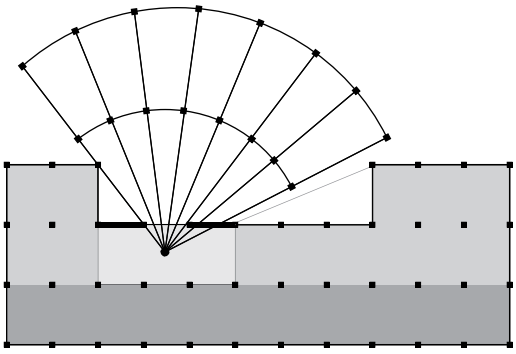


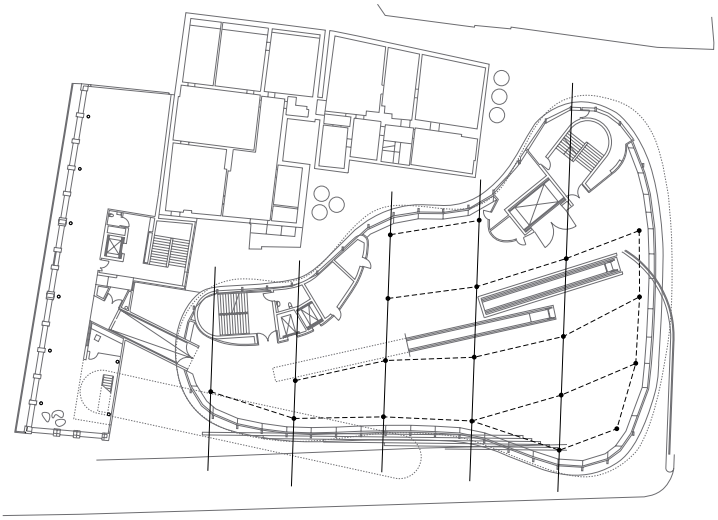
- Equal column spacing along the arc creates unequal column spacing on the rectangular grid.
- Equal column spacing on the rectangular grid creates a subtle inequality of column spacing along the arc.

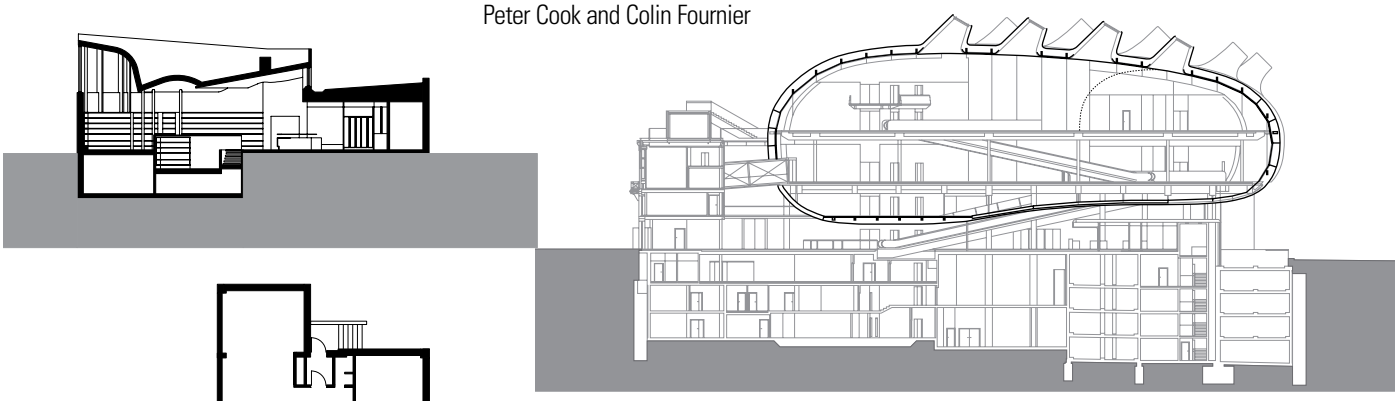
Although structural framing systems are usually developed in plan, consideration should also be given to the effect of the structure on the vertical aspects of a building—its elevations and the scale of its interior spaces. If column locations will be expressed in the facade, for example, the visible effect of a regular column spacing on a curving exterior wall plane should be considered.



Part of the challenge of structuring irregular plan shapes is to minimize the structural inefficiency that often results from the inevitable variations in span lengths.



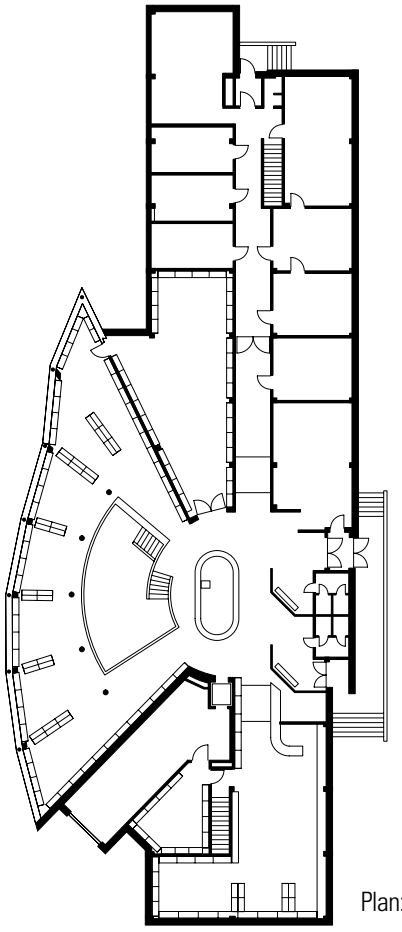




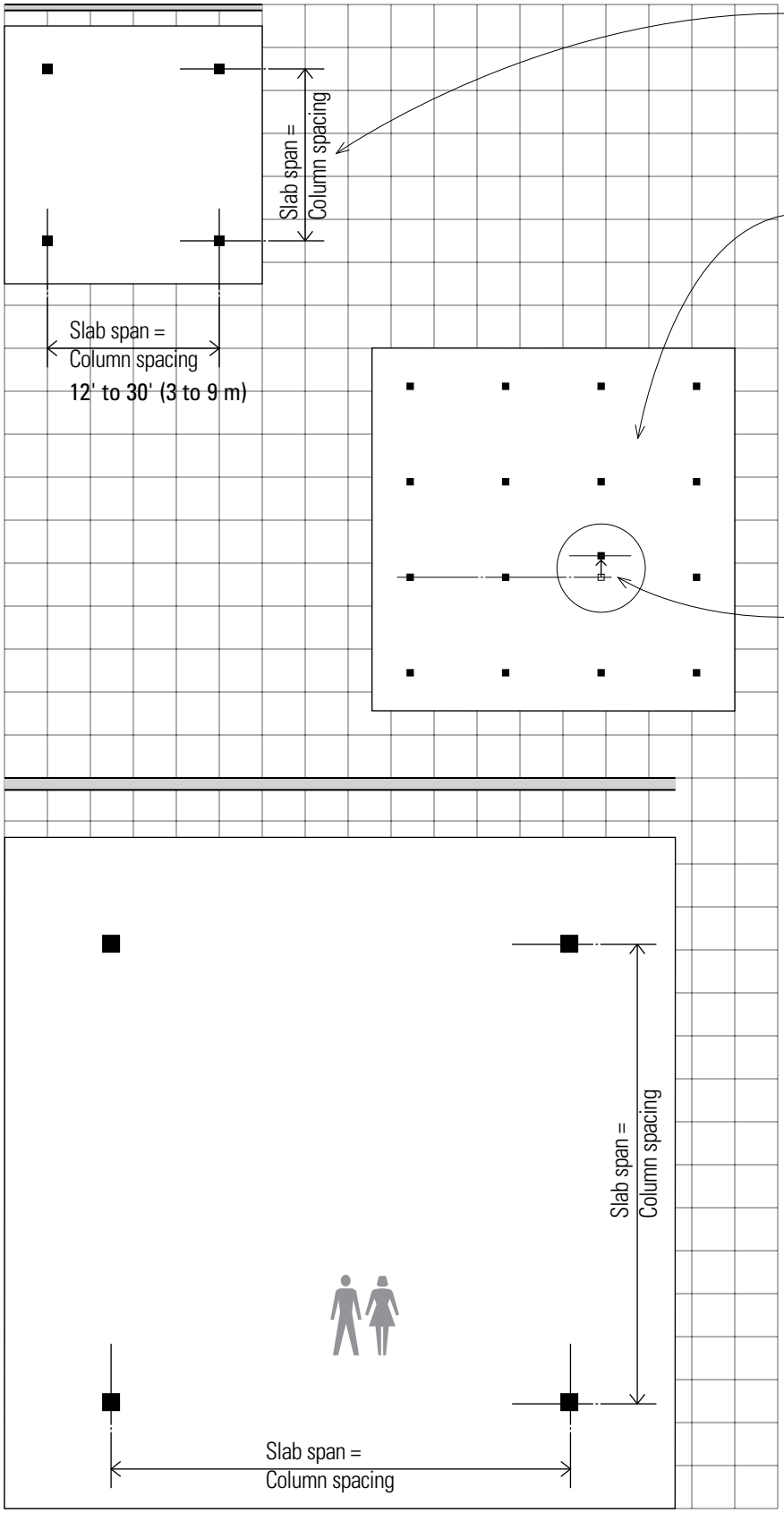
Plan and section: Kunsthaus, Graz, Austria, 1997–2003,
Peter Cook and Colin Fournier

The examples on this page illustrate two ways in which irregular forms have been integrated into the rectilinear geometry of a composition. The bulbous form housing the exhibition spaces and related public facilities in the Kunsthaus is partly a response to an irregular site and the required fire-separation distance from existing adjacent buildings. It appears to float above the geometry of the structural grid that supports it.

