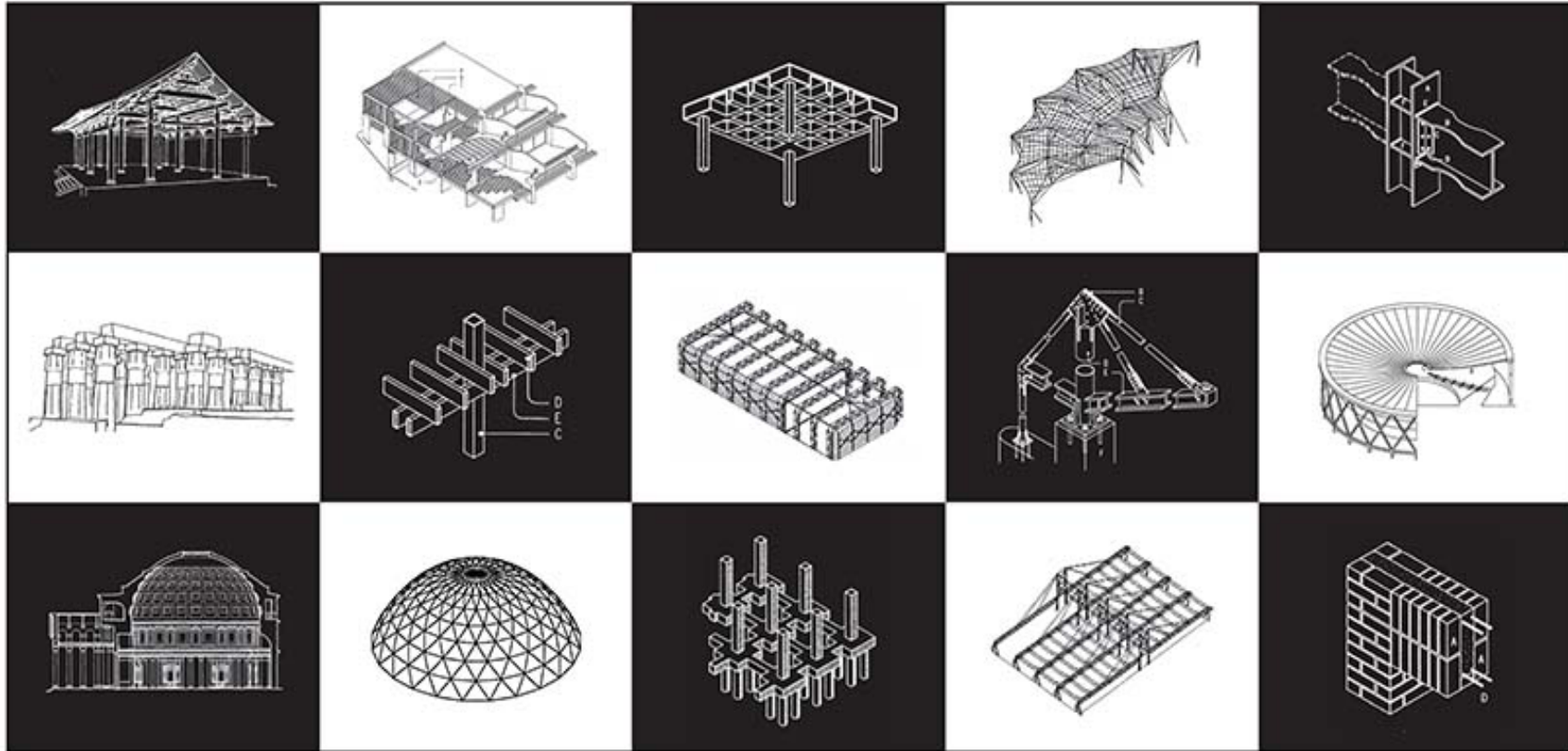


1ST EDITION



G G Schierle

STRUCTURE AND DESIGN

Structure and Design

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About the author

Professor Schierle is a Fellow of the American Institute of Architects, recipient of the ACSA Creative Achievement Award, NSF, HUD, and FEMA research grants, founding Director of USC's Master of Building Science Program, and a professional architect. He lectured and published extensively on Design for Earthquake Safety and tensile structures, including at AIA National Conventions. Dr. Schierle holds PhD and Master of Architecture degrees from UC Berkeley and a Dipl-Ing degree from Stuttgart University of Applied Sciences. Prior to USC he taught at UC Berkeley and Stanford. He served on the California structure license committee, the *Journal for Architectural Education* Editorial Board, and the *Fabric Architecture* advisory board. His professional practice includes major projects in America, Asia, and Europe.

About the book

Structures support load and are essential to define form and space. To design structures in synergy with form and space requires creativity and informed intuition of the structural principles. The objective of this book is to introduce the principles as foundation of creative design and demonstrate successful application on many case studies. Richly illustrated, the book clarifies complex concepts without calculus and provides greater insight for readers with mathematics background. The book includes details in wood, steel, masonry, concrete, and fabric. Many graphs streamline complex tasks like column buckling and design for wind and seismic forces and correlate SI metric with US units. The book is a reference book for architects, civil engineers and builders and a text book for education.

Testimonials

This book is a must for anyone aspiring to be an innovative architect, engineer or builder. Unique for its explanations of the relationship between engineering principles and architectural form

Dimitry Vergun, AIA, SE, Architect and Structural Engineer

Professor Schierle has struck a perfect balance between the pragmatic of structure and the creative of architectural design. His textbook is an invaluable resource for architects and structural engineers who collaboratively strive to achieve an inventive, competent structural solutions that help define the form and space of buildings, yet offer structural safety, reliability, and predictable long-term performance

Julie Mark Cohen, B.Arch., PhD, PE, Consulting Structural and Forensic Engineer

This is a magnum opus for teaching structures. G.G. Schierle has covered it all in both numbers and graphics, from structural theory and material behavior, to superbly delineated case studies and useful rules of thumb. This book will greatly assist both student architects or engineers and seasoned design professionals in their search for a solid conceptual understanding of the integration of form and structure

Will Shepphird, PE, AIA, LEED, Architect and Structural Engineer

To My Family

Units

SI * units (metric)			Conversion factor **	US units		
		Remark				Remark
Length						
Millimeter	mm		25.4	Inch	in	
Centimeter	cm	10 mm	30.48	Foot	ft	12 in
Meter	m	100 cm	0.9144	Yard	yd	3 ft
Kilometer	km	1000 m	1.609	Mile	mi	5280 ft
Area						
Square millimeter	mm ²		645.16	Square in	in ²	
Sq. centimeter	cm ²		929	Square foot	ft ²	144 in ²
Square meter	m ²		0.835	Sq. yard	yd ²	9 ft ²
Hectar	ha		2.472	Acre		1 acre = 4840 yd ²
Volume						
Cubic millimeter	mm ³		16387	Cubic inch	in ³	
Cubic centimeter	cm ³	1 k mm ³	28317	Cubic foot	ft ³	
Cubic meter	m ³	Mil cm ³	0.7646	Cubic yard	yd ³	
Liter	l		0.264	Gallon		US gal = 3.785 liter
Mass						
Gram	g		28.35	Ounce	oz	
Kilogram	kg	1000 g	0.4536	Pound	Lb, #	16 oz
Tonn	t	1000 kg	0.4536	Kip	k	1000 #
Force / load						
Newton	N		4.448	Pound	Lb, #	
Kilo Newton	kN	1000 N	4.448	Kip	k	1000 #
Newton/ meter	N/m		14.59	Pound/ ft	plf	
Kilo Newton/ m	kN/m		14.59	Kip/ ft	klf	1000 plf
Kilogram/ dm ³		Kg/dm ³	62.427	Pound/ ft ³	pcf	
Stress						
Pascal= N/m ²	Pa		6895	Pound/ in ²	psi	
Kilo Pascal	kPa	1000 Pa	6895	Kip / in ²	ksi	1000 psi
Fabric stress						
Newton / m	N/m		175	Pound/ in	Lb/in	
Load / soil pressure						
Pascal	Pa		47.88	Pound/ ft ²	psf	
Moment						
Newton-meter	N-m		1.356	Pound-foot	Lb-ft, #'	
Kilo Newton-m	kN-m		1.356	Kip-foot	k-ft, k'	1000 #'
Temperature						
Celsius	°C		.55(F-32)	Fahrenheit	°F	
Water freezing		0°C	=	32°F		
Water boiling		100°C	=	212°F		

* SI = System International (French - designation for metric system)

** Multiplying US units with conversion factor = SI units

Dividing SI units by conversion factor = US units

Prefixes

Prefix	Factor
Micro-	0.000001
Mlli-, m	0.00001
Centi-	0.01
Deci-	0.1
Semi-, hemi-, demi-	0.5
Uni-	1
Bi-, di-	2
Tri-, ter-	3
Tetra-, tetr-, quadr-	4
Pent-, penta-, quintu-	5
Sex-, sexi-, hexi-, hexa-,	6
Hep-, septi-,	7
Oct-, oct-, octa-, octo-	8
Non-, nona-	9
Dec-, deca-, deci, deka-	10
Hect-, hector-	100
Kilo-, k	1,000
Mega-, M	1,000,000
Giga-, G	1,000,000,000
Tera-	1,000,000,000,000

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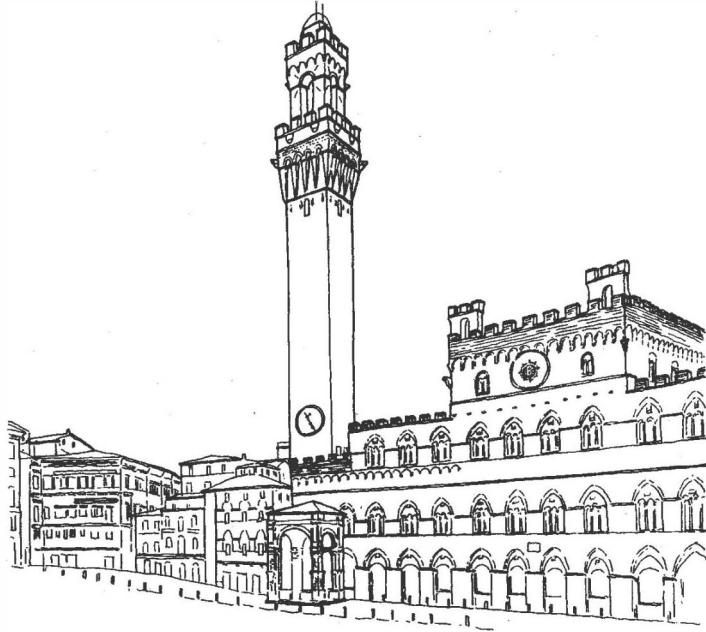
PART I

1

BACKGROUND

Historic Evolution

This chapter briefly introduces key structural developments, starting with basic walls; and post and beam systems; followed by dramatic increase in long span capacity using the funicular concept of arch, vault, and dome. This development also had a profound impact on architectural form. Other developments include suspension structures, truss, and high-rise structures.



Walls

Walls are among the oldest structures, providing both support and space enclosure to shelter from the elements. Walls may also provide the edge of civic spaces, an important factor to define urban fabric. Walls may also respond to natural topography.

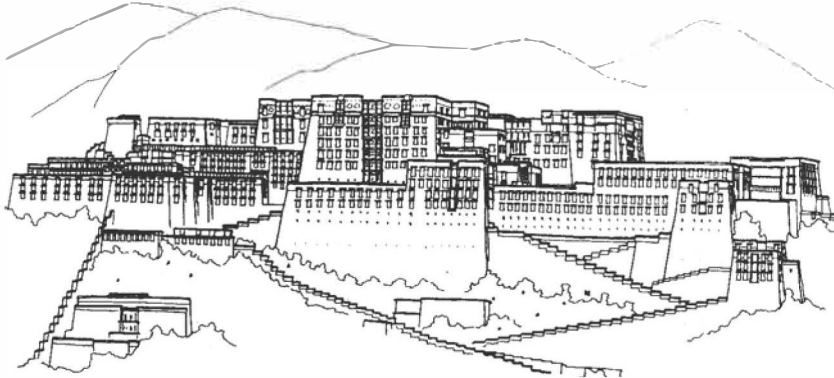
Siena city hall, *Palazzo Pubblico* (1250-1315)

Siena's city hall, a masterpiece of medieval architecture, is the focal point of *El Campo*, the popular marketplace, a prominent foreground of slight slope toward the city hall. The brick masonry structure is an archetype of medieval architecture. Siena had its best period during the 13th and 14th centuries, before the black plague hit Siena in 1348. The following decline preserved much of Siena's medieval character. The city hall (*Palazzo Pubblico*) was built for the Republican government. With the city hall and marketplace in the town center, Siena is focused around its government, not the cathedral as in other cities. The *Piazza del Campo* is one of Italy's most admired medieval squares with the city hall and its unique tower as focal point.



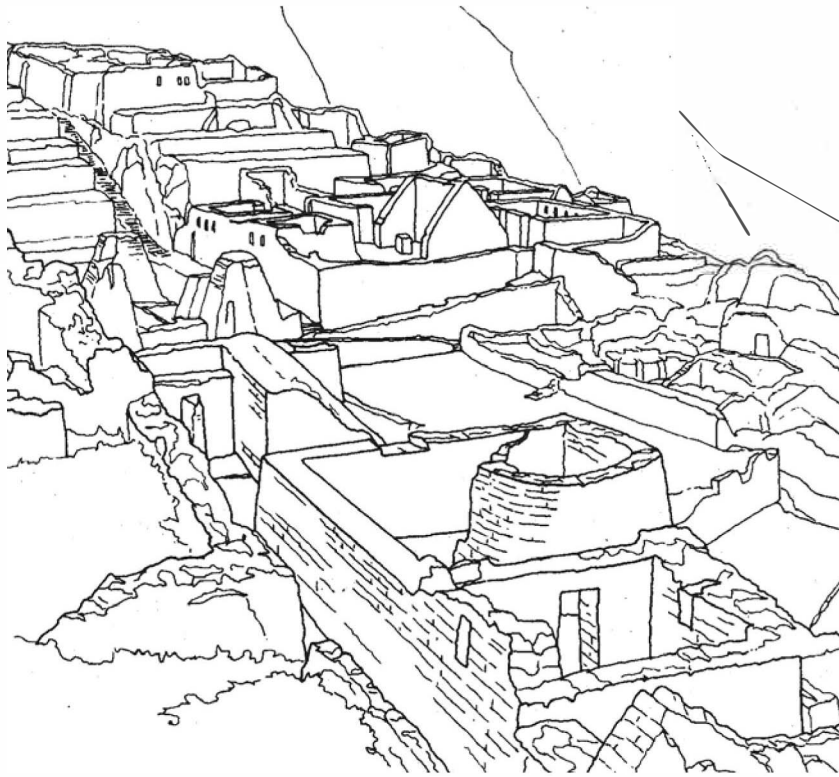
San Gimignano (C. 200 BC to 1300 AD)

San Gimignano rises on a hill with striking towers of medieval stone masonry. The tower heights expressed the wealth and importance of competing families which governed the city. San Gimignano developed from an Etruscan village of the Hellenistic period (200-300 BC) to a major town in the 10th century, named after bishop St Gimignano, who presumably saved it from barbarians. San Gimignano increased in wealth during the middle ages due to its location at a trading and pilgrim route. Internal power struggles between the Guelph and Ghibelline families divided the city into two factions. In 1348 the black plague drastically reduced the population, causing a serious crisis which led to its submission to Florence in 1353. Gradually San Gimignano overcame the decline when its beauty was rediscovered.