The significance of the main reading room of the Seinajoki Library is expressed in both plan and section by its fan-like shape, which is anchored at the circulation desk to the rectilinear geometry of the offices and support spaces.



Plan: Seinajoki Library, Seinajoki, Finland, 1963–1965, Alvar Aalto

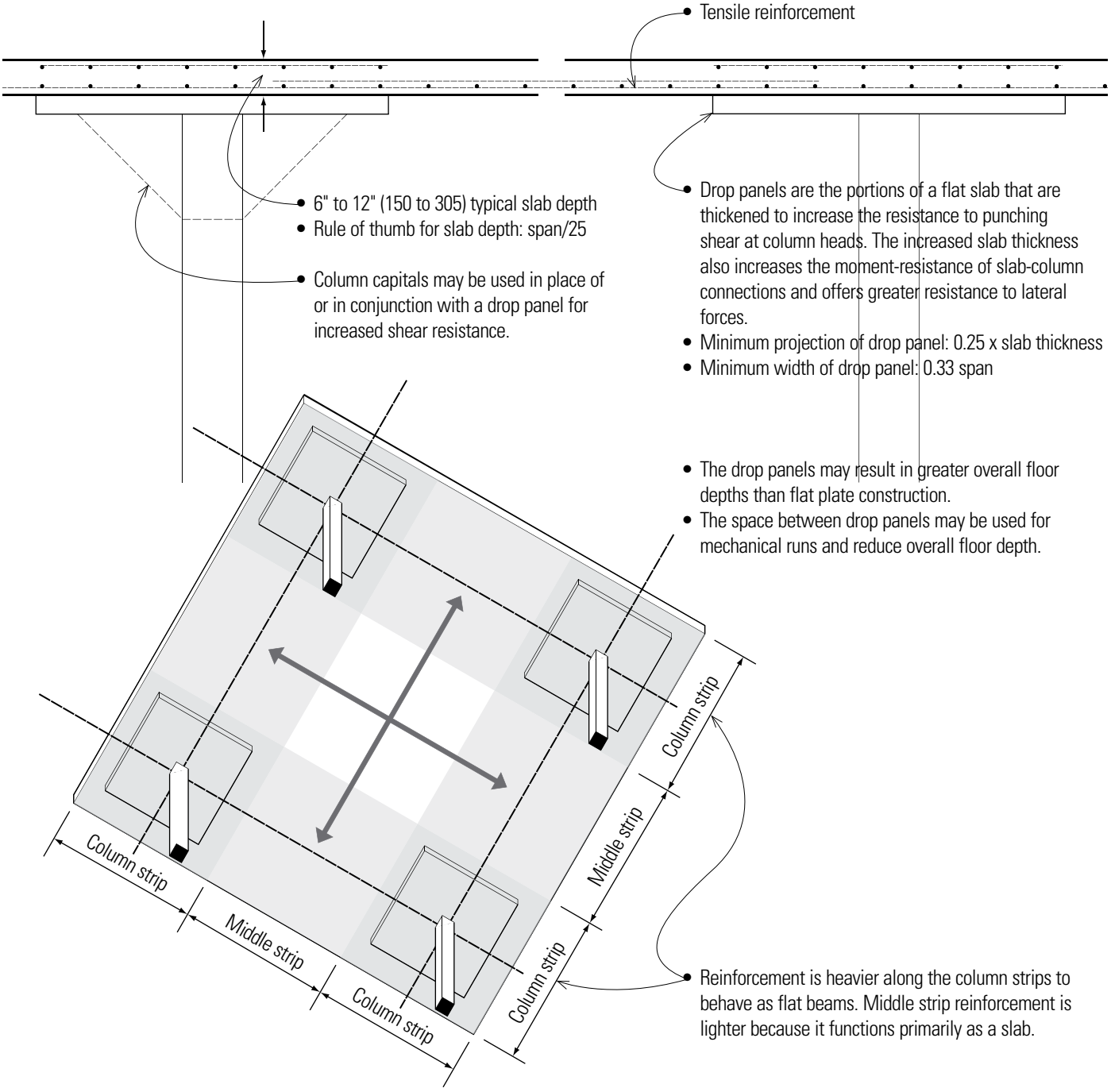


- Flat plates are suitable for light to moderate loads over relatively short spans of 12' to 30' (3.6 to 9.1 m). Greater spans and/or reduced slab thicknesses can be achieved with post-tensioning. Post-tensioning also offers increased control of deflection and cracking.
- Two-way systems are most efficient when spanning square or nearly square bays. The ratio of the long to the short dimensions should not be greater than 1.5:1.
- For maximum efficiency, flat plates should have a continuous span of at least three bays in both directions, and successive span lengths should not differ by more than a third of the longer span.
- While a regular column grid is most appropriate, some flexibility in column placement is possible.
- Individual columns may be offset by as much as 10 percent of the span from the regular column lines, but any shift should occur on all levels so that columns on successive floors remain vertically aligned.

- Grid is based on a 3-foot (915) square.

Flat Slabs

Flat slabs are flat plates thickened at their column supports to increase their shear strength and moment-resisting capacity.



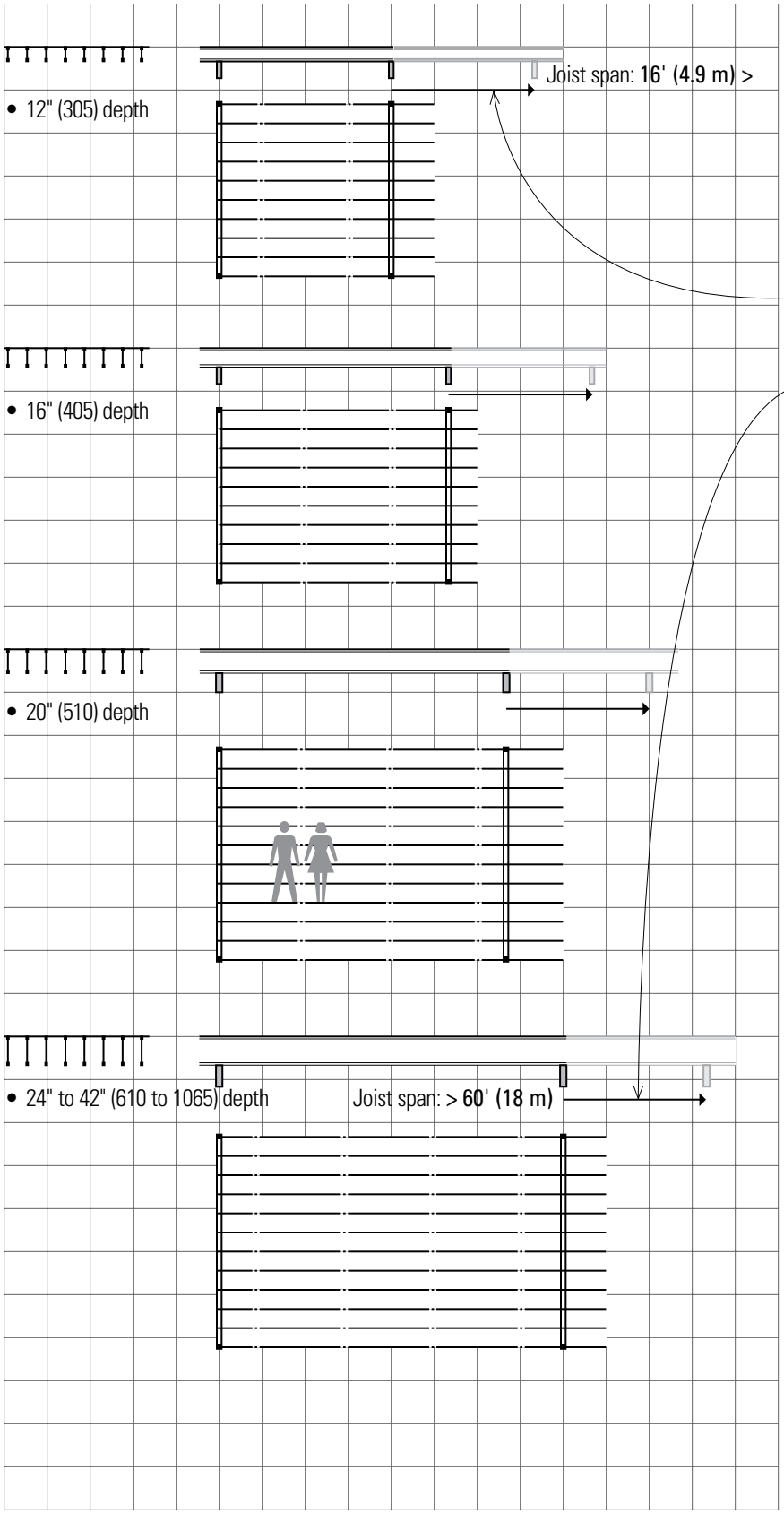
- 6" to 12" (150 to 305) typical slab depth
- Rule of thumb for slab depth: span/25

- Column capitals may be used in place of or in conjunction with a drop panel for increased shear resistance.