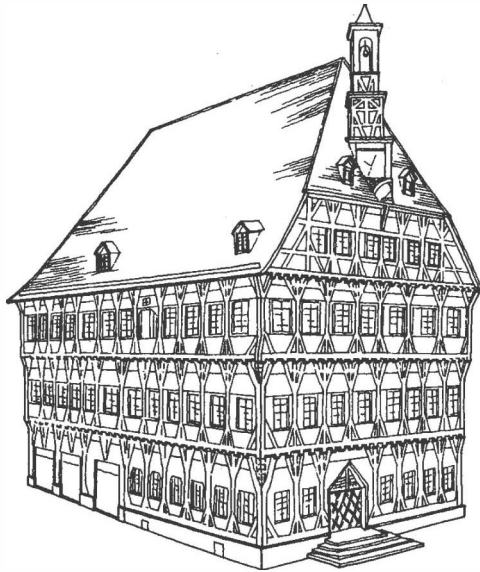
Potala Palace Tibet (1645)

Potala Palace rises from a buttressed stone masonry base to a top articulated by many windows, crowned by wood roofs and wood temples. The artful transition from solid base to graceful top makes this massive wall an enrichment of the environment rather than a bulky imposition. Located on the Bu-Da-La mountain, the palace is the former residence of the Dalai Lama, leader of the Gelug sect of Tibetan Buddhism and ruler of Tibet during the period when the Gelugpa controlled the country from mid 17th century until 1959. The palace was also the seat of the Tibetan government; housed a school for religious training of monks and administrators; and was one of Tibet's major pilgrim destinations to the tombs of past Dalai Lamas.



Machu Picchu, Peru (c. 1460 - 70)

Machu Picchu is located on top of a ridge high in the Andes Mountains of Peru. Machu Picchu (which means "manly peak") was likely a royal estate and religious retreat, built between 1460 and 1470. Given its altitude at 8,000 feet (2438 m), it probably did not have any administrative, military or commercial function. About 1,200 people lived in Machu Picchu and its vicinity. The buildings were probably planned and built by Inca architects. Most structures are built of granite blocks cut with bronze or stone tools and smoothed with sand by mutually rubbing them against one-another. The blocks join perfectly without mortar, although none of the blocks are the same size. Machu Picchu is beautifully integrated into the natural landscape, adapting the buildings to the site rather than adapting the site to the buildings. Existing stone formations were used for the construction, with sculptures carved into the rock.



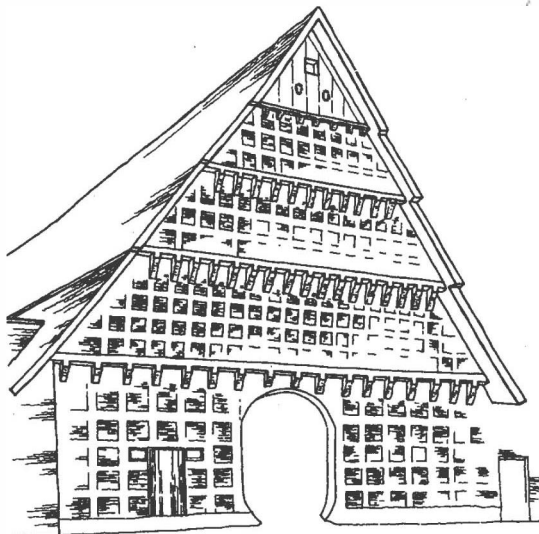
Half-timber construction

Half-timber construction is a medieval building type consisting of wood post-and-beam structure with diagonal bracing and the spaces between wood filled with masonry or mud with horse hair and covered with plaster. Half-timber construction started during the Middle Ages but is still popular because of its strong visual expression. Some early examples date back to the 12th century. By the 13th century half timber construction reached a peak development. The 14th to 16th centuries structures had increasing decorative features, with rich ornaments carved on the wood. A frequent feature, notably in Germany, was floors projected out over the floors below. These overhangs provided three advantages:

- Increased floor area in upper levels, taking advantage of air rights
- Forced rain water to drop off to avoid leaks at timber/masonry joints
- Negative overhang bending reduced positive bending, allowing smaller beams

City Hall Mark Gröningen Germany (1450)

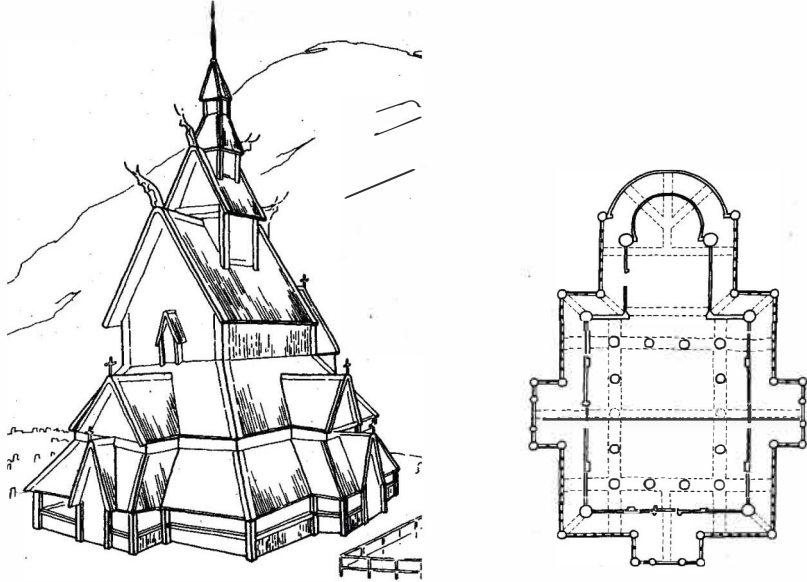
Post sizes of this civic structure increase from top down. This logical response to increasing load at lower levels demonstrates understanding of static principles by the builders. Diagonal braces on both sides of posts make a unique formal vocabulary. This building represents the final development of the rhythmic *Allemanique* patterns.



Farmhouse *Wehlburg* near Quakenbrück, Germany (16th century)

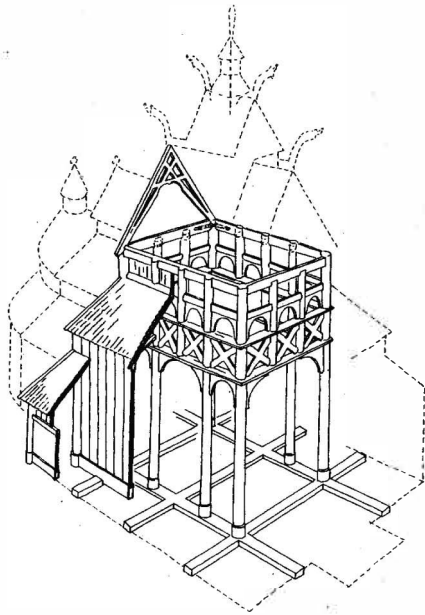
The *Wehlburg* in Northern Germany is considered Germany's most beautiful farm building. The imposing gable, without windows, expresses a unique vocabulary:

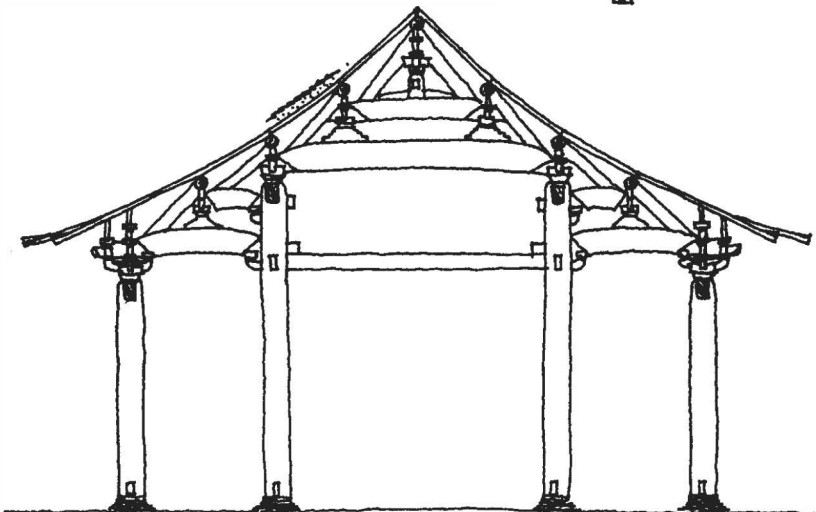
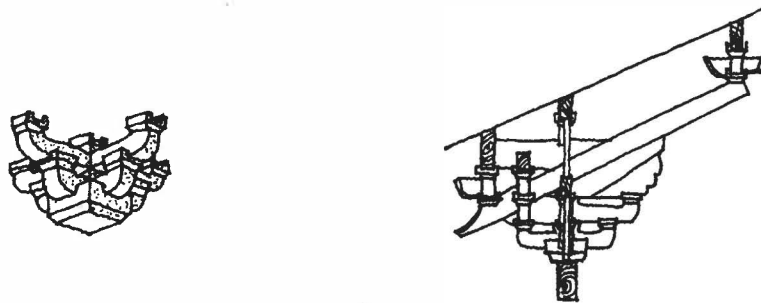
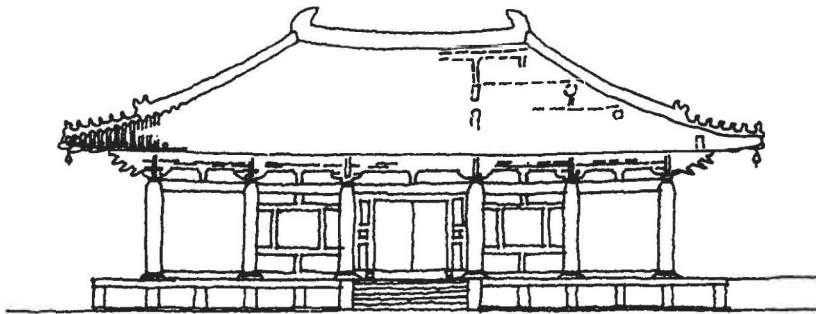
- No diagonal braces are used
- Horizontal struts between posts form square patterns
- Projecting floors feature outriggers which visually emphasize the overhangs
- A large barn door is prominently placed slightly off center



Stave Church Borgund, Norway (ca. 1180 AD)

Borgund is Norway's best preserved stave church, built of treated pine wood with runic inscriptions on the walls, like most stave churches. Viking boat construction and home building developed the tradition of combining art with wood working that culminated in stave churches. In early stave constructions, posts were dug directly into the ground, which caused them to rot. Later builders constructed a base of timber grade beams, or sills, laid on a stone foundation. Vertical posts were mounted into grooves on the sill, with up to four posts per wall. The top of posts, 8 to 9 m (26-30 ft) high, was joined by two sill bands with bracing that provided lateral resistance. Walls were assembled on the ground and raised on top of the foundation sills. There are several stave church types. The simplest have only a nave with the roof supported by walls. Some stave churches have a high center mast supporting the roof top. The most complex have an elevated room in the centre, supported by free-standing posts, and surrounded by a gallery. The wooden entries are often decorated with intricate carvings. The oldest stave churches were built around 1000 AD. Only 28 stave churches remain in all of Norway, the five oldest in the Sognefjord region, all of them are of the 12th century.





Post and beam

Timber post-and-beam

Post-and-beam buildings include beams that are subject to bending. Under gravity load they shorten on top and elongate on the bottom, causing compressive and tensile stress, respectively. Wood is efficient to resist both tensile and compressive stress and thus a good material for post-and-beam structures. Oriental timber structures in China, Japan, etc. evolved over thousands of years. The earliest record of Chinese post-and-beam structures was *A Treatise of Architecture* by Li Chieh, superintendent of construction of Emperor Hui-Tsung (12th century, Sung dynasty). Chinese timber structures are based on a modular system, unifying technical imperatives and artistic expression, relating post-and-beams size to building size and importance. A wood platform provides the base for the timber structures. The principle elements are:

Bracket set (Tou-Kung)

Tou-Kung is an assembly of tou (block) and kung (arm) to transfer load from beam to post, placed above posts but also between posts on beams. The Tou-Kung may have one to five layers of kungs to shorten beam span and allow large roof overhang.

Beam

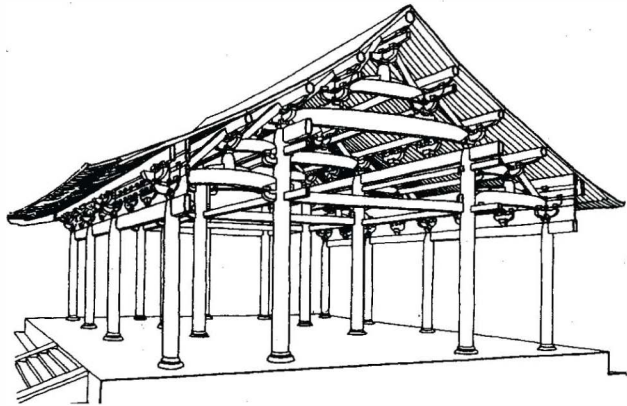
Beam size and shape vary according to position. Typical width/height ratios are 2:3. Beams may be straight or slightly arched, called Yueh-liang (crescent-moon beam).

Post

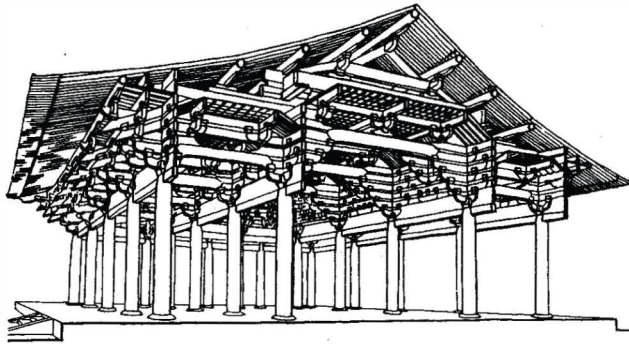
Posts are typically round and either straight or slightly tapered toward the top third. Posts are slightly slanted inward (about 1:100) to give an illusion of stability. Posts increase gradually in height toward the corner (in early structures only).

Roof

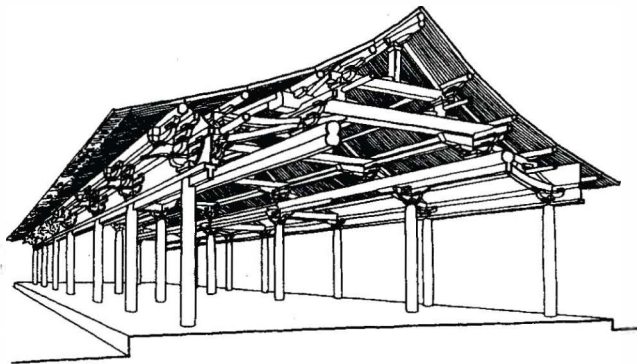
Unique features of Chinese timber structures are curved roofs and large eave overhangs. The concave roof facilitates roof tiles to fit together with water tight joints. The concave roof curvature is achieved by rafters that extend only between round purlins. The large roof overhangs protect the timber structure from rain, an important factor to resist decay. The roof pitch varies from 1:2 for small houses to 2:3 for large halls.



Prototype Chinese temple, from *A Treatise of Architecture* by Li Chieh, court architect of the Sung Dynasty, first published 1103



Fao-Guan temple, Shan-xi province, China (857, Tang Dynasty)



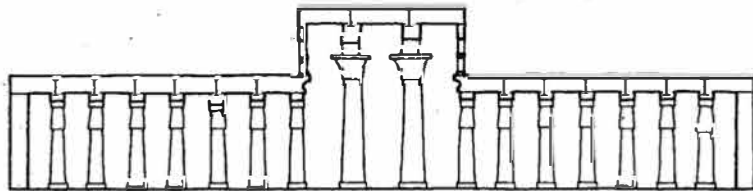
Guan-Sheng Lower Temple, Shan-xi Province, China (1309, Yuan Dynasty)

Stone post and beam

The temples of Karnak and Luxor in Egypt demonstrate the span limit of stone post and beam, due to the limit of stone to resist tensile bending stress.

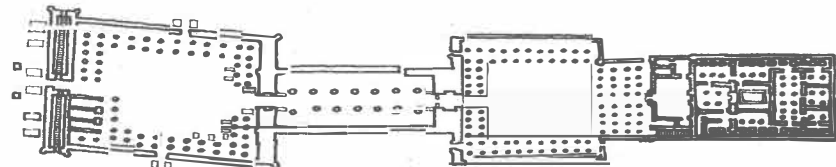
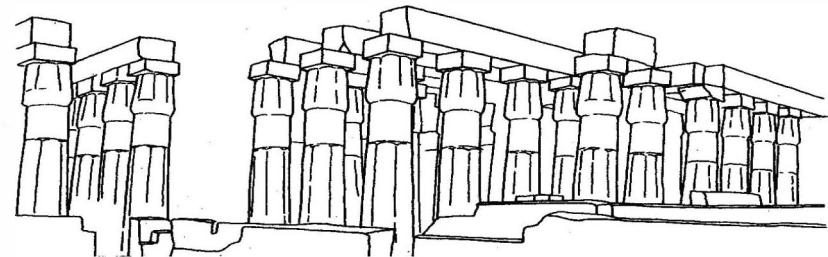
Karnak Temple (1530 - 332 BC)

The central spine of the hypostyle hall between the second and third pylons has tall columns with clerestory windows on both sides. Narrow column spacing, 7m (23 ft) and large bell capitals, result in very short beam spans, a proper response to the limit of stone to resist tensile bending stress associated with long beams.



Luxor Temple (1408 – 1300 BC)

The Luxor temple also has closely spaced posts with small bud capitals, spaced only about 4.5 m (14 ft), resulting in very short spans for beams and stone slabs.





1

Greek temples are highly refined post-and-beam structures, a great artistic and tectonic achievement. However the limit of stone to resist tension was a major limitation to create large spaces. Hence typical spans of post-and-beam Greek temples ranged from only about 4 m to maximum 7 m (13 to 23 ft).

1 Parthenon Doric columns

The Doric order developed in mainland Greece in the 7th century BC based on earlier wood construction, featuring posts with rounded capitals. Columns rest directly on the platform without a base.

2 Ionic columns at Hadrian's Villa

The Ionic order developed at the same time in Greek cities of Asia Minor. The Ionic columns are thinner, with a scroll-like capital and square base.

3 Corinthian columns at Forum Romanum

The Corinthian order started in 335 BC in Athens. It was seldom used in Greece but often used in Roman architecture. Corinthian columns have elaborate capitals of acanthus leaves and square bases.



2



3



1



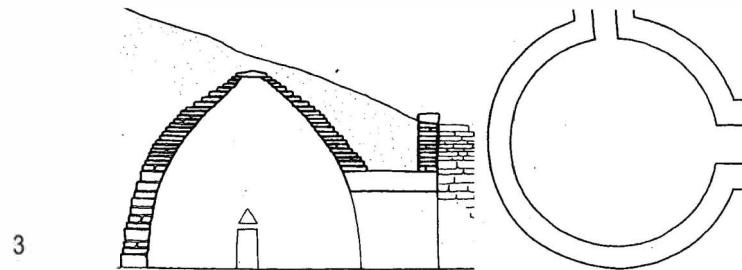
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Arch, Vault, Dome

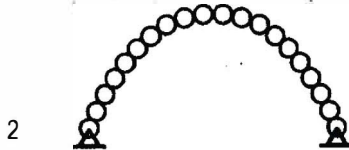
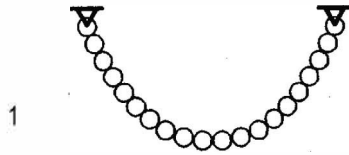
Corbelled arch and dome

Corbelled arches represent early attempts to span larger spaces with stone structures, to exceed the 7 m (23 ft) limits of post-and-beam in stone. Corbelled arches consist of stone masonry with each row cantilevering over the row below and both sides joined on top. Rotated corbelled arches define corbelled domes. Corbelled arches and domes provide longer spans than post-and-beam structures but shorter than true arches. The Citadel of Mycenae in Greece has corbelled arches and domes. The famed Lions Gate, main entry of the Citadel, features a corbelled arch. The tomb of Agamemnon, a corbelled dome in close proximity to the Lions Gate, is the largest corbelled dome with a diameter of 15 m (49 ft), but only about one third the span of the Pantheon dome in Rome.

- 1 Lions Gate, corbelled arch at Mycenae Citadel (1325 BC)
- 2 Tomb of Agamemnon entry, corbelled arch (1250 BC)
- 3 Tomb of Agamemnon, corbelled dome, 15 m (49 ft) diameter (1250 BC)



3



True arch

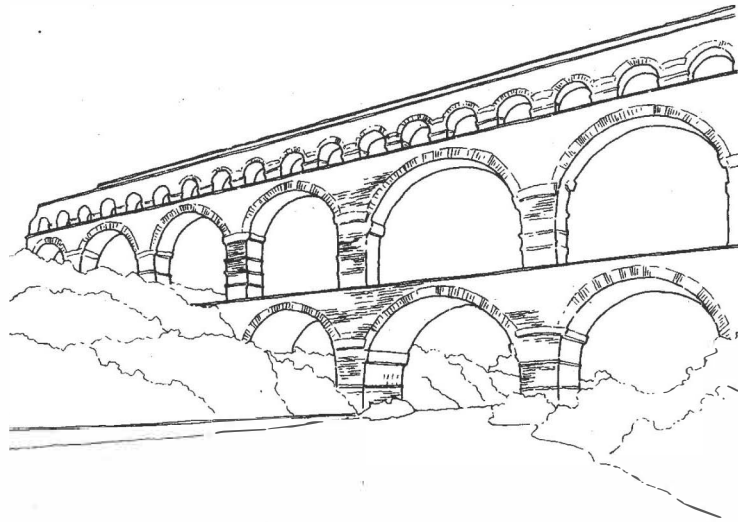
The emergence of arch, vault, and dome structures in ancient Rome was a major advance in technology, allowing much longer spans than post-and-beam structures. Beams resist load in bending which causes stress that varies from compression on top to tension on the bottom, using only half the beam stress capacity. Also, stone used for beams, though strong in compression, is very weak to resist tensile stress. In contrast, arch, vault, and dome structures approximate *funiculars* (the line a chain assumes to resist gravity load in tension). The reversed (upside-down) funicular supports load in compression. However, while flexible tension members adjust their funicular form for any load, a rigid arch may be subject to bending stress if its form varies from the funicular of a given load.

The funicular shapes for common load conditions are:

- Catenary - under uniform load applied along the suspension member
- Parabola - under uniform load applied along a horizontal projection
- Circular - under radial load

Vaults had been used already in early Egypt for small spans, but ancient Rome recognized their potential to allow large spans for buildings, aqueducts and bridges. Though the circular Roman arches, vaults and domes only approximated funiculars, if funicular lines remain within the inner third of a cross section, tensile stress is avoided.

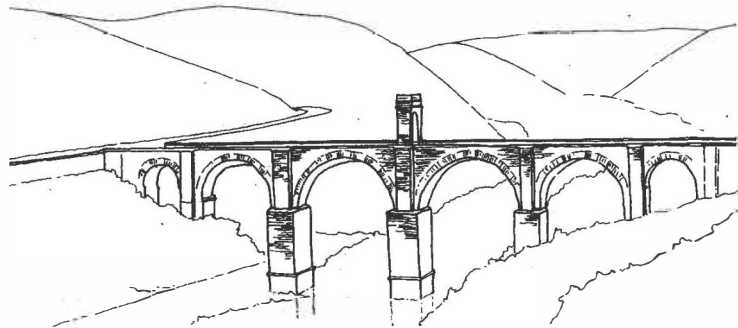
1. Tension funicular
2. Compression funicular
3. Circular arch - funicular at inner third (core) avoids tensile stress
4. Vaulted tomb at Ramesseum, Thebes, Egypt (c. 1300 BC)
5. Fabricius Bridge Rome, twin arch, 80 feet span each (62 - 21 BC)



1

1 Pont du Gard, Nîmes (19 BC – 81 AD)

This monumental Roman aqueduct, begun by Agrippa about 19 BC, was completed over a century later during Trajan's reign. The aqueduct brought water 50 km (30 miles) from springs at Uzès to Nîmes with a total gradient of only 17 m (56 ft). The aqueduct over the river Gard is 275 m (900 ft) long and 49 m (161 ft) high. The largest arch across the river spans about 24 m (79 ft). The first level carries a road. The top water conduit has a gradient of 0.4 per cent. The aqueduct was built of limestone blocks weighing up to six tons each. The two lower levels were built in dressed stone without mortar. Projecting blocks supported a scaffolding during construction. The top level was built of mortar masonry. Two thousand years after its construction, the edifice is still a masterpiece of technical prowess and beauty.



2

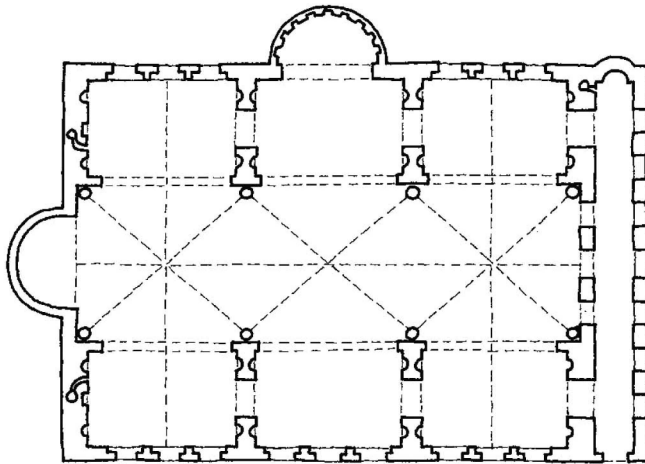
2 Alcántara Bridge, Spain (105 – 118 AD)

This Roman bridge across the Tagus river in Toledo, 194 m (636 ft) long, is supported by six arches with spans that range from 13.8 m (45 ft) to 27.4 m (90 ft). This fine example of a Roman bridge was built of stone masonry without mortar. Built during the reign of the Roman Emperor Trajan, it is also known as Trajan Bridge. The bridge was of great military significance, since it is one of the few bridges across the Tagus River, which is wide at this point and goes through a series of canyons that makes crossing very difficult. Due to its military significance, the Alcántara bridge has a turbulent history: it was partially destroyed in 1214 by the Moors and restored in 1543 under Carlos I. In 1778 it was again restored from war damage by Carlos III. In 1809 the second arch from the south was destroyed in the Napoleonic wars and restored from 1859 - 1869. The bridge takes its name from the Arabic for bridge: Alcántara.

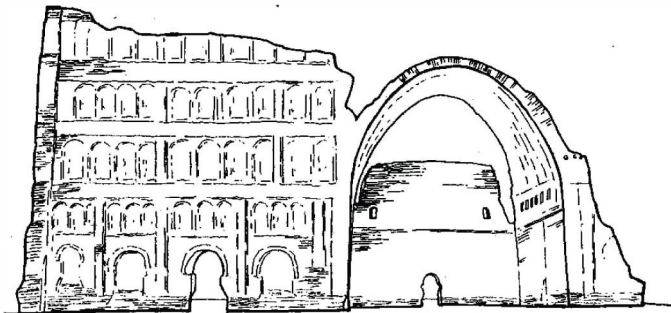


1 Basilica of Constantine, Roman Forum (308-312 AD)

The Basilica of Constantine, also called Basilica of Maxentius, begun by emperor Maxentius and completed by Constantine was used as public court. Basilica is defined as an oblong building with semi-circular apse. The rectangular plan is oriented East-West, covering an area of 100×65 m (328×213 ft) with a central nave between two lateral aisles. The Basilica features vaults (linear extrusion of arches). The vaulted construction, similar to baths halls, was a departure from traditional basilicas which usually had flat timber roofs. The central nave of 80×25 m (262×82 ft) was covered by three cross vaults, supported by eight Corinthian columns. Each of the two aisles features coffered vaults of about 23 m (75 ft) span. Of the original building only the three vaults of the north aisle remain. The rest probably collapsed in an earthquake 847 AD.



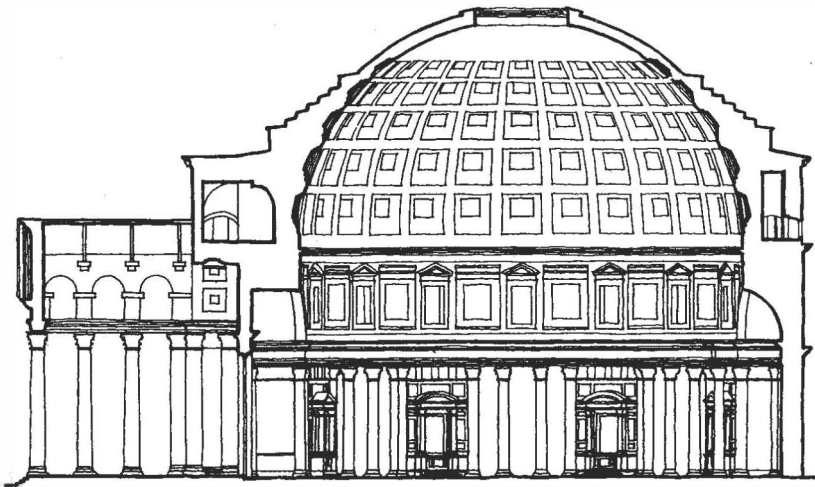
1



2

2 Palace Ctesiphon, Iraq (3rd century AD)

Ctesiphon, the winter palace of Parthian and Sassamid empires, is located on the northeast bank of the Tigris river south of Baghdad. Ctesiphon owes its fame to the grand vaulted banquet hall, with 25.5 m (84 ft), the largest vault in ancient history. The parabolic vault, a common form in Mesopotamia, is a closer approximation of the funicular than the circular vault of the Basilica of Constantine and other structures of ancient Rome. The Ctesiphon vault of thin brick was presumably built without centering during construction. At the vault's lower part bricks are laid flat, similar to a corbelled arch, but toward the top bricks are perpendicular to the line of thrust, as in a true arch.