- Drop panels are the portions of a flat slab that are thickened to increase the resistance to punching shear at column heads. The increased slab thickness also increases the moment-resistance of slab-column connections and offers greater resistance to lateral forces.
- Minimum projection of drop panel: 0.25 x slab thickness
- Minimum width of drop panel: 0.33 span

- The drop panels may result in greater overall floor depths than flat plate construction.
- The space between drop panels may be used for mechanical runs and reduce overall floor depth.

- Reinforcement is heavier along the column strips to behave as flat beams. Middle strip reinforcement is lighter because it functions primarily as a slab.



I-Joists

- 16' to 60' (4.9 to 18.3 m) spans

Wood Trussed Joists

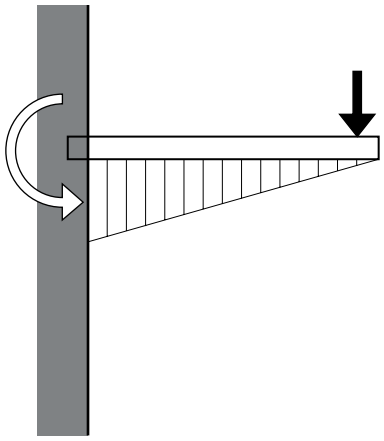
- 16' to 60' (4.9 to 18.3 m) spans

- Rule of thumb for estimating depth of prefabricated joists and trusses: span/18

- Grid is based on a 3-foot (915) square.

Cantilevers

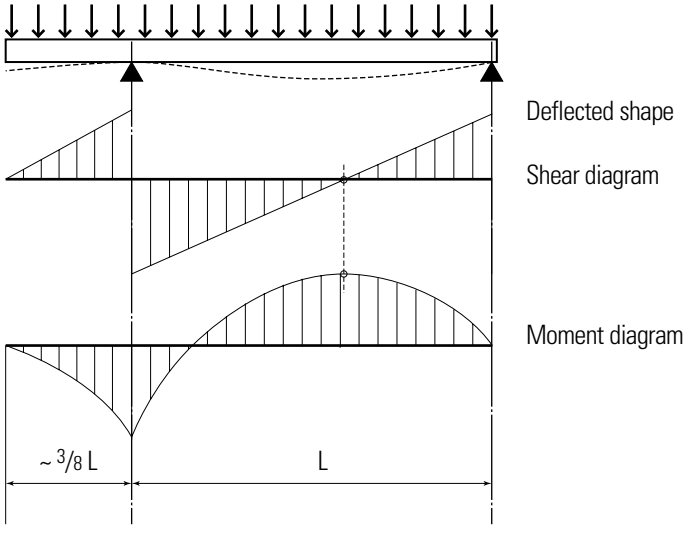
A cantilever is a beam, girder, truss, or other rigid structural framework that is securely fixed at one end and free at the other end. The fixed end of a cantilever resists loads transversely and rotationally while the other end is free to deflect and rotate. Pure cantilever beams exhibit a single downward curvature when loaded from above. The top surface of the beam will be stressed in tension while the bottom fibers are subjected to compressive stresses. Cantilever beams tend to have very large deflections and the critical bending moment develops at the support.



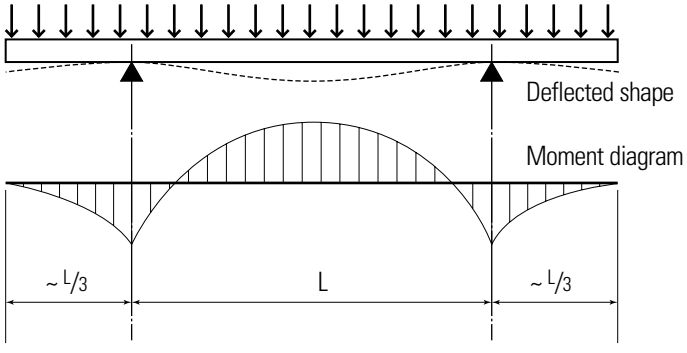
Overhanging Beams

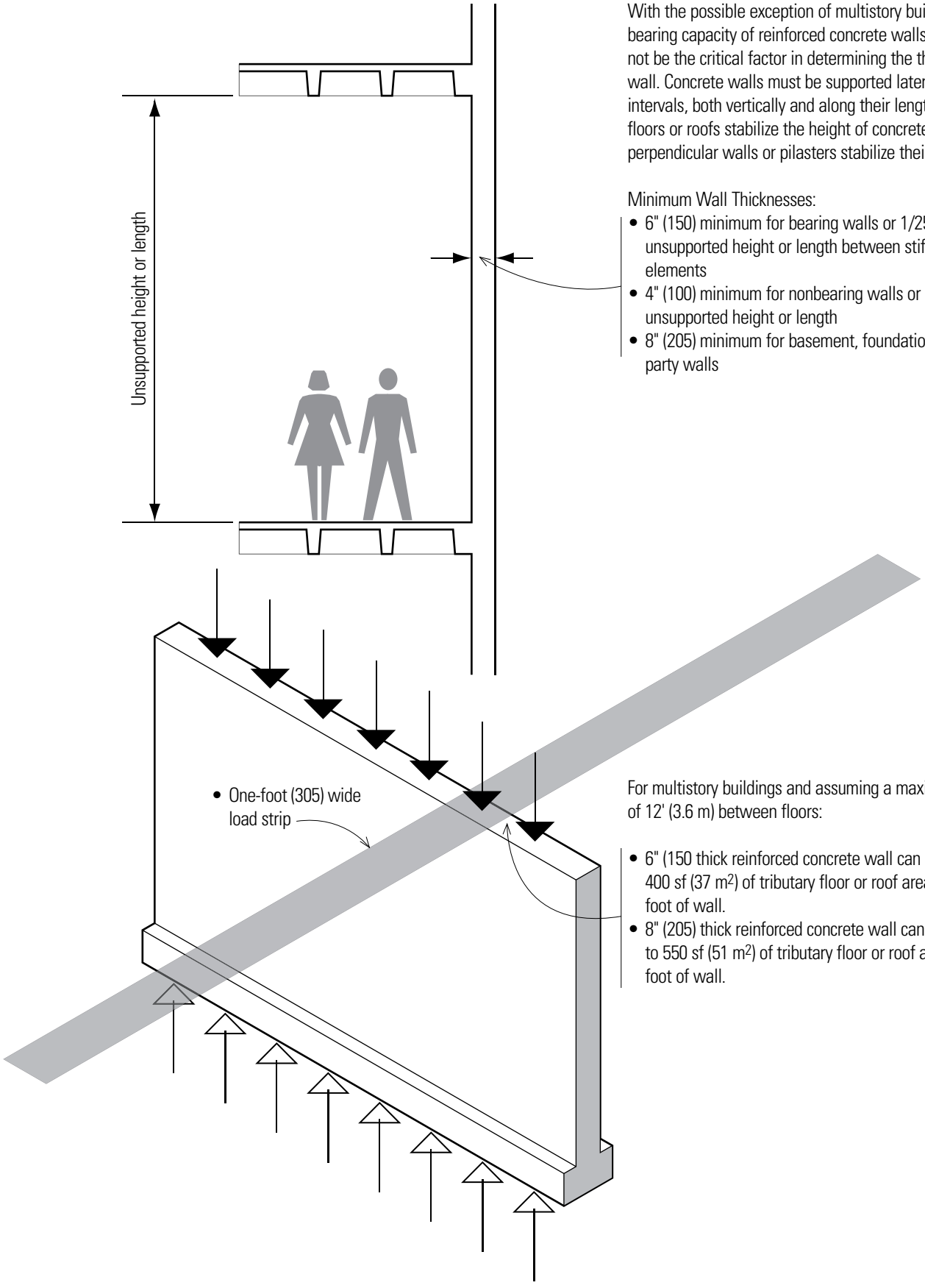
An overhanging beam is formed by extending one or both ends of a simple beam. Cantilever action results from the beam extension, which has the positive effect of counteracting the deflection present in the interior span. Overhanging beams exhibit multiple curvatures, unlike a simple cantilever beam. Tensile and compressive stresses reverse along the beam's length corresponding to the deflected shape.

- Assuming a uniformly distributed load, the projection of a single overhanging beam for which the moment over the support is equal and opposite to the moment at midspan is approximately 3/8 of the span.



- Assuming a uniformly distributed load, the projections of a double overhanding beam for which the moments over the supports are equal and opposite to the moment at midspan are approximately 1/3 of the span.





With the possible exception of multistory buildings, the bearing capacity of reinforced concrete walls typically will not be the critical factor in determining the thickness of the wall. Concrete walls must be supported laterally at regular intervals, both vertically and along their length. Intersecting floors or roofs stabilize the height of concrete walls while perpendicular walls or pilasters stabilize their length.