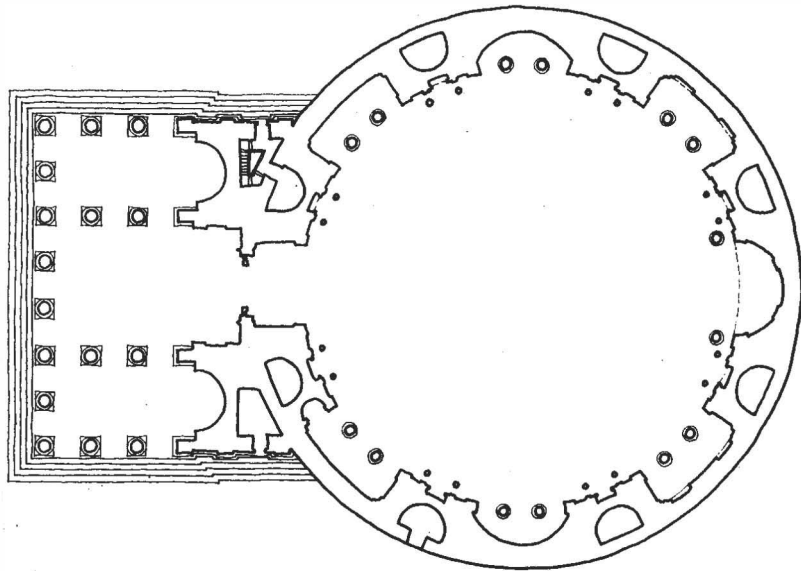


Pantheon Rome (120 AD)

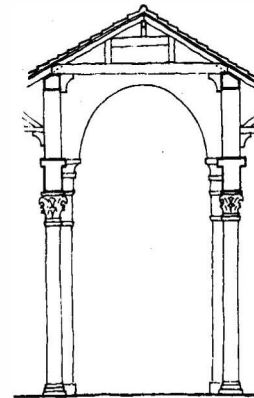
The Pantheon was built as a Roman temple during emperor Hadrian's reign and consecrated as a Catholic Church in the early 1500s. The Pantheon dome was a major breakthrough. The 43.3 m (143 ft) span increased the 7 m (23 ft) span limit of previous post-and-beam structures about ten-fold and was the longest span for 17 centuries. In 1824 the 45.7 m (150 ft) wood truss of the Moscow Manege (page 25) exceeded it. The Florence dome spans 42 m to the face and 45.5 m (149 ft) to the octagonal corners. Thus the comparable face-to-face span is less than the Pantheon. The Pantheon dome consist of concrete and brick in tapering courses, 6 m (20 ft) thick at the base and 1.2 m (4 ft) on top, with heavy basalt aggregate at the base and lighter pumice on top. The half-dome rises from a cylindrical base to a height equal to the diameter, inscribing a sphere. Ballast rings around the dome base resist outward thrust to minimize tensile stress. Transportation of the 16 granite portico columns was a major task. The columns were quarried in Egypt's eastern mountains, dragged on wooden sledges to the Nile, shipped to Alexandria and across the Mediterranean to the Roman port of Ostia Antica. From there they were barged up the Tiber river.

The Pantheon's long span is often credited to the use of concrete. However, Roman concrete without steel reinforcement is equally weak in tension as stone or brick. The brick domes of Florence and S. Peters, have similar spans. The Pantheon long span is due to the funicular compression rather than post-and-beam bending. The Pantheon dome had a profound and lasting influence on architecture for many centuries.

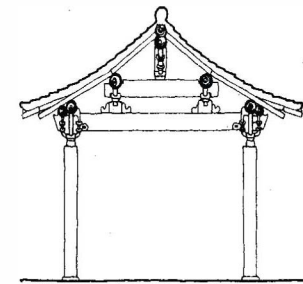
The Pantheon portico trusses are similar to Chinese temple trusses of layered chords.



Pantheon portico



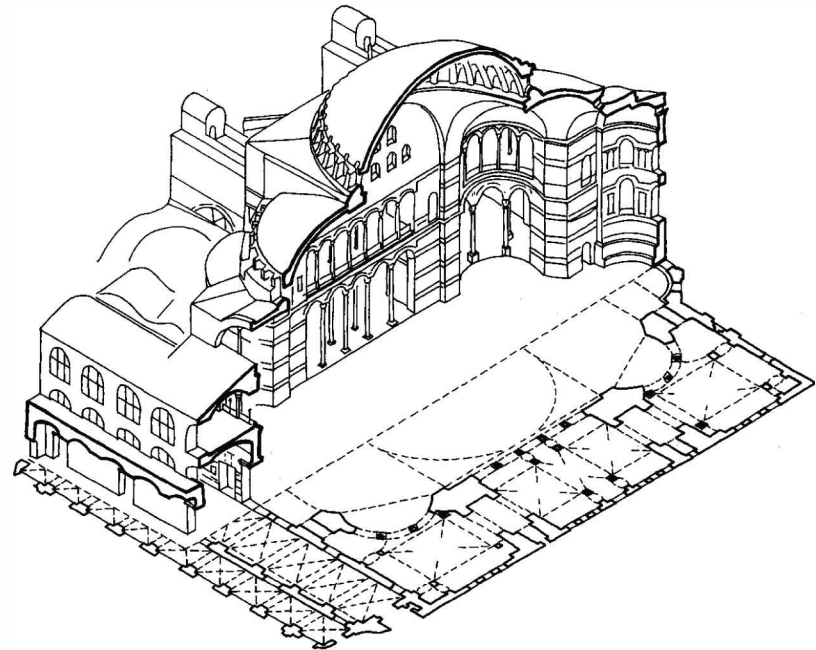
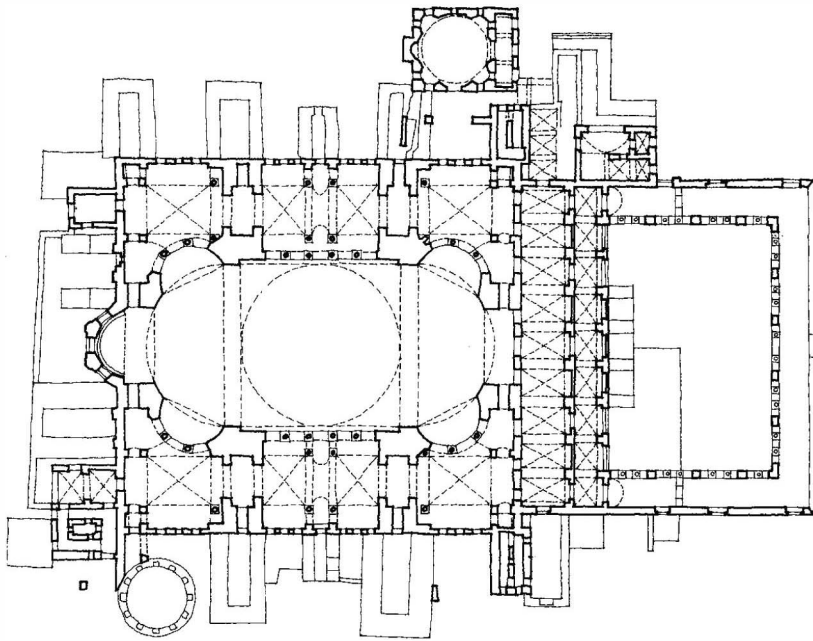
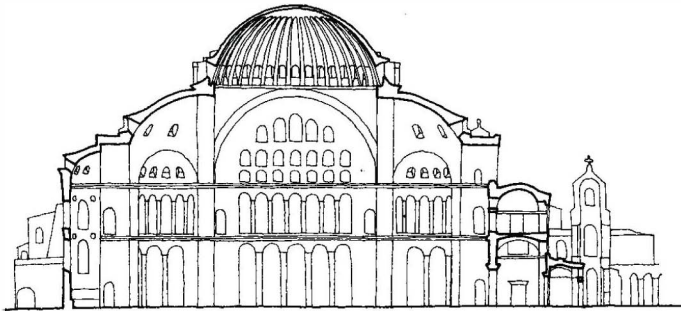
Chinese temple

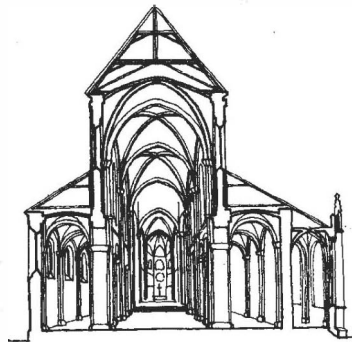
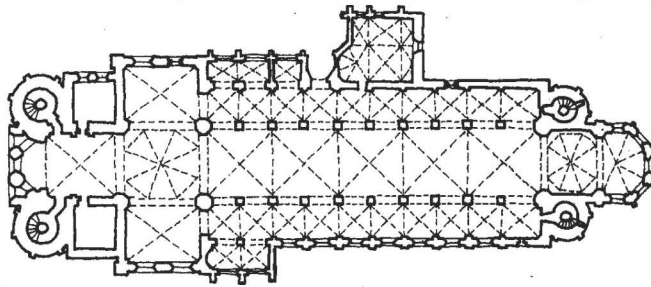


Hagia Sophia Istanbul (532 – 537)

The Emperor Justinian commissioned mathematics professor Anthemius of Tralles and architect Isidorus of Miletus to design this most beautiful church associated with the creative Byzantine period of over one thousand years. Hagia Sophia was built in only five years but collapsed in an earthquake and its replacement in 563 with a higher profile dome had to be repaired after partial collapses in the ninth and fourteenth centuries.

The dome's shallow profile avoids the hoop tension at the base of half-spherical domes, but increases the outward thrust of radial pressure. This thrust is resisted by buttress piers north and south and by half domes east and west. The brick dome is supported by four arches rising from four large piers. Four pendentives make the transition from a square base to the round dome. The interior is flooded with light from many windows, including a window row at the dome base. The dome diameter is only 32.5 m (107 ft), but combined with two half domes covers an area of 32.5x81 m (107x266 ft). The church was converted to a mosque by Sultan Mehmet in 1453.

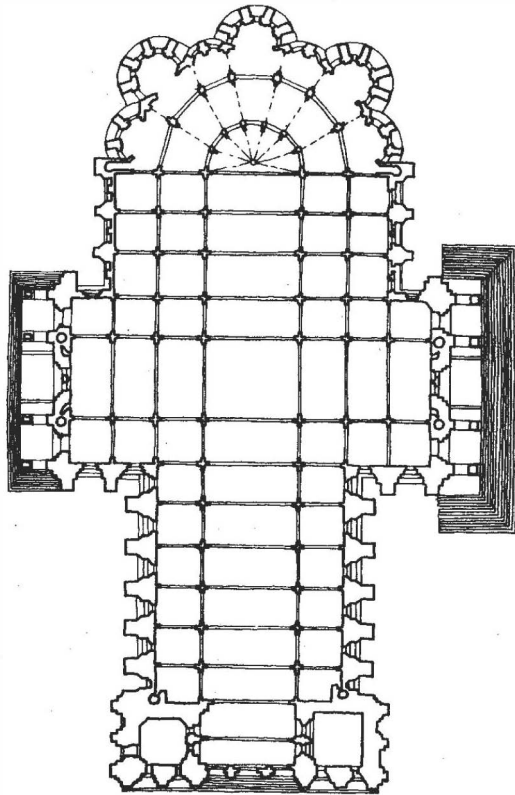
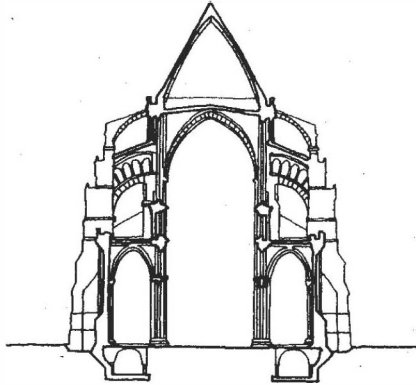




Cathedral of Worms, Germany (1130 – 1230)

The Cathedral (also called dome) of Worms is located at the highest hill of Worms. Since this hill is protected from flooding of the Rhine river, it was the site of early settlements from 300 BC. Celtic tribes were followed by Germanic tribes and the Romans, who built an administration center on the hill. This center of one square kilometer became a province capital. The decline of Rome caused them to vacate Worms in 401 AD. Twelve years later Burgundy was to secure the Roman frontier in Worms but, trying to seek independence of Rome, they were beaten by the Romans in a battle 435 AD. One year later the Huns destroyed much of the settlements.

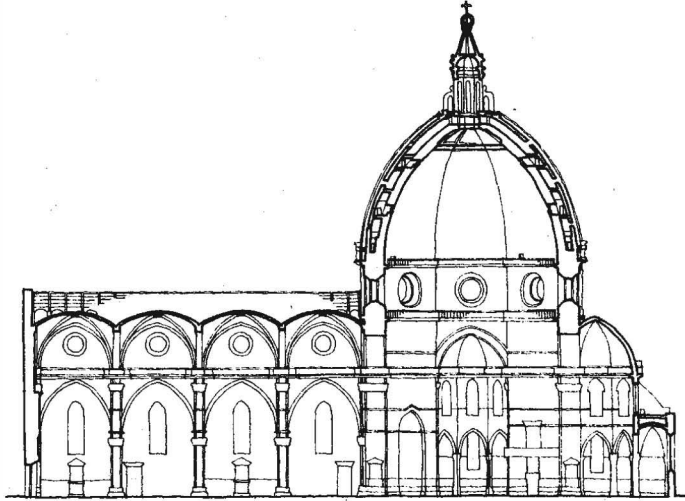
The dome of Worms is representative of the Romanesque period, like the nearby domes of Mannheim and Speyer. The plan is based on the Latin cross of east-west orientation with apses and two round towers at both ends and an octagonal low tower on one side. Clerestory windows flood the interior with light. The cathedral features round Roman arches and cross-vaults. Lateral thrust of the vaulted ceiling is resisted by wall pilasters. Only the ground plan and the lower part of the western towers belong to the original building, consecrated in 1110 AD. The remainder was finished by 1181. The west choir and vaulting were built in the 13th century. The elaborate south portal was added in the 14th century. The cathedral is 110 m (362 ft) long and 27 m (89 ft) wide, or 36 m (118 ft) including the transepts near the west end. The nave height is 26 m (85 ft).



Chartres Cathedral, France (1194 – 1260)

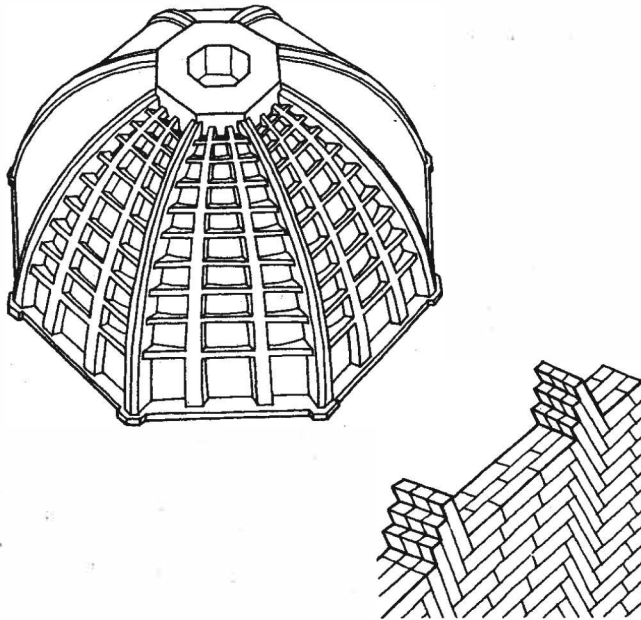
Chartres Cathedral, one of the greatest achievements in the history of architecture, is almost perfectly preserved including the original stained-glass windows. Chartres cathedral is a great example of Gothic architecture. The large nave, the sculptured porches and beautiful stained-glass windows are a masterpiece of Gothic architecture. But Chartres Cathedral was a new principle and prototype of 13th century architecture with a conservative structure. Lateral thrust of the vaulted ceiling is resisted by flying buttresses that are more massive than at other Gothic cathedrals, notably of Notre Dame in Paris. The spacious nave provides an unbroken view from the western end to the dome of the apse in the east. Clustered columns rise dramatically to pointed ceiling arches. Clerestory windows flood the interior with natural light.

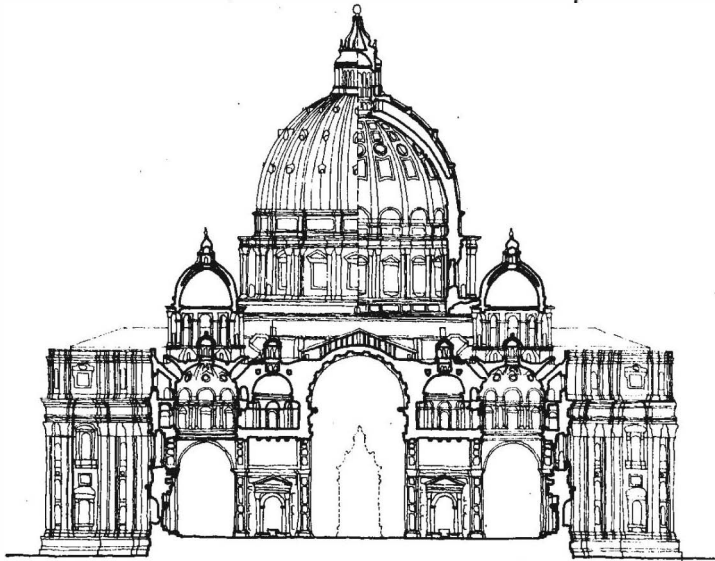
The cruciform plan features a 128 m (420 ft) long nave, and narrow south and north transepts. The rounded east end includes five semi-circular chapels. The massive flying buttresses resist the outward thrust of very high vaults, at the time of construction the highest in France. The High Gothic cathedral at Chartres has four rectangular rib vaults, instead of six square vaults, as earlier Gothic cathedrals. The support structure allowed large stained glass windows and a high space.



Florence Cathedral (1296 -1436)

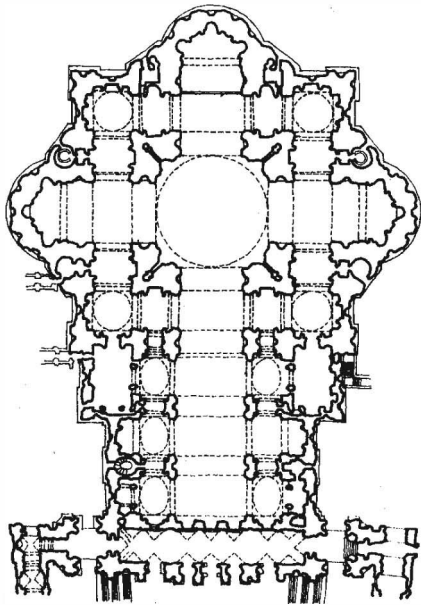
Construction of the Florence cathedral Santa Maria del Fiore began in 1296 in the Gothic style. In 1366 an octagonal dome of 42 m (138 ft) span was later added at the east end of the nave. Since the dome starts 54 m (177 ft) above ground it would have been difficult to find timber long enough to support formwork at such a height. The dome was not built until the early 15th century, when Filippo Brunelleschi, a goldsmith and sculptor, proposed building the dome without formwork. To demonstrate his method Brunelleschi built a 1:12 model in brick. His design was accepted and built under his supervision from 1420 to 1436. The bricks were laid on sloping beds, perpendicular to the line of thrust. Each layer of bricks was stable after completing a ring. To stabilize incomplete rings during construction, masons placed some bricks upright to connect the next ring, an arrangement known as herring-bone pattern. The dome has a unique form, approximating a parabolic profile, the ideal funicular which also reduces lateral thrust at the base. The top is pointed in response to the point load of the lantern above. To increase the dome thickness to resist buckling without increasing dead weight, the dome consists of two shells joined by radial and hoop ribs. The ribs of stone resist compression and transfer shear from inner to outer shell. However one hoop rib near the base is of wood to resist the tensile hoop force at the base. The dome of Florence demonstrates Brunelleschi's genius long before the formal development of the respective static theory.

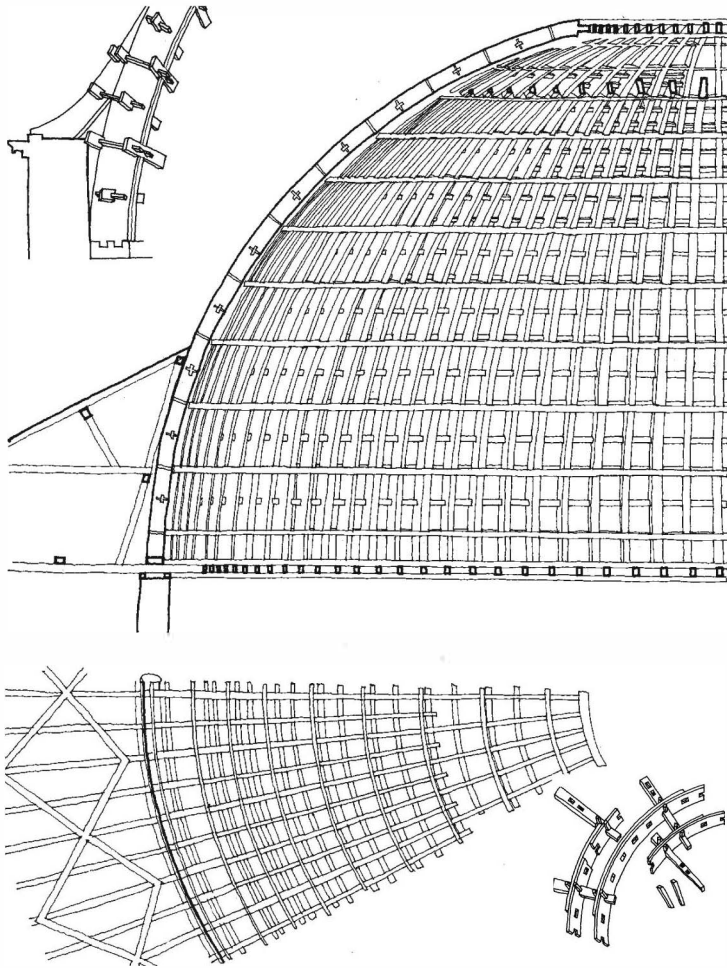




St Peter's Dome, Rome (1546-90)

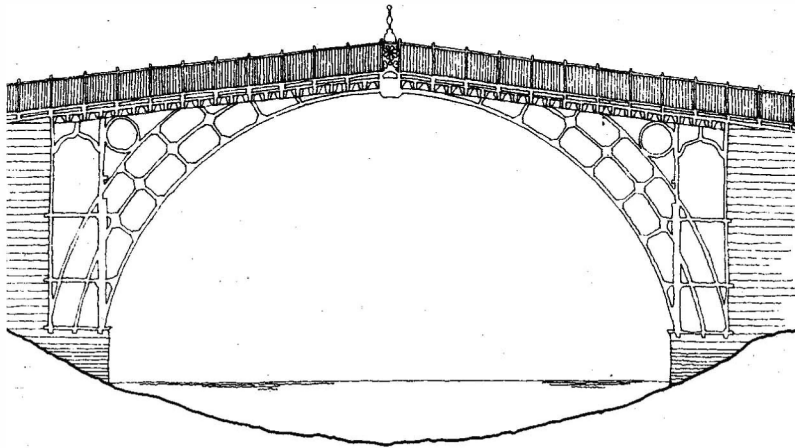
The dome conceived by Donato Bramante at the outset in 1503 was designed with a single masonry shell that was discovered not to be feasible. San Gallo designed the double shell, and Michelangelo improved it. The actual dome was built between 1585 and 1590 by architect Giacomo della Porta and engineer Domenico Fontana. Fontana built the lantern on top of the dome the following year. Similar to the dome of Florence, the dome of St Peter's consists of two brick shells approximating a parabolic profile. The original iron tension rings placed near the dome base were apparently insufficient. After serious cracks appeared by the 18th century engineers added several more tension rings to resist the outward thrust at the dome base. The dome rises above a ring of twin Corinthian columns. Four large piers, initially designed for Bramante's heavy single masonry shell, support the dome.





Philibert de L'Orme wood dome (1561)

The French architect Philibert de L'Orme was born about 1512 and died 1570. In his youth he went to Rome and would probably have remained there if a cardinal and others did not urge him to return to his native Lyon in 1536. In Rome he probably was inspired by domes. In 1561 he published his invention of wood domes assembled from short wood boards. His objective was to reduce weight and thrust on support structures by a lightweight dome of small wood boards instead of heavy masonry or concrete. His domes consist of radial ribs braced by ring girths. The ribs consist of two to three boards nailed together. The ring girths consist of alternating single and twin boards, joined to the ribs by brackets. Single girths pass through the ribs, but twin girths are attached to both sides of ribs to resist rib twisting. De L'Orme built several domes with his invention. However, none of them still exists. His largest dome for the Murette Castle spans 17m (56 ft). The design he proposed for a basilica would have covered 78x48 m (256x158 ft). At left is George Moller's design for the Ludwig Church in Darmstadt, Germany that features a 33 m (108 ft) span.



Coalbrookdale Bridge (1775-79)

Architect: Thomas Pritchard

Designer: Abraham Darby III

In 1773, Thomas Pritchard proposed an arch bridge to span the Severn Gorge; but Pritchard died in 1777 before the bridge was built. Local businessmen commissioned Abraham Darby, a local ironmaster, to build the bridge. Darby's bridge was the first bridge entirely of cast iron. As owner of an iron mill, Darby built the bridge to advertise the use of cast iron for structures. The bridge spans 100 ft (30.5 m) assembled of prefab elements put together in three months without obstructing river boat traffic. When the bridge was complete, artists, writers, and engineers came from all over the world to admire the unique design. Assembled of discrete elements, the bridge is an important contribution to the process of prefabrication which evolved during the Industrial Revolution. The arch resists load primarily in compression, an important factor since cast iron is weak in tension. The bridge is considered a British National Monument.



Garabit Viaduct (1880-84)

Engineer/builder: Gustave Eiffel

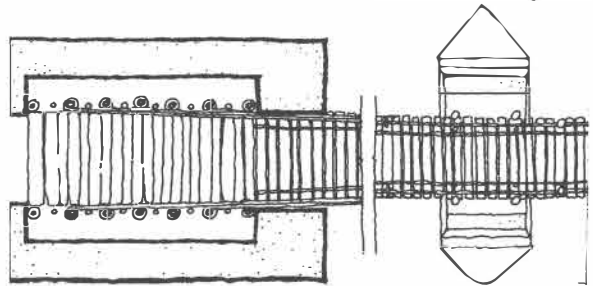
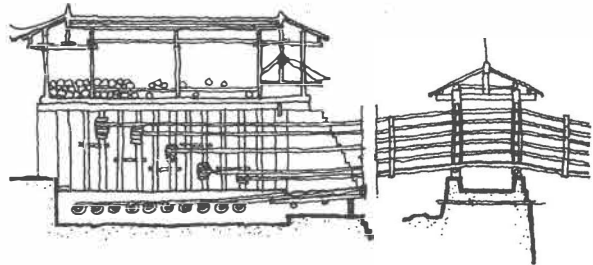
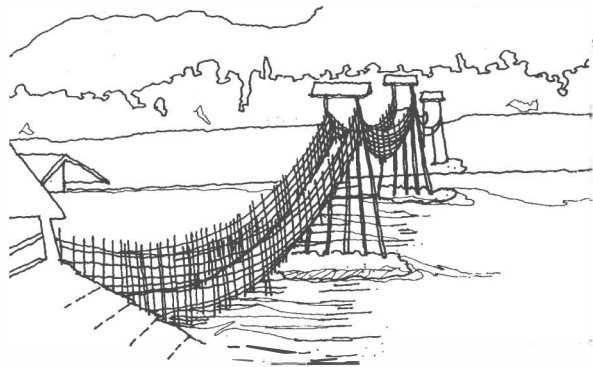
The Garabit Valley in France's *Massive Central* prevented railroads from reaching southern France until Gustave Eiffel found a solution to bridge it. Compared to a solid girder bridge, Eiffel's iron truss arch reduced wind pressure and bending but increased stiffness. The arch form resists load primarily in compression rather than less efficient bending. The triangular truss panels provide stiffness and minimize wind load due to openness. With a length of 565 m (1854 ft) and an arch span of 165 m (542 ft), the viaduct was a major engineering achievement for its time.

Suspension Structures (after Richard Gensert)

Ancient suspension bridges in China and South America date back as far as 1350. Early pedestrian suspension bridges had the road bed directly attached to suspension ropes and required dead load to resist wind uplift.

Min River Bridge, China (1803)

The Min River bridge in Szechwan, China, a fiber rope suspension bridge, has a total length of 551 m (1808 ft), with two intermittent wood pylons.



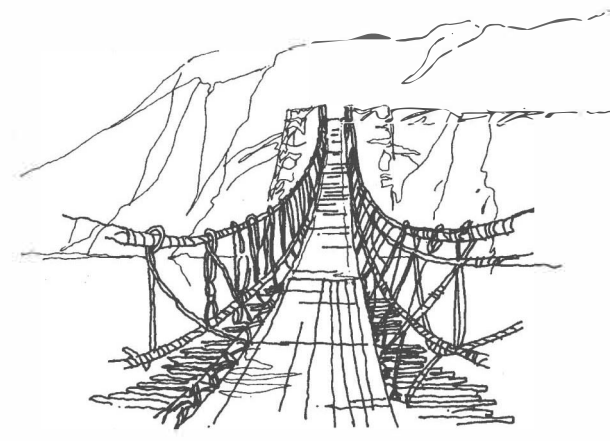
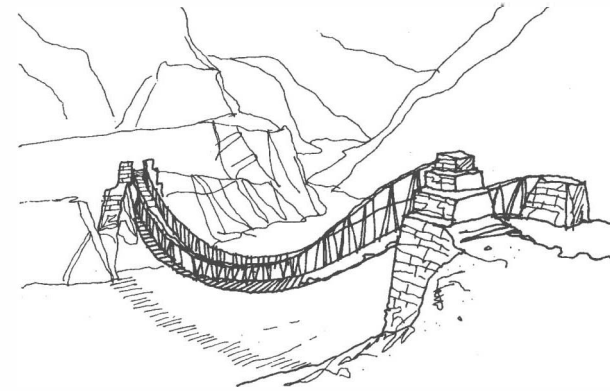
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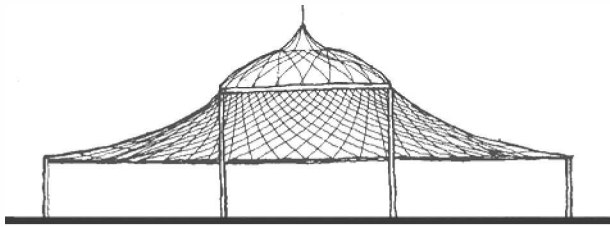
Pampas River Bridge, Peru

Bottom:

Apurimac River Bridge, Peru (1350 AD)

(Inka bridge, 45 m (148 ft) span, lasted 540 years)

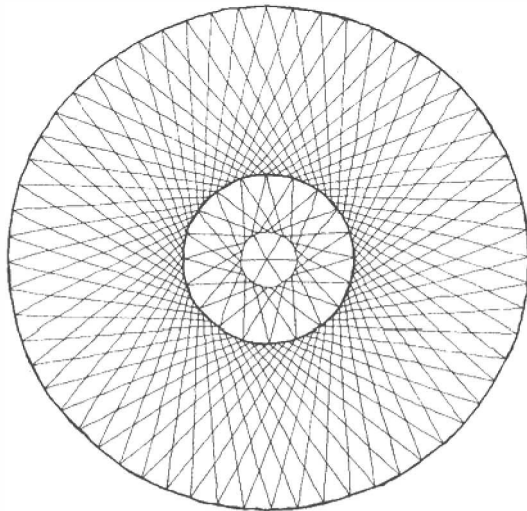




Nishni Nowgorod Exhibit pavilion (1896)

Engineer: Vladimir Suchov

The great Russian engineer Suchov designed this first anticlastic roof for a circular pavilion (one of four pavilions by Suchov) for the 1896 Russian exhibit at Nishni Nowgorod. The configuration of nearly straight cables generates an anticlastic roof curvature, similar to a parabolic paraboloid. The tension roof net extends from a peripheral compression ring of 68 m (223 ft) diameter to an inner tension ring of 25 m (82 ft) supported by posts. The roof net consists of a mesh of 640 steel bands, joined by rivets at their intersections. Suchov's visionary design of this anticlastic roof provided stability for both gravity load and wind uplift. Vladimir Grigorievich Suchov, 1853 to 1939, was a creative and visionary engineer. After his engineering education at the Moscow Technical University, he participated in an excursion to the US in 1876. In 1878 Suchov moved to Baku to work in oil deposits and as chief engineer for the first pipeline in Russia. In 1878 he developed a cylindrical oil storage reservoir, followed by several other inventions, related to oil exploration. About 1885 Shukhov began to build the first Russian tankers. From 1886-89 Shukhov with colleagues developed Moscow's new water supply system. In 1892 Shukhov built his first railway bridges and started the development of roof structures. He designed large glass vaults for the GUM department store and the Moscow rail station.