Minimum Wall Thicknesses:

- 6" (150) minimum for bearing walls or 1/25 of the unsupported height or length between stiffening elements
- 4" (100) minimum for nonbearing walls or 1/36 of unsupported height or length
- 8" (205) minimum for basement, foundation, fire, or party walls

For multistory buildings and assuming a maximum height of 12' (3.6 m) between floors:

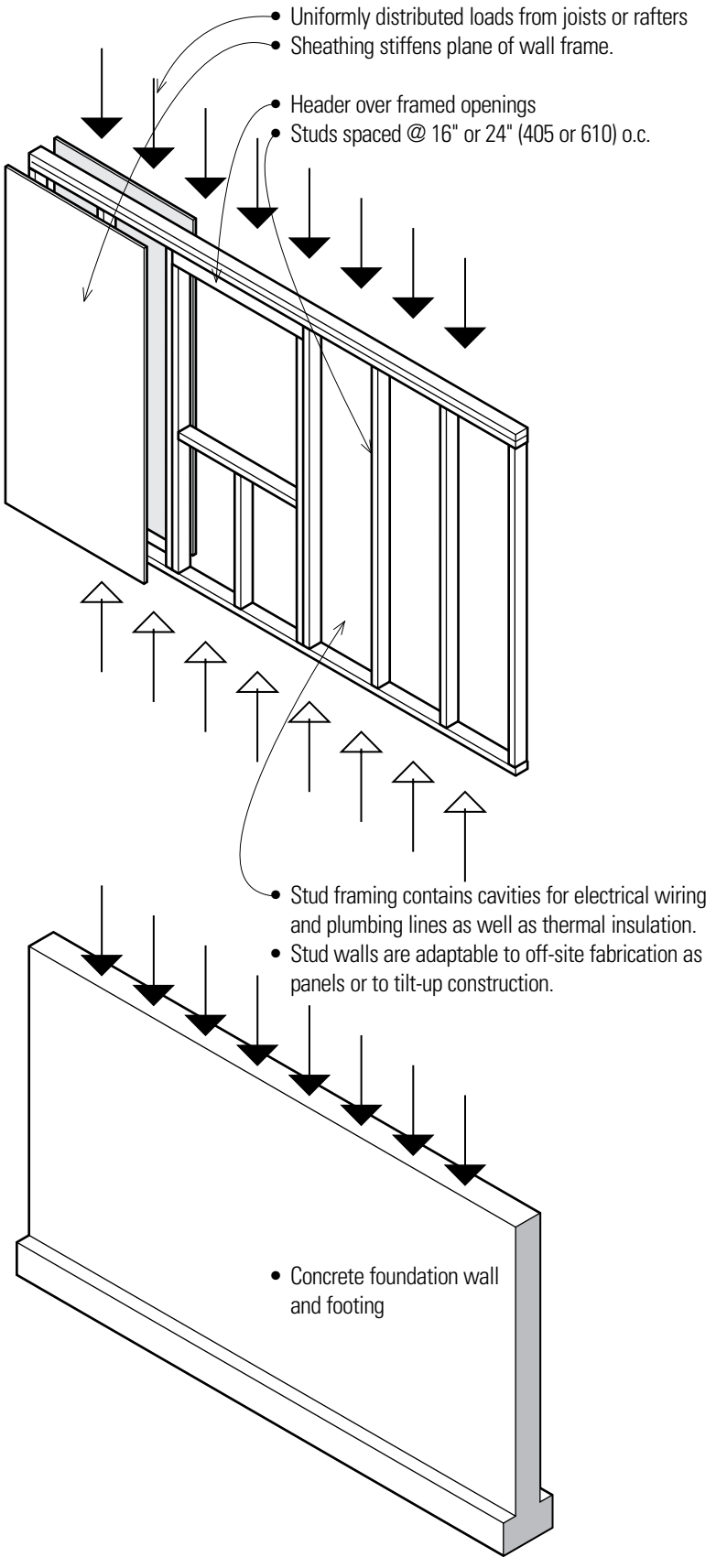
- 6" (150 thick reinforced concrete wall can support up to 400 sf (37 m^2) of tributary floor or roof area per lineal foot of wall.
- 8" (205) thick reinforced concrete wall can support up to 550 sf (51 m^2) of tributary floor or roof area per lineal foot of wall.

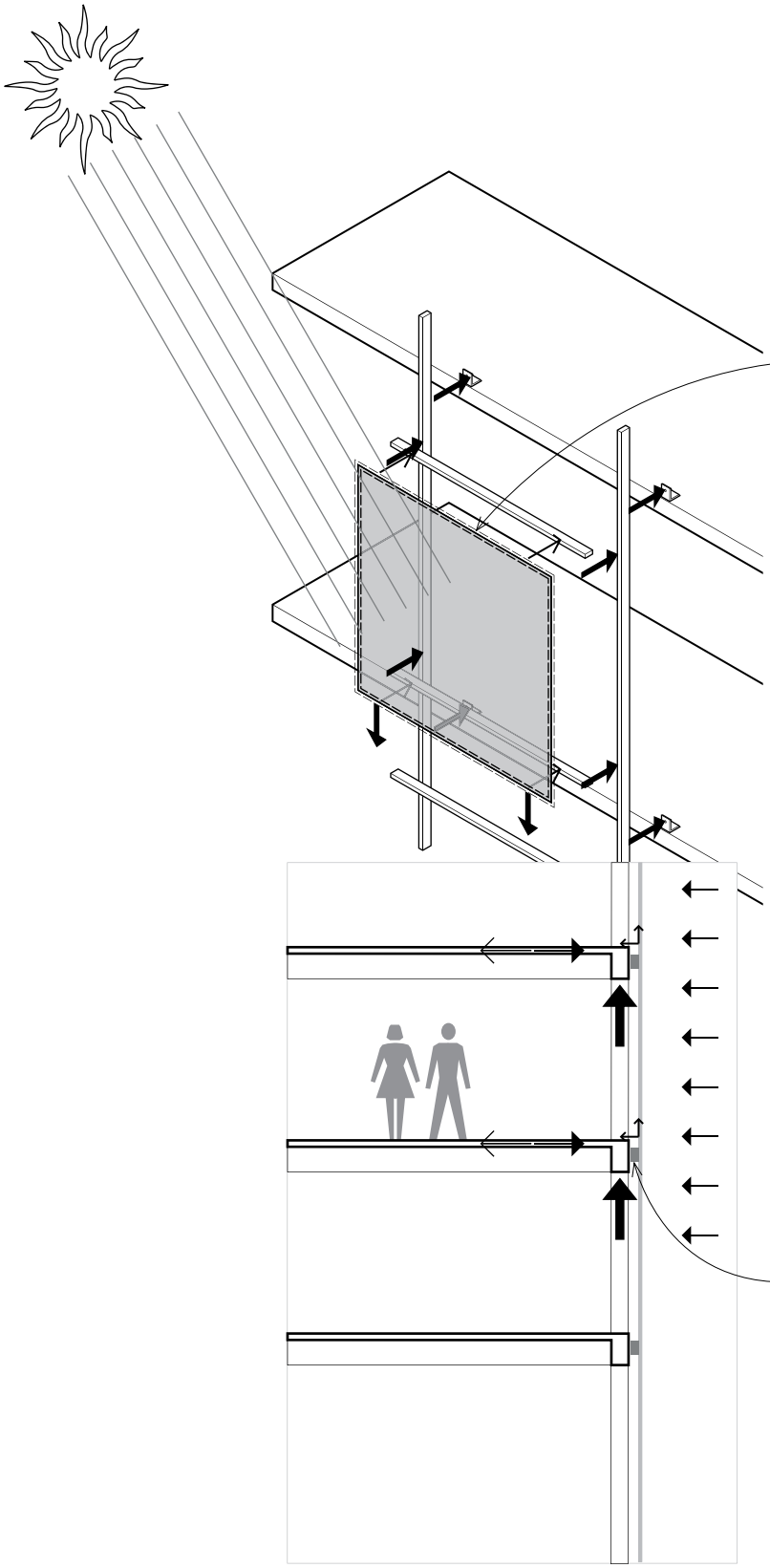
Stud-Framed Walls

Light frame walls are constructed of light-gauge metal or wood studs that are typically spaced 12", 16", or 24" (305, 405, or 610) on center, depending on the desired wall height and the size and spanning capability of common sheathing and surfacing materials. Light frame construction is typically used for bearing walls in low-rise structures that take advantage of the lightweight components and ease of assembly. The system is particularly well suited for buildings that are irregular in form or layout.

Light-gauge metal studs are manufactured by cold-forming sheet or strip steel. The cold-formed metal studs can be easily cut and assembled with simple tools into a wall structure that is lightweight, noncombustible, and dampproof. Metal stud walls may be used as nonloadbearing partitions or as bearing walls supporting light-gauge steel joists. Unlike wood light framing, metal light framing can be used for fabricating partitions in noncombustible construction. However, the fire-resistance rating of both wood and metal light frame wall assemblies is based on the fire resistance of the surfacing materials.

Both metal and wood stud walls can be idealized as monolithic walls when loaded uniformly from above. The studs carry the vertical and horizontal bending loads while the sheathing stiffens the plane of the wall and distributes both horizontal and vertical loads between individual studs. Any opening in the wall framing requires the use of header beams that redirect the loads to either side of the openings. Concentrated loads from the header reactions must be supported by a build-up of studs resembling a column.





Sun

- Brightness and glare should be controlled with shading devices or the use of reflective or tinted glass.
- The ultraviolet rays of the sun can also cause deterioration of joint and glazing materials and fading of interior furnishings.

Temperature

- Daily and seasonal variations in temperature cause expansion and contraction of the materials comprising a wall assembly, especially metals. Allowance must be made for differential movement caused by the variable thermal expansion and contraction of different materials.
- Joints and sealants must be able to withstand the movement caused by thermal stresses.
- Heat flow through glazed curtain walls should be controlled by using insulating glass, insulating opaque panels, and by incorporating thermal breaks into metal frames.
- Thermal insulation of veneer panels may also be incorporated into the wall units, attached to their backsides, or provided with a backup wall constructed on site.