1



2



3

The inherent beauty of suspension bridges is because they represent the global bending moment and thus eliminate bending, but clearly express the forces acting on them. The first suspension bridge with flat roadbed to allow vehicular traffic was patented in 1808 by James Finley, a judge. Early flatbed suspension bridges had chain link “cables,” until John Roebling developed a technique to spin suspension cables on site and used it first to build the Allegheny and Monongahela River bridges in Pennsylvania then the Niagara and Brooklyn bridges in New York. John R bbling was born 1806 in M lhausen, Germany and studied engineering at the Royal Polytechnic school of Berlin before emigrating to the United States.

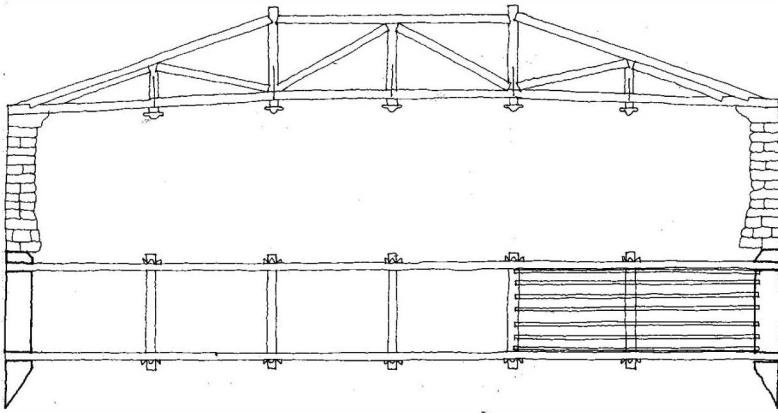
1 & 2 Chain-link Bridge Budapest (1842-49)

Designed by the English engineer T W Clark, the chain-link bridge of Budapest was the first bridge to span the Danube river, connecting the two city parts Buda and Pest. The bridge is 380 m (1247 ft) long.

3 Golden Gate Bridge San Francisco (1933–37)

Designed by J Straus and C Ellis, the Golden Gate bridge of San Francisco has a main span of 4200 feet (1280 m) between the two towers. It was built using the same technique of making suspension cables on site invented by John R bbling. The R bbling company actually fabricated the Golden Gate Bridge cables.

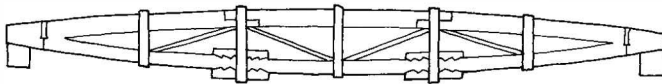
Photo courtesy Rich Niewiroski Jr.



Truss

The evolution of trusses started with roof trusses, based on the concept of triangular panels of intrinsic stability. The development of long-span trusses is credited to Palladio with his design of the Cimone River bridge. The development accelerated during the 19th century, with the development of the Warren, Pratt and other trusses.

Cimone River bridge by Palladio (16th century) 30 m (98 ft) span



Parabolic trusses by Ludwig Laves (1840)

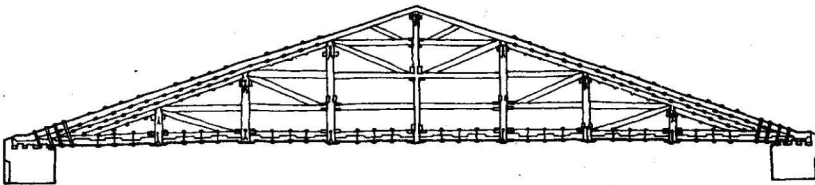
Under uniform load the parabolic truss results in uniform stress in top and bottom chords and no stress in the vertical and diagonal web bars. However, web bars are needed to prevent chord bar buckling and resist non-uniform load. In response to top compression and bottom tension, both trusses have large top chords and small bottom chords.



Wood truss Manege, Moscow (1823 – 24)

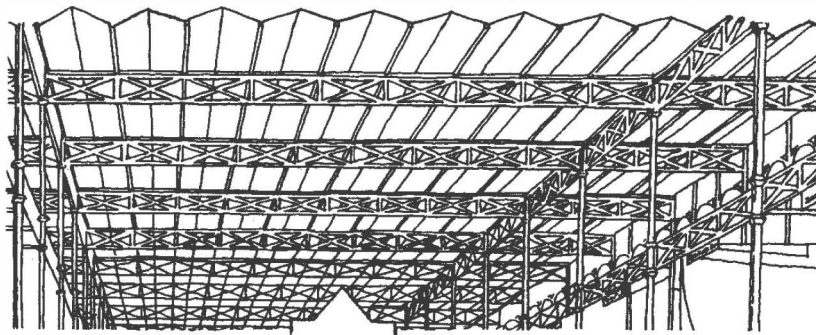
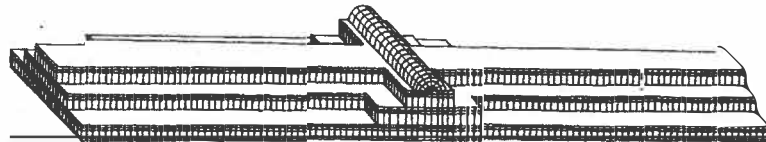
Engineer: Betancourt

With 45.7 m (150 ft) span this roof truss was the first structure after 17 centuries to exceed the Pantheon span of 43.3 m (142 ft).



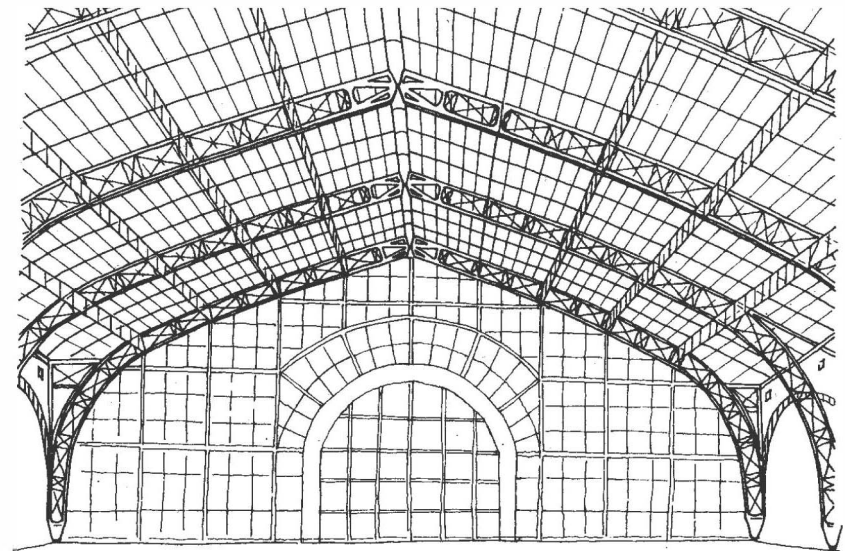
Crystal Palace, London (1851)

John Paxton, a gardener, designed the Crystal Palace for the International Exhibition of 1851 in London. The exhibition was to showcase the industrial, military and economic achievements of Great Britain. John Paxton used his experience of building glass green houses for the Crystal Palace. Prefabricated parts facilitated rapid assembly and pioneered a new method to assemble prefab parts rather than building with traditional site construction. Identical prefab panels of triangular configuration were assembled into long-span trusses. The lightness of these trusses covered with glass created a new sense of grand open spaces devised by industrial methods.



Galerie des Machines Paris (1887 - 89)

Designed by Ferdinand Dutert, Charles Leon and Stephen Sauvestre, the Galerie des Machines for the 1889 International Exhibit in Paris was the French response to the Crystal Palace of the 1851 London exhibition. The size of 115 x 420 m (377 x 1378 ft) was an enormous span for the time. The three-hinge frame allowed thermal expansion and uneven settlement without causing secondary stress. The three-hinge concept was widely used in 19th century railroad stations and is still used in contemporary facilities, such as the Waterloo station in London.



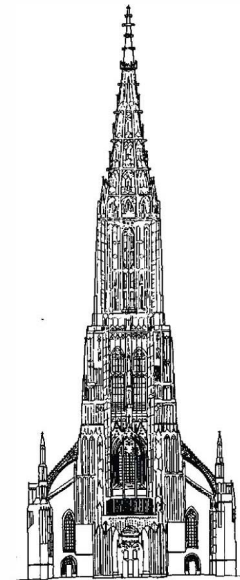
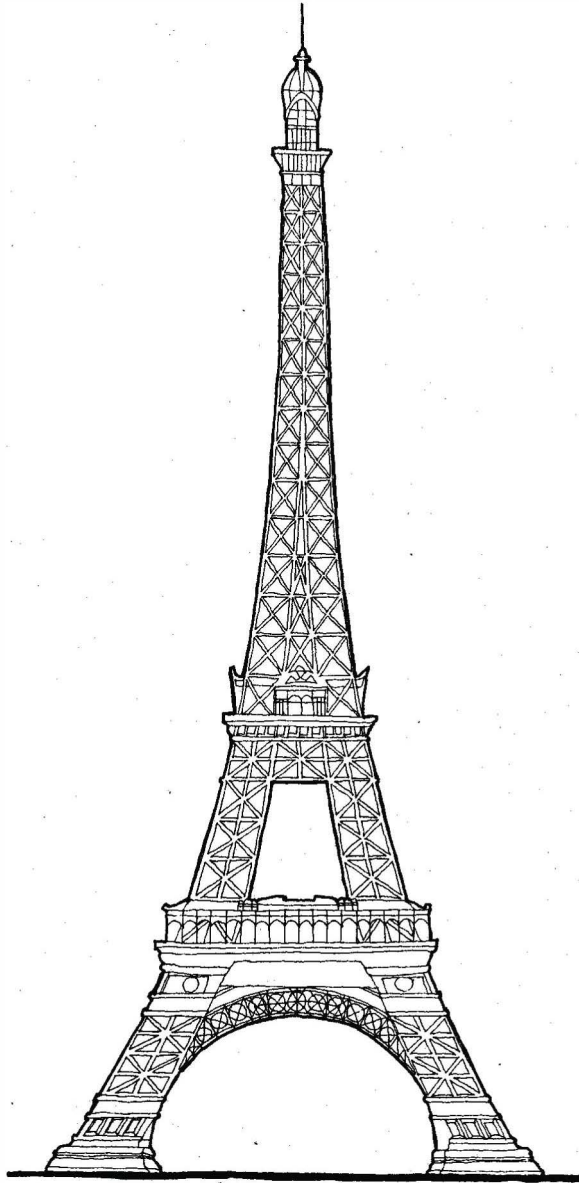
Skyscraper

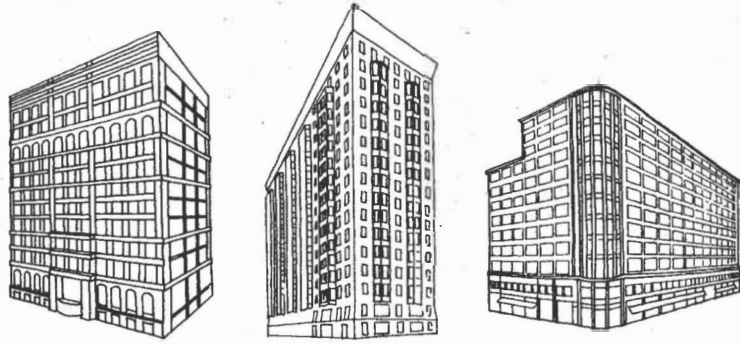
Eiffel Tower, Paris (1887- 89)

The Eiffel Tower, designed by Gustave Eiffel, evoked much controversy in the artistic community due to its unusual form and material, replacing traditional stone with iron. However, the form was a logical response to global bending under lateral wind load, since iron reduced the weight and thus gravity load compared to stone. The open truss also reduced exposure to wind, and the triangular structure provided stiffness for reduced drift. The Eiffel Tower rises to a height of 324 m (1063 ft), the tallest structure for about 40 years. The broad base provides stability; the narrow top reduces wind load. Two belt trusses joining four parabolic tower segments transfer global shear to engage the tower in tension and compression on the windward and leeward sides respectively.

Ulm cathedral (1377 – 1890)

With a height of 161.53 m (530 ft), the tallest church steeple in the world, the Ulm cathedral, prominently located at the city center of Ulm, Germany, is a famous example of Gothic architecture. Built of sandstone masonry, buttresses on both sides of the tower provide lateral stability.



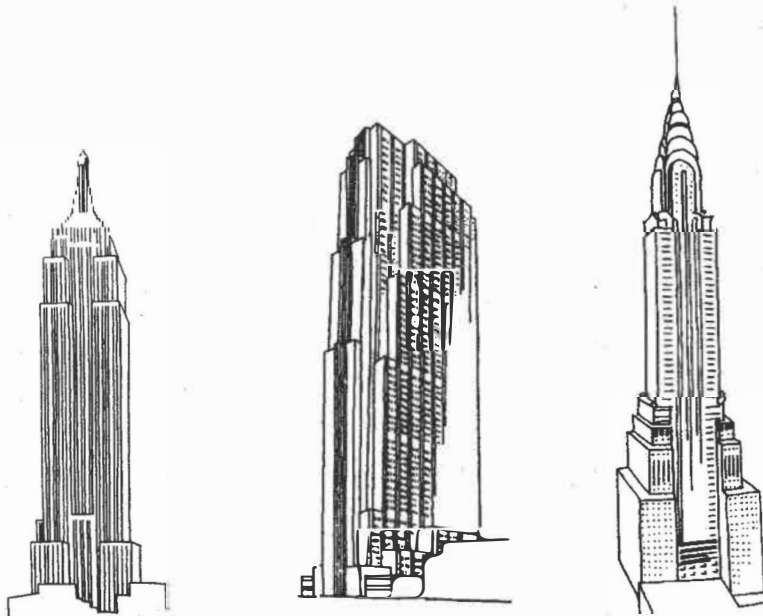


High-rise development

High-rise buildings were made possible primarily by two developments: steel skeleton, and elevators with automatic safety breaks (invented by Otis, 1853)

Top left-to-right:

- **Home Insurance Company, Chicago** (1883 – 1885)
Architect: William Le Baron Jenney
10 stories, 180 feet (55 m), first steel skeleton structure, masonry cladding
- **Monadnock Building, Chicago** (1891)
Architect: Burnham and Root
16 stories (the last tall building in Chicago with load bearing walls)
- **Carson, Pirie, Scott Department Store, Chicago** (1899)
Architect: Louis Sullivan
12 stories (initially 9 stories, 3 stories added 1903)



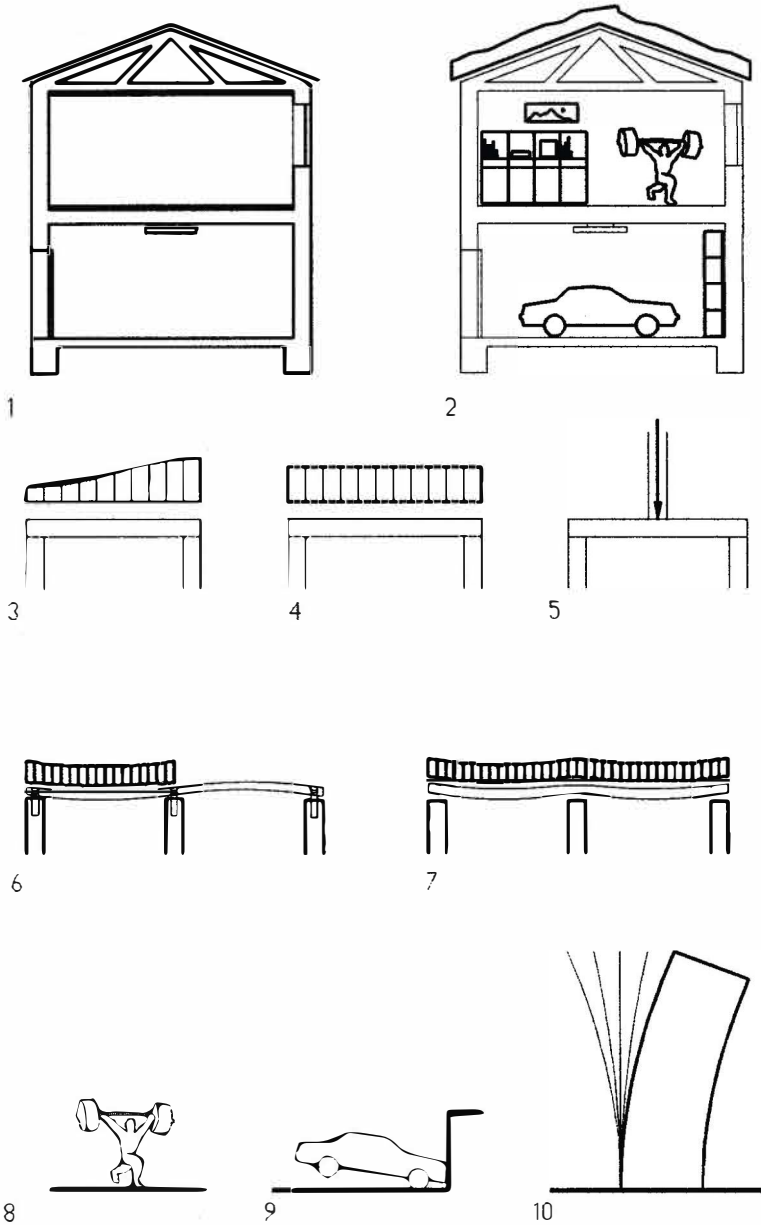
Bottom left-to-right:

- **Woolworth Building, New York** (1911 – 13)
Architect: Cass Gilbert
52 stories, 792 feet (241 m)
- **Rockefeller Center, New York** (1931 – 40)
Architect: Hofmeister, Corbett, Hood
70 stories, 850 feet (259 m)
- **Chrysler Building, New York** (1930)
Architect: William Van Allen
85 stories, 1046 feet (319 m)
replaced 1931 as tallest building by the Empire State Building of 1250 ft (381 m)

2

Load

Understanding loads on buildings is essential for structural design and a major factor in defining structural requirements. Load may be static, like furniture, or dynamic, like earthquakes, or impact load, like a car hitting a building. Load may also be man-made, like equipment, or natural like snow or wind load. Although actual load is unpredictable, design loads are usually based on statistical probability. Tributary load is the load imposed on a structural element, like a beam or column, used to design the element. All of these aspects are described in this chapter.



Introduction

Structures must resist various loads, classified as follows:

- 1 Dead load (DL) *: structure and permanently attached items (table 2.1)
- 2 Live load (LL) *: unattached items, like people, furniture, snow, etc (table 2.2)
- 3 Distributed load (random – snow drift, etc.)
- 4 Uniform load (uniform distribution)
- 5 Point load (concentrated load, like posts, etc.)
- 6 Uniform load on partial beam, more critical than full load
- 7 Negative bending over support reduces positive bending
- 8 Static load (load at rest)
- 9 Impact load (moving object hitting a structure)
- 10 Dynamic load (cyclic loads, like earthquakes, wind gusts, etc.)

Wind and earthquakes are **lateral loads** (loads that act primarily horizontally)

* Classification as DL and LL is due to the following:

- Seismic load = mass x acceleration (mass is primarily DL)
- Dead load can resist overturning
- Permanent DL can cause material fatigue
- DL deflection may be compensated by a *camper* (upward deflection)
- On beams with more than two supports partial load may be more critical than full load; thus LL is only considered if it is more critical

Dead Load (table 2.1)

Dead load is the weight of the structure itself and items permanently attached.

Dead load defines the building mass for seismic design. Approximate dead loads are:

- Wood platform framing: 14 psf (671 Pa)
- Wood platform framing with lightweight concrete: 28 psf (1.2 kPa)
- Steel framing with concrete deck: 54 to 124 psf (~3-6 kPa)
- Concrete framing 120 to 200 psf (~6-10 kPa)

Table 2.1. Material weight		
Weight by volume	US units	SI units
Masonry / concrete / etc.	pcf	kg/dm ³
Brick	120	1.92
Concrete masonry units (CMU)	100	1.60
Light-weight CMU	60	0.96
Concrete	150	2.40
Vermiculite concrete	25 - 60	0.40-0.96
Gravel / sand	90-120	1.44-1.92
Soil	75-115	1.20-1.84
Water at 4° C	62.4	1.00
Metals		
Aluminum	165	2.64
Cast iron	450	7.21
Steel	485	7.77
Stainless steel	492-510	7.88-8.17
Copper	556	8.91
Lead	710	11.37
Stone		
Granite / slate	175	2.81
Lime stone / marble	165	2.64
Sandstone	150	2.40
Wood		
Cedar	22	0.35
Douglas fir	34	0.55
Oak	47	0.75
Pine, white	25	0.40
Redwood	28	0.45

Table 2.1. Material weight - continued		
Weight by area	psf	Pa
Gypsum board, 5/8" (16 mm)	2.5	120
Stucco, 7/8" (22 mm)	8	383
Acoustic tile, 1/2"	0.8	38
Ceramic tile, 1/4" (6.3 mm)	2.5	120
Glass		
Sheet glass, 1/8" (3 mm)	1.5	72
Sheet glass, 1/4" (6 mm)	3	144
Glass block, 4" (102 mm)	20	958
Roof material		
Built-up roof	7	335
Clay / concrete tiles	13-20	622-958
Metal	1-3	48-144
Shingles	3	144
Single ply roof / fabric roof	1-2	48-06
Industrial fabric (PVC , fiber glass)	1-2	48-96
Steel floor constructions		
Steel deck / concrete slab, 6" (15 mm)	20-60	1915-2873
Suspended ceiling	2	96
Floor finish	2	96
Steel framing (varies with height)	10-40	479-1916
Partitions (required by code)	20	958
Total	54-124	2587-5940
Wood platform framing		
Wood platform framing + floor / ceiling	14	670
Light-weight concrete option	14	670
Total (with and without concrete)	14-28	670-1341

IBC table 1607.1 excerpts. Minimum uniform live load			
Use or Occupancy		Pounds / ft ²	kPa
Category	Description	psf	kPa
Access floors	Office use	50	2.39
	Computer use	100	4.79
Auditoria and Assembly areas	Fixed seating	50	2.39
	Movable seating	100	4.79
	Stage	125	5.99
Garages	Storage and repair	100	4.79
	Private	50	2.39
Hospitals	Wards and rooms	40	1.92
Libraries	Reading room	60	2.87
	Stack room	125	5.99
Manufacturing	Light	75	3.59
	Heavy	125	5.99
Offices		50	2.39
Printing plants	Press room	150	7.18
	Composing, etc.	100	4.79
Residential	Basic floor area	40	1.92
	Exterior balconies	60	2.87
Reviewing stands, etc.		100	4.79
Schools	Classrooms	40	1.92
Sidewalks and driveways	Public access	250	11.97
Storage	Light	125	5.99
	Heavy	250	11.97
Stores		100	4.79
Pedestrian bridges		100	4.79

Live Load

IBC table 1607.1 defines live loads for various occupancies. Except for live load >100 psf (4.79 kPa) these loads may be reduced for large tributary areas as follows:

$$R = r (A - 150) \quad (A = \text{tributary area})$$

$$R = r (A - 14) \quad [\text{for SI units}]$$

Reductions R shall not exceed

- 40% for horizontal members
- 60% for vertical members
- $R = 23.1 (1 + D/L)$

R = reduction in percent

r = 0.08 for floors

A = tributary area in square foot (m²)

D = dead load

L = unreduced live load per square foot (m²)

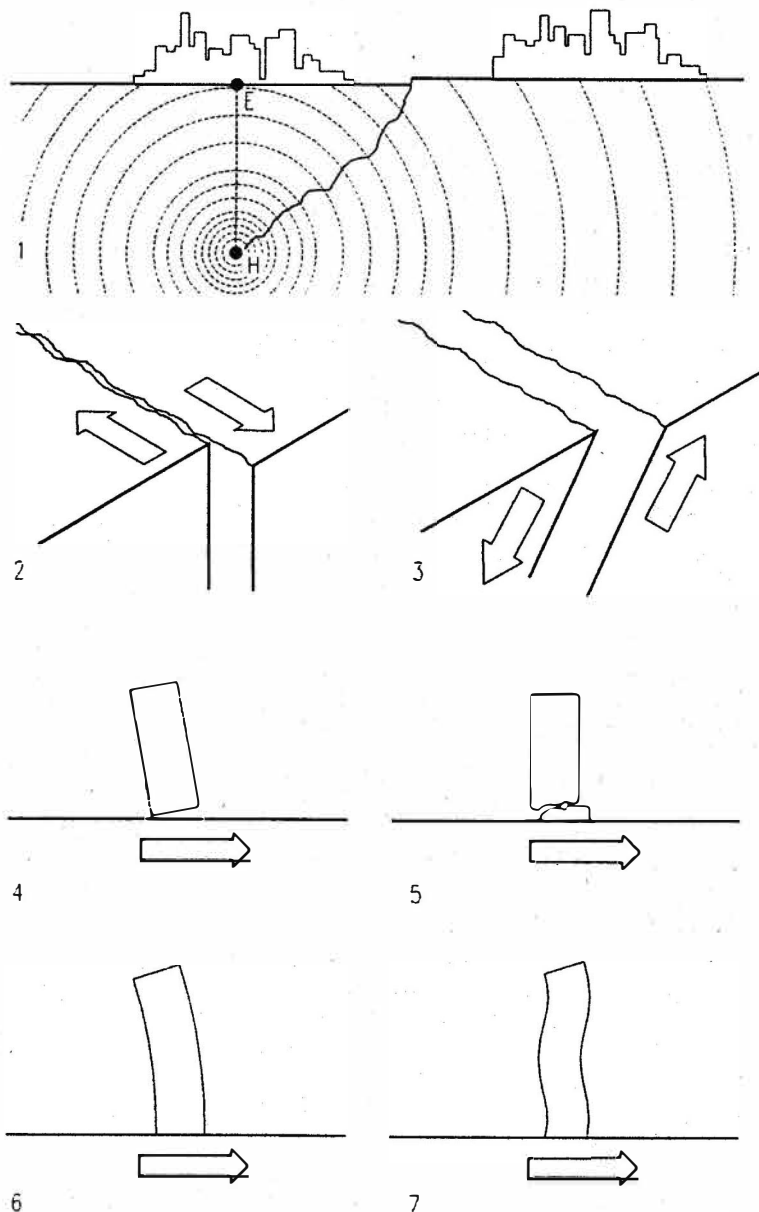
Roof Load

Roof loads are defined by IBC

- Wind load per IBC 1609
- Snow load per IBC 1608
- Minimum roof loads:

Roof type	psf	Pa
Awnings and canopies	5	240
Green houses	10	479
Landscaped roofs (soil + landscaping as DL)	20	958
General flat, pitched, and curved roofs	$L_r L_r$	
	$L_r = 20 R_1 / R_2$	$12 < L_r < 20$
	For SI units	$0.58 < L_r < 0.96$
	$R_1 = 1$	for $A \leq 200$ sq. ft
	$R_1 = 0.6$	for $A \geq 600$ sq. ft
	$R_2 = 1$	for slopes $\leq 1:3$
	$R_2 = 0.6$	for slopes $\geq 1:1$
		$\leq 18^\circ$
		$\geq 45^\circ$

See IBC1607.11 for other R_1 and R_2 factors



Seismic load

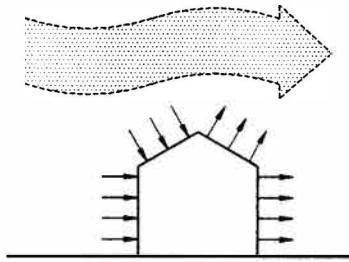
Earthquakes cause horizontal and vertical ground shaking. The horizontal (lateral) shaking is usually most critical on buildings. Earthquakes are caused by slippage of seismic fault lines or volcanic eruption. Fault slippage occurs when the stress caused by differential movement exceeds the soil shear capacity. Differential movement occurs primarily at the intersection of tectonic plates, such as the San Andreas fault which separates the Pacific plate from the US continental plate. Earthquake intensity is greatest after a long accumulation of fault stress. Seismic waves propagate generally in radial patterns, much like a stone thrown in water causes radial waves. The radial patterns imply shaking primarily vertical above the source and primarily horizontal with distance. The horizontal shaking usually dominates and is most critical on buildings. Although earthquakes are dynamic phenomena, their effect may be treated as equivalent static force acting at the base of buildings. This lateral force, called **base shear**, is basically governed by Newton's law:

$$f = m a \quad (\text{force} = \text{mass} \times \text{acceleration})$$

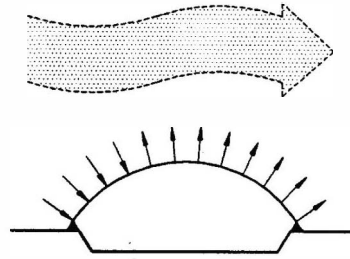
Base shear is dampened by ductility, a structure's capacity to absorb energy through elastic deformation. Ductile structures deform much like flowers in the wind, yet brittle (non-ductile) structures sustain greater inertia forces. Steel moment resisting frames are ductile, though some shear walls are brittle. In earthquake prone areas seismic base shear as percentage of mass is approximately:

- ~ 4 % for tall ductile moment frames
- ~ 10 % for low-rise ductile moment frames
- ~ 15 % for plywood shear walls
- ~ 20 to 30 % for stiff shear walls

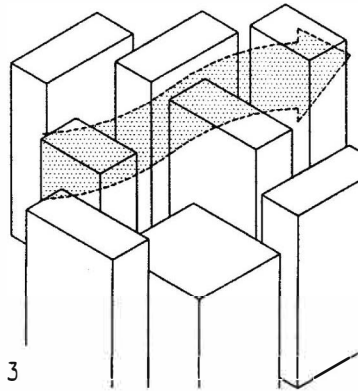
- 1 Fault rupture / wave propagation (vertical above rupture, lateral at distance)
 - 2 Lateral slip fault
 - 3 Thrust fault
 - 4 Building overturning
 - 5 Base shear
 - 6 Bending deformation (first mode)
 - 7 Bending deformation (higher mode)
- E **Epicenter** (earthquake source above ground)
H **Hyper Center** (actual earthquake source under ground)