Water

- Rain can collect on the wall surface and be wind-driven under pressure through the smallest openings.
- Water vapor that condenses and collects within the wall must be drained to the outside.
- Pressure-equalized design principles become critical in the detailing of curtain walls, especially in larger and taller buildings, where the pressure differential between the outside atmosphere and an interior environment can cause rainwater to migrate through even the smallest openings in wall joints.

Fire

- A noncombustible material, sometimes referred to as safing, must be installed to prevent the spread of fire at each floor within column covers and between the wall panels and the slab edge or spandrel beam.
- The building code also specifies the fire-resistance requirements for the structural frame and the curtain wall panels themselves.

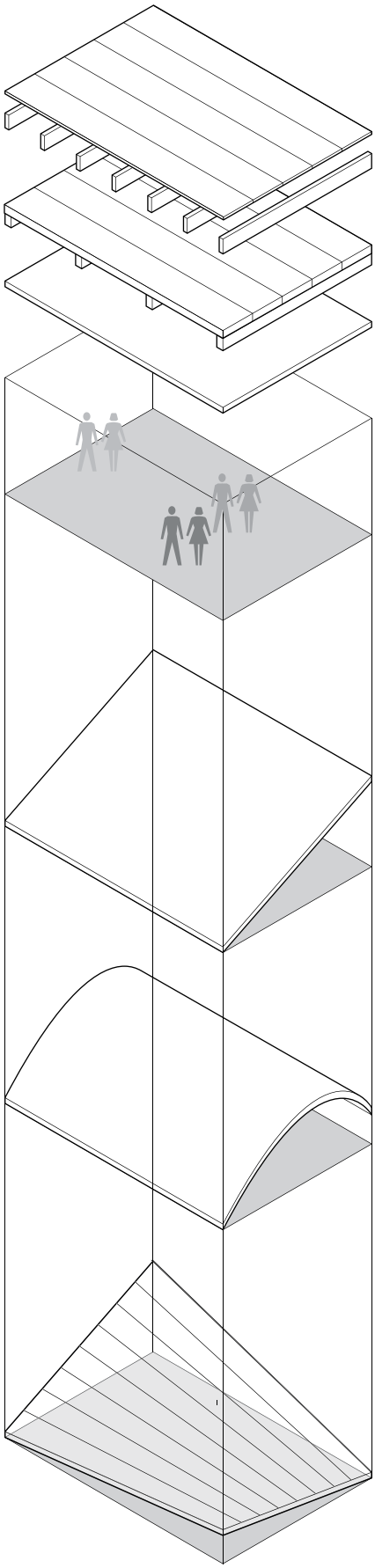
ROOF STRUCTURES

Roof structures, like floor structures, are horizontal spanning systems. However, while floor structures provide flat and level platforms for the support of our activities and furnishings, roof structures have a vertical aspect that can dramatically impact the exterior form of a building as well as the quality of the spatial volumes beneath their canopy. A roof structure may be flat or pitched, gabled or hipped, broad and sheltering, or rhythmically articulated. It may be exposed with edges flush with or overhanging the exterior walls, or it may be concealed from view, hidden behind a parapet. If its underside remains exposed, the roof also transmits its form to the upper boundaries of the interior spaces below.

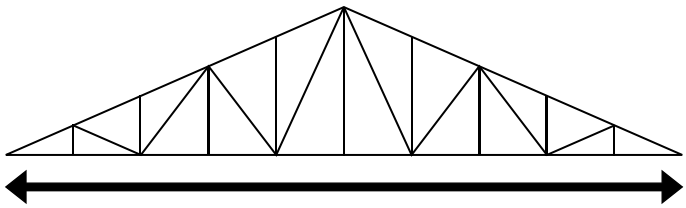
Because the roof system functions as the primary sheltering element for the interior spaces of a building, its form and slope must be compatible with the type of roofing—shingles, tiles, or a continuous membrane—used to shed rainwater and melting snow to a system of drains, gutters, and downspouts. The construction of a roof should also control the passage of moisture vapor, the infiltration of air, and the flow of heat and solar radiation. Depending on the type of construction required by the building code, the roof structure and assembly may have to resist the spread of fire.

Like floor systems, a roof must be structured to span across space and carry its own weight as well as the weight of any attached equipment and accumulated rain and snow. Flat roofs used as decks are also subject to live occupancy loads. In addition to these gravity loads, the planes of the roof may be required to resist lateral wind and seismic forces, as well as uplifting wind forces, and transfer these forces to the supporting structure.

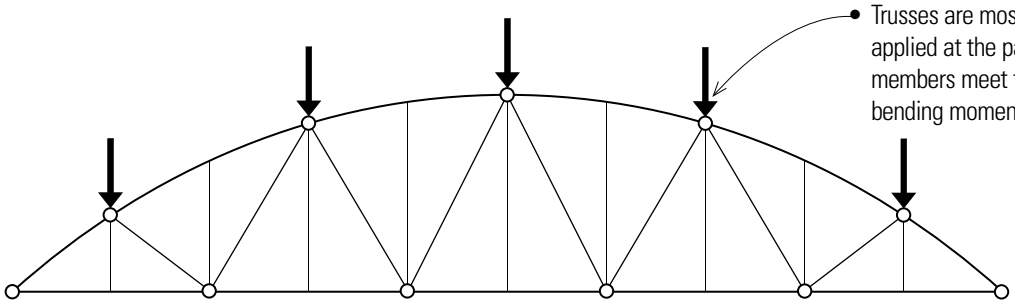
Because the gravity loads for a building originate with the roof system, its structural layout must correspond to that of the column and bearing wall systems through which its loads are transferred down to the foundation system. This pattern of roof supports and the extent of the roof spans, in turn, influences the layout of interior spaces and the type of ceiling that the roof structure may support. Long roof spans would open up a more flexible interior space while shorter roof spans might suggest more precisely defined spaces.



Trusses use material more economically and are more efficient in spanning long distances than solid beams but are relatively expensive to fabricate because of the number of connections and the complexity of the joints. They become more economical when spanning 100 feet (30 m) or more and when used as primary structural members supporting secondary trusses or beams.



- Long-span trusses are used most often for roof structures and come in a multitude of profiles. When used occasionally for floors, the trusses have parallel chords.

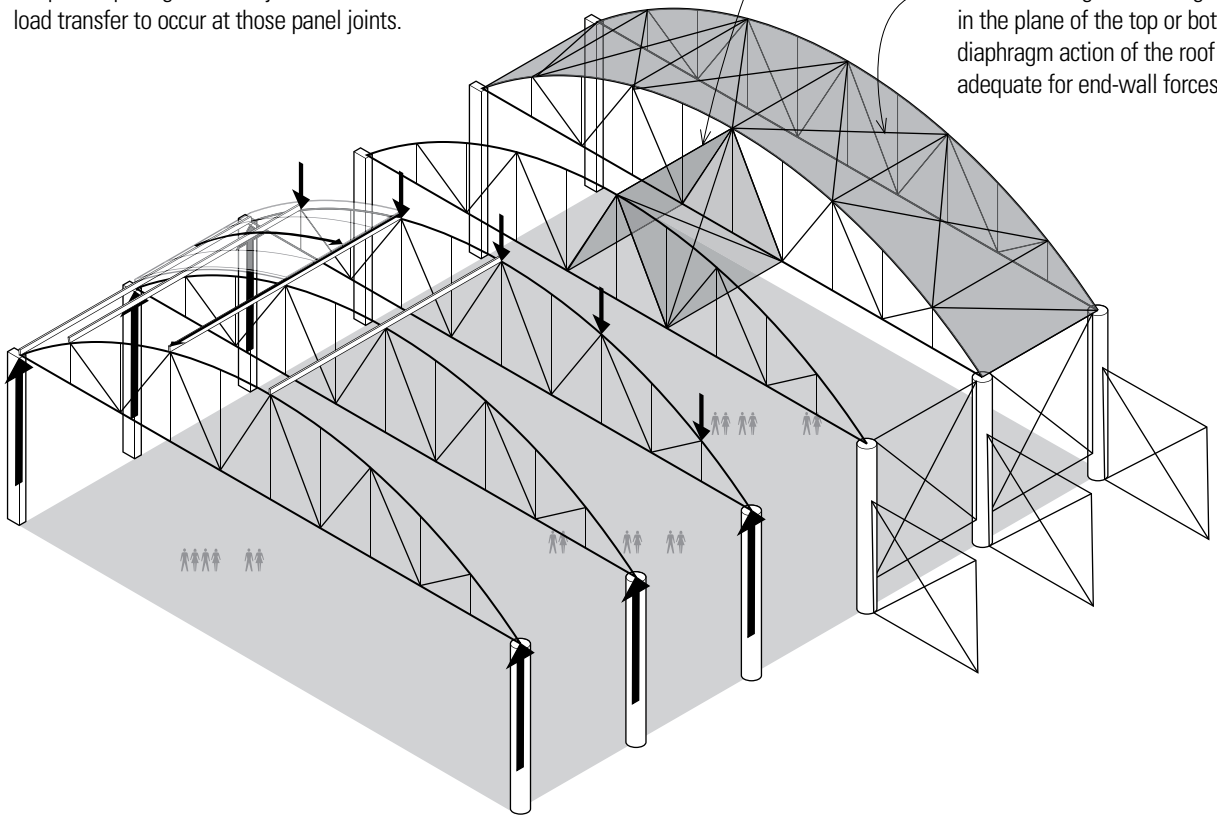


- Trusses are most effective when loads are applied at the panel points—where the web members meet the chords—so as to minimize bending moments in the individual members.

- The spacing of major long-span trusses is a function of the spanning capability of the secondary framing elements running perpendicular to the truss span. Commonly used truss spacing ranges from 6 to 30 feet (1.8 to 9 m) on center.

- The spacing of the secondary elements is controlled by the panel spacing of the major trusses to enable the load transfer to occur at those panel joints.

- Vertical sway bracing may be required between the top and bottom chords of adjacent trusses to provide resistance against lateral wind and seismic forces.
- The top chords of trusses should be buttressed against buckling by secondary framing members and lateral diagonal bracing.
- Horizontal diagonal bracing may be required in the plane of the top or bottom chord if the diaphragm action of the roof framing is not adequate for end-wall forces.



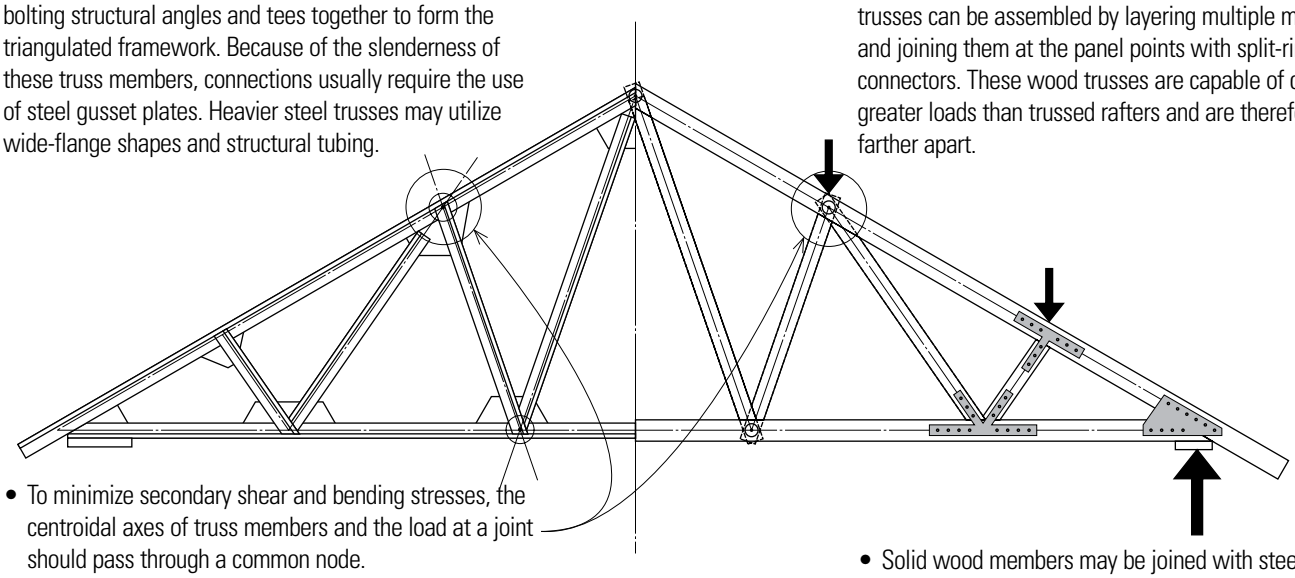
Trusses are generally constructed out of timber, steel, and sometimes a combination of timber and steel. Due to its weight, concrete is seldom used for trusses. The decision to use timber or steel depends on the desired appearance, compatibility with the roof framing and roofing materials, and the required type of construction.

Steel Trusses

Steel trusses are generally fabricated by welding or bolting structural angles and tees together to form the triangulated framework. Because of the slenderness of these truss members, connections usually require the use of steel gusset plates. Heavier steel trusses may utilize wide-flange shapes and structural tubing.

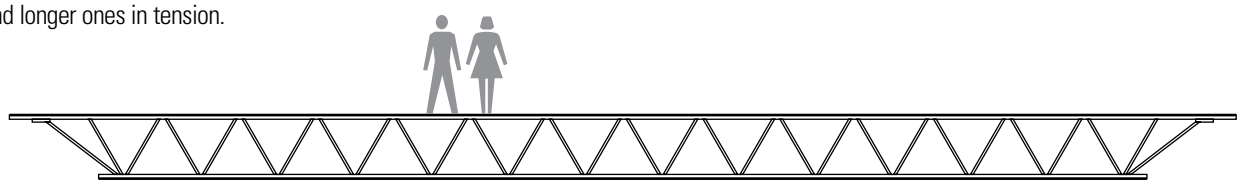
Wood Trusses

In contrast to monoplanar trussed rafters, heavier wood trusses can be assembled by layering multiple members and joining them at the panel points with split-ring connectors. These wood trusses are capable of carrying greater loads than trussed rafters and are therefore spaced farther apart.



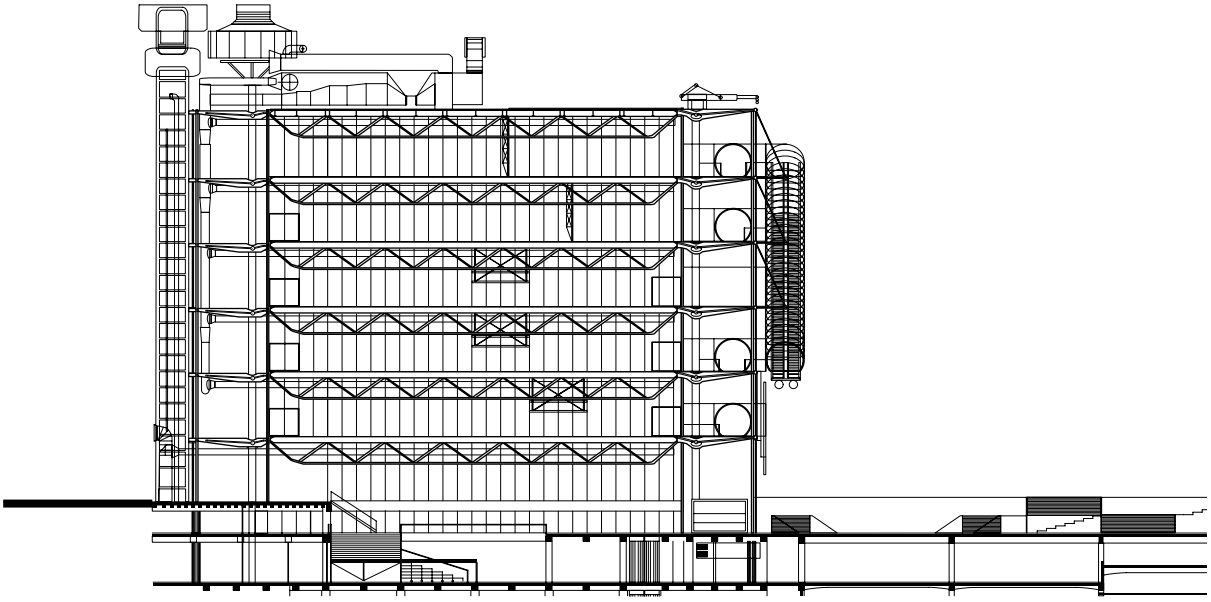
- To minimize secondary shear and bending stresses, the centroidal axes of truss members and the load at a joint should pass through a common node.
- Members are bolted or welded with gusset plate connectors.
- Any knee bracing should also connect to the top or bottom chord at a panel point.
- The cross sectional size of compression members, being governed by buckling, is larger than that of tension members, which is controlled by tensile stresses. It is better to place shorter truss members in compression and longer ones in tension.

- Solid wood members may be joined with steel plate connectors.
- Composite trusses have timber compression members and steel tension members.
- Member sizes and joint details are determined by engineering calculations based on truss type, load pattern, span, and grade and species of lumber used.

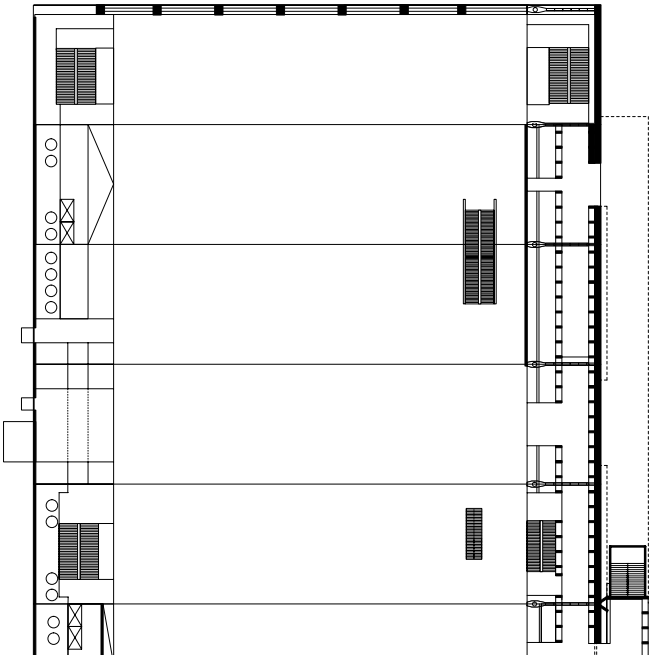


Open-Web Joists

- Commercially manufactured open-web timber and steel joists are much lighter than regular trusses and are capable of spans up to 120 feet (37 m).
- Composite open-web joists have top and bottom wood chords and a web of diagonal steel tubing. Composite joists suitable for spans in excess of 60 feet (18.3 m) have depths from 32" to 46" (810 to 1170). Heavier weight composite joists range in depth from 36" to 60" (915 to 1525).
- The LH and DLH series of open-web steel joists are suitable for long-span applications. The LH series are suitable for the direct support of both floors and roof decks while the DLH series are suitable only for the direct support of roof decks.
- LH series joists have depths from 32" to 48" (810 to 1220) for spans in the 60- to 100-foot (18- to 30-m) range. The DLH-series ranges in depth from 52" to 72" (1320 to 1830) with spanning capabilities in the 60- to 140-foot (18.3- to 42.7-m) range.



Partial plan and section: Pompidou Center, Paris, France, 1971–1977, Renzo Piano and Richard Rogers



The major steel trusses of the Pompidou Center are spaced at 42-foot (12-m) intervals and span approximately 157 feet (48 m). On top of the supporting columns at each level are custom molded steel hangers, each measuring 26 feet (8 m) in length and weighing 20,000 pounds. Composite concrete and steel wide-flange beams span the major trusses.

The roof of the central space of the Phaeno Science Center (facing page) is supported by a long-spanning space frame. The center's intricate forms were made possible by the use of advanced finite-element analysis modeling software developed by structural engineers Adams Kara Taylor. Complex forces within the entire structure were calculated and resolved as a single element, thus optimizing the integrity and material efficiency of the structure. If engineered in the traditional manner a few years ago, the structural systems would have been engineered separately, resulting in a significantly over-designed structure.



30 St. Mary Axe—informally known as The Gherkin and previously, the Swiss Re Building—is a skyscraper in London's financial district. With 41 floors, the tower is 591 feet (180 m) tall and stands on the site of the former Baltic Exchange, which was extensively damaged in 1992 by the explosion of a bomb placed by the Provisional IRA. After plans to build the Millennium Tower were dropped, 30 St. Mary Axe was erected, soon becoming an iconic symbol of London and one of the city's more widely recognized examples of modern architecture.

The shape of the tower was partially influenced by the need to have a smooth flow of wind around the building and minimize its impact on the local wind environment. Across this curved surface the diagrid structure is formed by generating a pattern of intersecting diagonals spiraling in two directions.

The unusual geometry of the tower gives rise to significant horizontal forces at each node level where the diagonal columns intersect, which are resisted by perimeter hoops. As with dome structures, the hoops in the upper region are in compression while those at the middle and lower levels are subject to significant tensile forces. The hoops also serve to transform the diagrid into a very stiff triangulated shell, freeing the interior core from the need to resist lateral wind forces. Foundation loads are also reduced when compared with a high-rise structure stabilized by its core.

Typical floor plan and section: 30 St. Mary Axe (The Gherkin), London, England, 2001–2003, Norman Foster/ Foster + Partners

DAMPING MECHANISMS

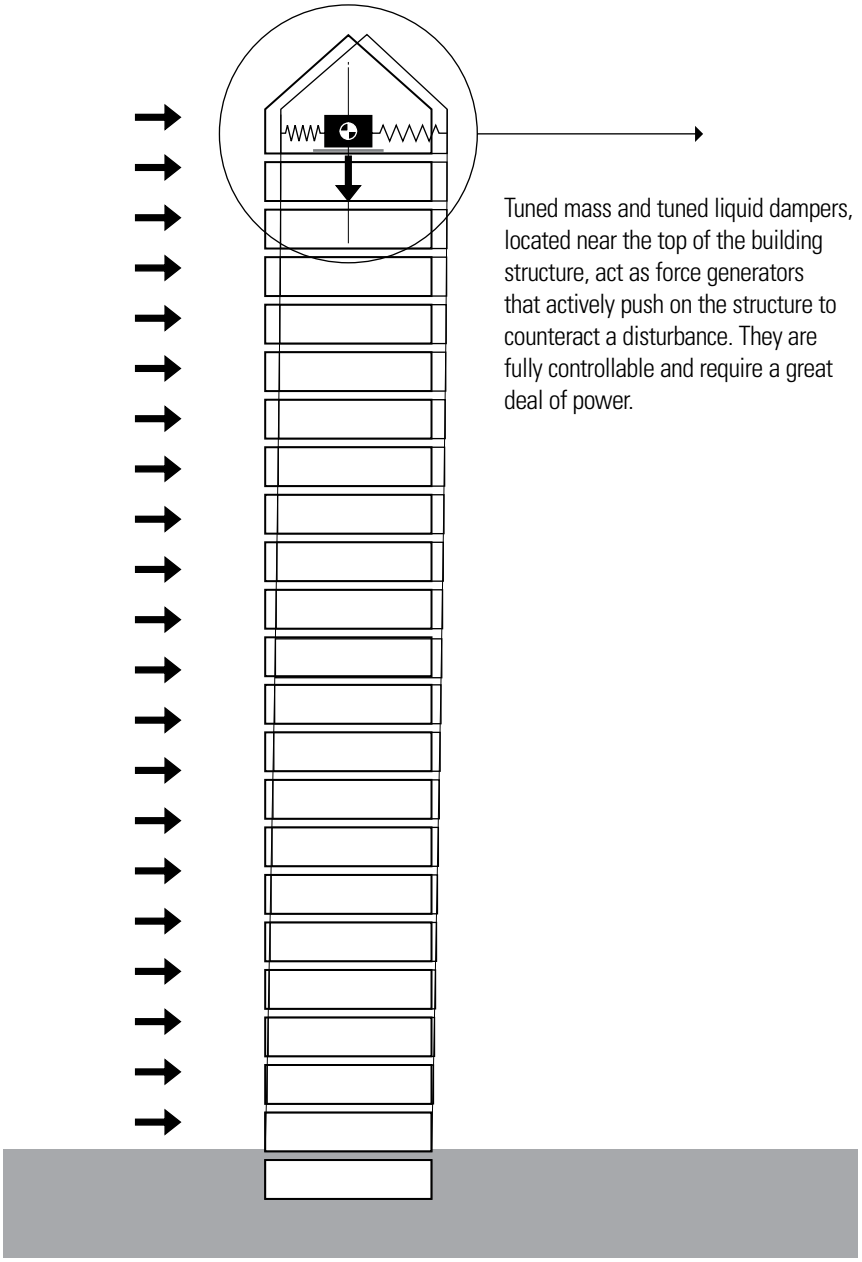
Although stiffening a tall structure to reduce sway and limit deflections and deformation under lateral loading, large increases in structural size relative to those required for strength alone are often required to achieve satisfactory dynamic performance. A more cost-effective approach is to use damping systems that mitigate the effects of wind-induced vibration and earthquake shaking on tall structures, as well as on its nonstructural architectural elements and mechanical components. By absorbing and dissipating a significant portion of the energy transmitted to the building during high winds or a seismic event, damping systems limit excessive motion and deflections, moderate structural member sizes, and add to occupants' comfort level against sway perception.

The base isolation system described in Chapter 5 is an effective damping system for stiff buildings up to seven stories in height. For taller buildings subject to overturning, there are three types of damping systems used to control excessive motions and deflections and ensure occupancy comfort. These are active damping systems, passive damping systems, and aerodynamic damping.

Active Damping Systems

Damping systems that require power for motors, sensors, and computer controls are known as active systems; those that do not are passive systems. The most significant drawback to active damping systems is that external power is required to regulate their movement and may be undependable during a seismic event when the power supply could be disrupted. For this reason, actively controlled dampers are more suitable for tall buildings subject to wind-induced loading rather than the more unpredictable cyclic loading caused by earthquakes.

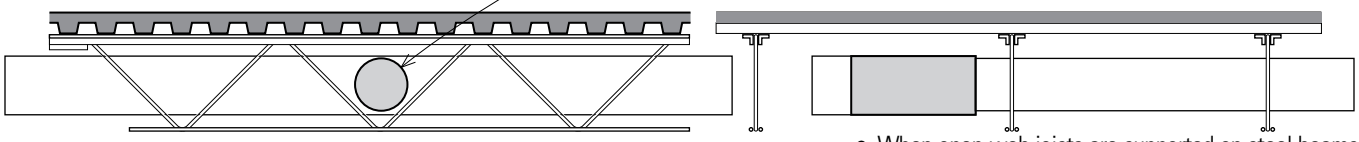
Semi-active damping systems combine the features of passive and active damping systems. Rather than push on a building's structure, they use a controlled resistive force to reduce motion. They are fully controllable yet require little input power.



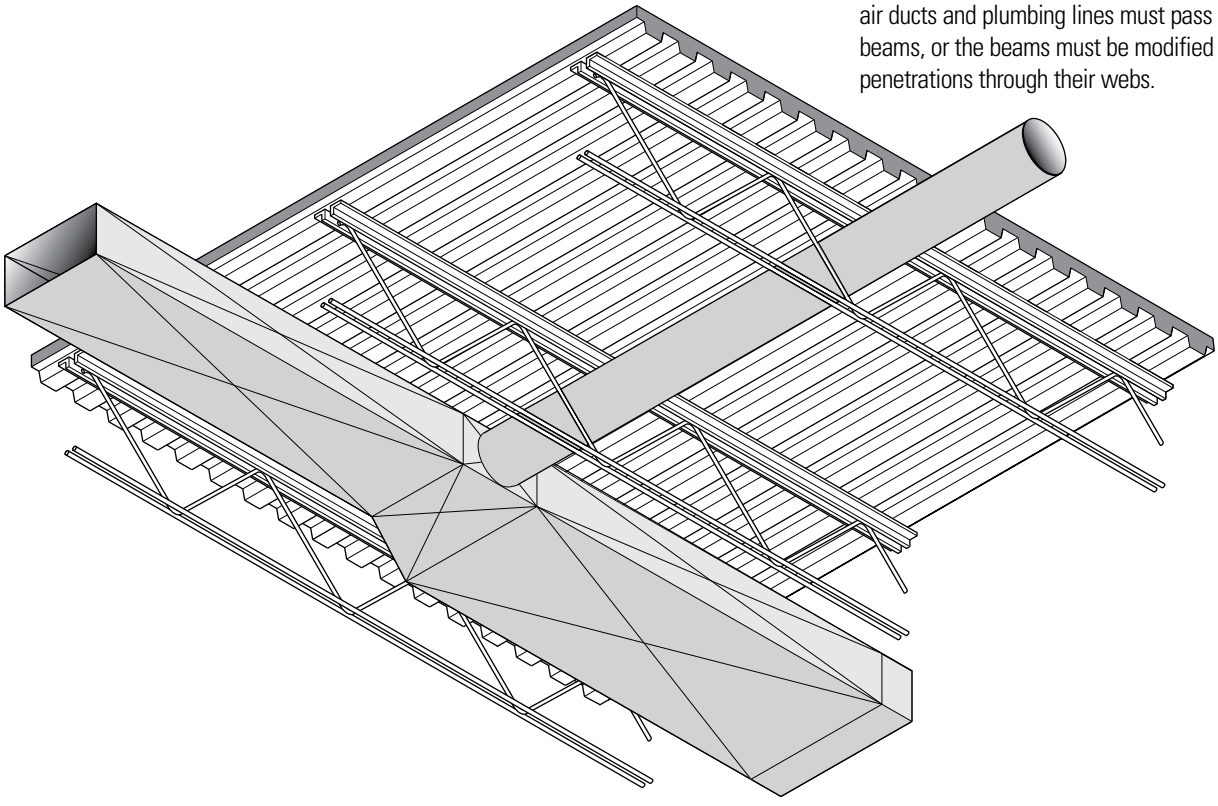
Tuned mass and tuned liquid dampers, located near the top of the building structure, act as force generators that actively push on the structure to counteract a disturbance. They are fully controllable and require a great deal of power.

Open-Web Steel Joists

- Open-web steel joists permit the passage of mechanical services through the webs as well as parallel to the joists.



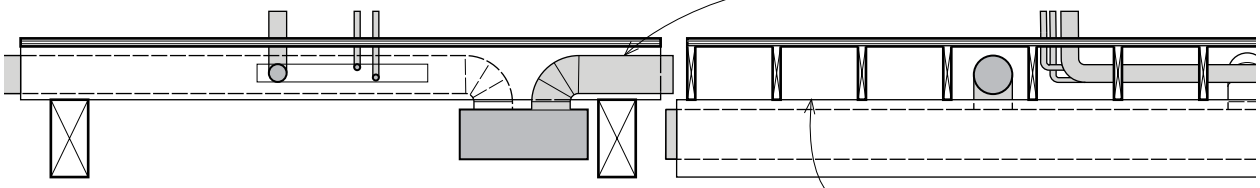
- When open-web joists are supported on steel beams, air ducts and plumbing lines must pass below the beams, or the beams must be modified to accommodate penetrations through their webs.



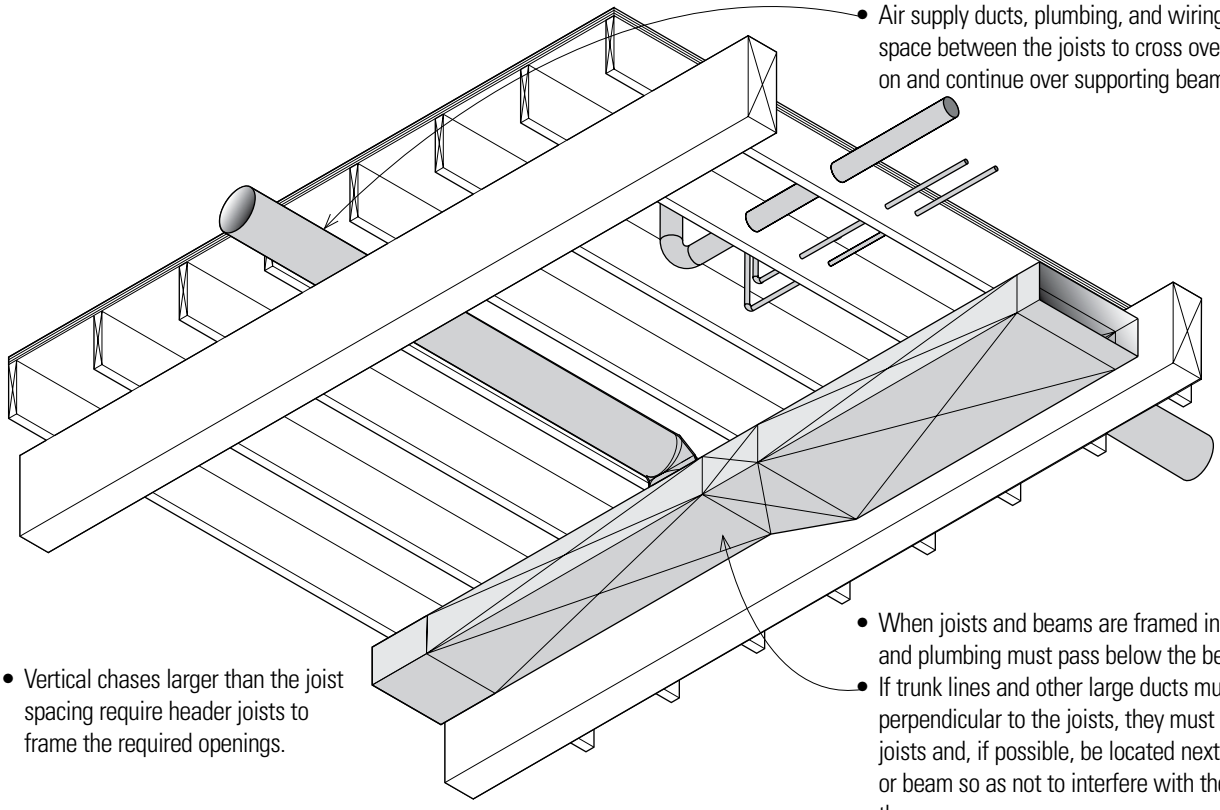
- Supporting open-web joists on girder trusses may allow mechanical services to pass through the girders when running parallel to the open-web joists. Note that a girder truss is typically deeper than a steel beam carrying an equivalent load, creating a deeper floor construction.

- Small vertical openings may be framed with steel angle headers supported by trimmer joists. Large openings, however, require structural steel framing.

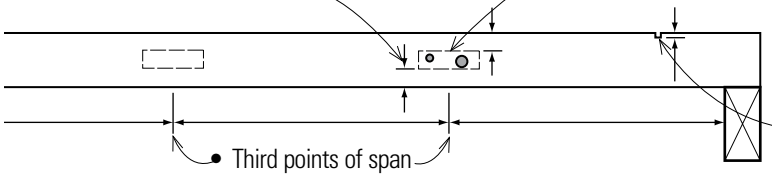
Light Frame Construction



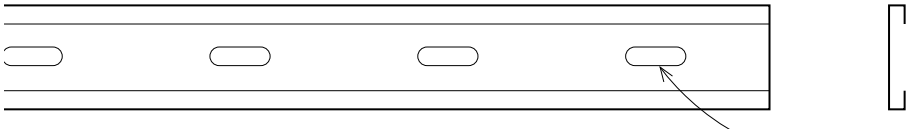
- Branch supply ducts may run between joists.
- Return air ducts may be created by sealing the space between the joists.
- Air supply ducts, plumbing, and wiring can use the space between the joists to cross over if the joists bear on and continue over supporting beams or walls.



- When joists and beams are framed in-plane, air ducts and plumbing must pass below the beams.
- If trunk lines and other large ducts must run perpendicular to the joists, they must pass below the joists and, if possible, be located next to a bearing wall or beam so as not to interfere with the vertical scale of the space.
- Vertical chases larger than the joist spacing require header joists to frame the required openings.



- Middle third of cross section
- Third points of span
- Wiring, plumbing supply lines, and small drainage pipes may be run through openings in the joists where shear and bending stresses are at a minimum. For a simple span, this is at or near the third point of the span and in the middle third of the cross section of the joist. Manufactured I-joists often have precut knock-out holes for wiring.
- Notches should be limited to 1/6 th of the joist depth and only occur along the compression edge but never in the middle third of the joist span.



- Light-gauge joists have cutouts for running wiring, plumbing supply lines, and small drainage lines.

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