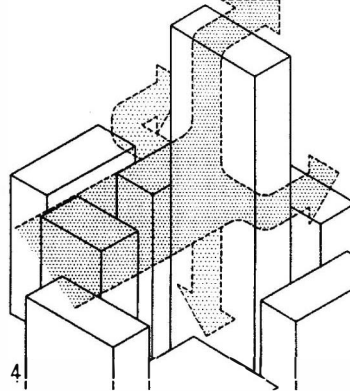
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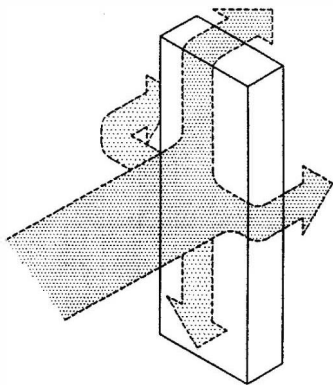
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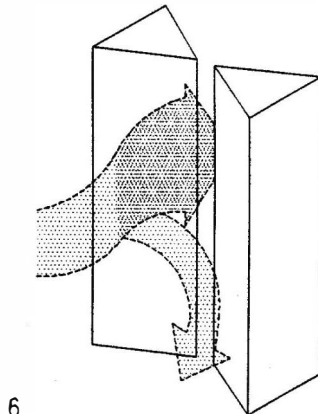
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6

Wind load (see also *Lateral Force Design*)

Wind causes lateral load, much like earthquakes. But while seismic load is dynamic, wind load is usually static, except gusty wind and wind on flexible structures. In addition to pressure on the side facing the wind (**wind side**), wind also causes suction on the opposite side (**lee side**) and uplifting on roofs. Wind pressure on buildings increases with velocity, height and exposure. IBC Figure 16-1 gives wind velocity. Velocity wind pressure (33 feet, 10 m above the ground) is:

$$q = 0.00256 V^2 (H/33)^{2.7}$$

$$q = \text{velocity pressure in psf} \quad [1 \text{ psf} = 47.9 \text{ Pa}]$$

$$V = \text{velocity in mph} \quad [1 \text{ mph} = 1.609 \text{ km/h}]$$

$$H = \text{height in feet} \quad [1 \text{ ft} = 0.305 \text{ m}]$$

The actual wind pressure P is the velocity pressure q times adjustment factors based on empirical data for type of exposure, orientation, and peak pressure along edges, roof ridge. IBC defines three exposures and two design methods:

- **Exposure B** (sites protected by buildings or a forest)
- **Exposure C** (open sites outside cities)
- **Exposure D** (sites near an ocean or large lake)
- **Method 1** **Simplified design** (for buildings ≤ 60 ft high)
- **Method 2** **Analytical procedure**

Depending on location, height, and exposure, wind pressure ranges from 10-110 psf (0.5 to 5 kPa). For moderate wind, schematic design is usually based on ~30 psf.

Design objectives for wind load:

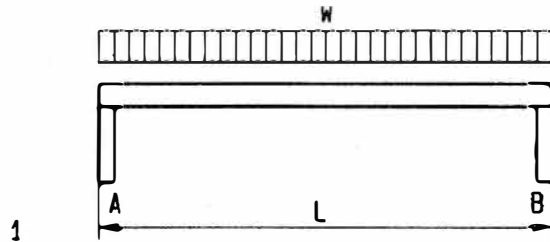
- **Maximize mass to resist uplift**
 - **Maximize stiffness to reduce drift**
- 1 Wind load on gabled building (left pressure, right suction)
 - 2 Wind load on dome or vault (left pressure, right suction)
 - 3 Buildings within cities are protected by other buildings
 - 4 Tall building exposed to full wind pressure
 - 5 Wind on wide façade is more critical than on narrow façade
 - 6 Building forms increase wind speed

Tributary load and load path

Tributary load is the load acting on any element, like a beam, column, slab, wall, foundation, etc. Tributary load is needed to design / analyze any element.

Load path is the path load travels from where it originates on a structure to where it is ultimately resisted (usually the foundation). It is essential to define the tributary load.

The following examples illustrate tributary load and load path



1 Simple beam / 2 columns

Assume

Uniform beam load $w = 200$ plf

Beam span $L = 30'$

Find

Load path: beam / post

Tributary load: Reactions at columns A and B

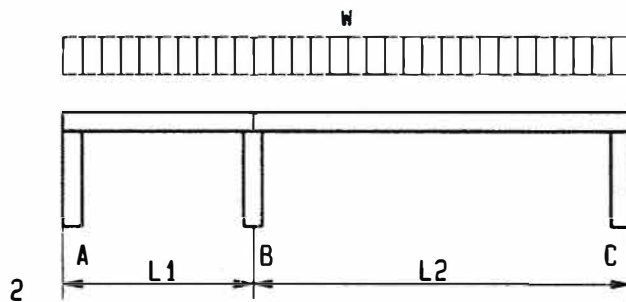
$$R_a = R_b = R = w L / 2$$

$$R = 200 \times 30 / 2 = 3000 \#$$

Convert pounds to kip

$$R = 3000 \# / 1000$$

$$R = 3.0 \text{ k}$$



2 Two beams / three posts

Assume

Uniform beam load $w = 2$ klf

Beam spans $L_1 = 10'$, $L_2 = 20'$

Find

Load path: beam / post

Tributary load: Reactions at posts A, B, C

$$R_a = 2 \times 10 / 2$$

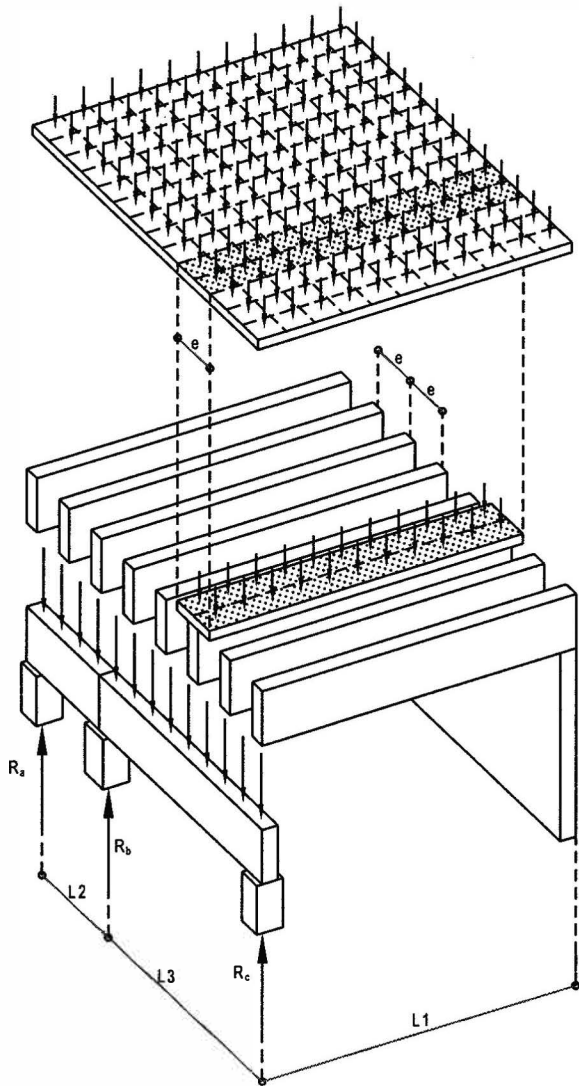
$$R_a = 10 \text{ k}$$

$$R_b = 2(10 + 20) / 2$$

$$R_b = 30 \text{ k}$$

$$R_c = 2 \times 20 / 2$$

$$R_c = 20 \text{ k}$$



Deck / joist / beam / post

Assume

Uniform load

$w = 80 \text{ psf}$

Joist spacing

$e = 2'$

Joist span

$L_1 = 12'$

Beam spans

$L_2 = 10'$

$L_3 = 20'$

Find load path and tributary load

Load path

Plywood deck / joist / beam / columns

Tributary loads

Joist load

$w_j = w e = 80 \text{ psf} \times 2'$

$w_j = 160 \text{ plf}$

Beam load (assume uniform load due to narrow joist spacing)

$w_b = 80 \text{ psf} L_1 / 2 = 80 \text{ psf} \times 12' / 2$

$w_b = 480 \text{ plf}$

Column reaction

$R_a = w_b L_2 / 2 = 480 \text{ plf} \times 10' / 2$

$R_a = 2,400 \text{ \#}$

$R_b = w_b (L_2 + L_3) / 2 = 480 (10' + 20') / 2$

$R_b = 7,200 \text{ \#}$

$R_c = w_b L_3 / 2 = 480 \times 20' / 2$

$R_c = 4,800 \text{ \#}$

One-story concrete structure

Assume

$L_x = 30'$, $L_{xc} = 34'$, $L_y = 25'$

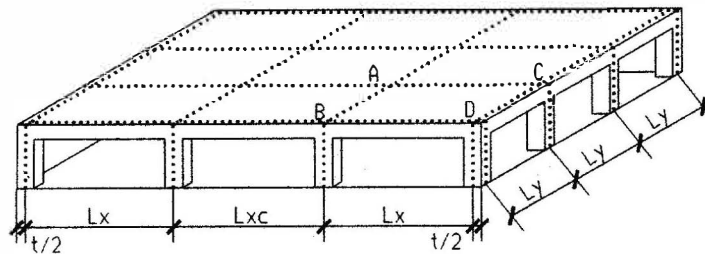
Roofing	3 psf
Ceiling	2 psf
<u>10" concrete slab at 150 pcf x10"/12"</u>	<u>125 psf</u>

Dead load	DL = 130 psf
Live load	LL = 20 psf
Total load	$\Sigma = 150$ psf

Post size 1' x 1' (center line to post edge = 0.5')

Post reactions A, B, C, D

$R_a = 150 \text{ psf } (30+34)/2 (25)$	$R_a = 120,000 \text{ \#}$
$R_b = 150 (30+34)/2 (25/2+0.5)$	$R_b = 62,400 \text{ \#}$
$R_c = 150 (30/2+0.5) (25)$	$R_c = 58,125 \text{ \#}$
$R_d = 150 (30/2+0.5) (25/2+0.5)$	$R_d = 30,225 \text{ \#}$



Three-story concrete structure

Roof dead load DL = 150 psf

Floor live load (office) LL = 50 psf

Total w = 200 psf

Post size, 2'x2' (post center to building edge = 2/2 = 1')

Level 2 reactions w = 150 psf

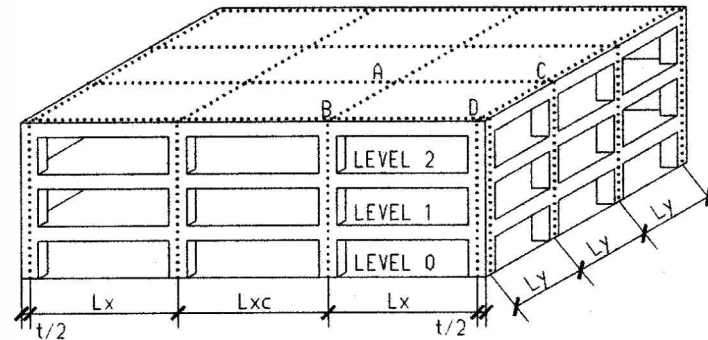
$R_a = 150 \text{ psf } (30+34)/2 (25)$	$= 150 \times 800$	$R_a = 120,000 \text{ \#}$
$R_b = 150 (30+34)/2 (25/2+1)$	$= 150 \times 432$	$R_b = 64,800 \text{ \#}$
$R_c = 150 (30/2+1) (25)$	$= 150 \times 400$	$R_c = 60,000 \text{ \#}$
$R_d = 150 (30/2+1) (25/2+1)$	$= 150 \times 216$	$R_d = 32,400 \text{ \#}$

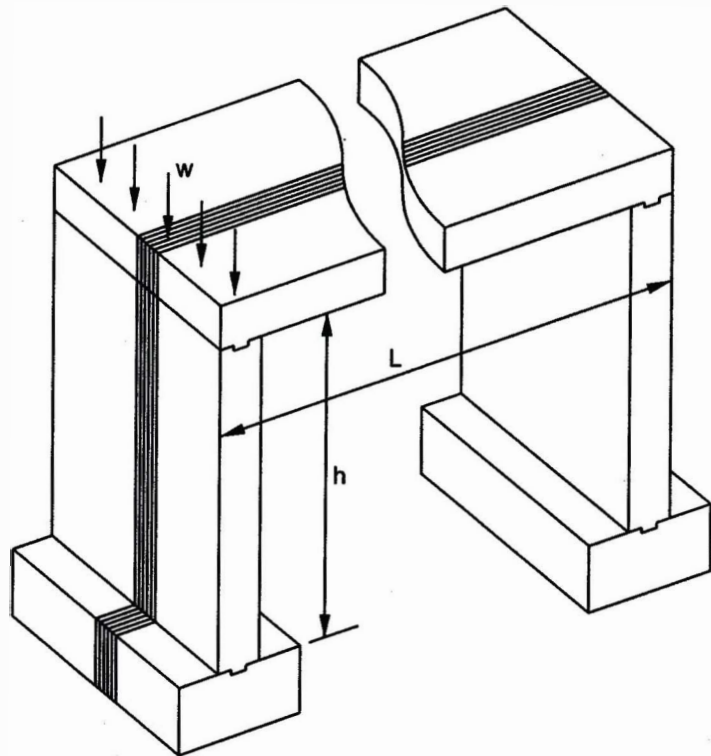
Level 1 reactions w = 150+200

$R_a = 350 \times 800$	$R_a = 280,000 \text{ \#}$
$R_b = 350 \times 432$	$R_b = 151,200 \text{ \#}$
$R_c = 350 \times 400$	$R_c = 140,000 \text{ \#}$
$R_d = 350 \times 216$	$R_d = 75,600 \text{ \#}$

Level 0 reactions w = 150+200+200

$R_a = 550 \times 800$	$R_a = 440,000 \text{ \#}$
$R_b = 550 \times 432$	$R_b = 237,600 \text{ \#}$
$R_c = 550 \times 400$	$R_c = 220,000 \text{ \#}$
$R_d = 550 \times 216$	$R_d = 118,800 \text{ \#}$





Concrete slab / wall / footing / soil

Assume:

Allowable soil pressure 2000 psf (stiff soil)

Concrete slab, 9.6" thick

Slab length $L = 20'$

Wall height $h = 10'$

8" CMU wall, 10' high at 80 psf (CMU = **C**oncrete **M**asonry **U**nits)

(8" nominal = $7 \frac{5}{8}" = 7.625"$ actual)

Concrete footing 2' x 1' at 150 pcf

Loads

DL = 120 psf (150 pcf x 9.6"/12")

LL = 20 psf (roof load)

$\Sigma = 140$ psf

Find load path und tributary load

Load Path: slab / wall / footing / soil

Tributary load: analyze a 2ft wide strip (1meter in SI units)

Slab load

$$w = 140 \text{ psf} \times 20 / 2$$

$$w = 1400 \#$$

CMU wall load

$$w = 80 \text{ psf} \times 10'$$

$$w = 800 \#$$

Footing load

$$w = 150 \text{ pcf} \times 2' \times 1'$$

$$w = 300 \#$$

Total load on soil

$$P = 1400 + 800 + 300$$

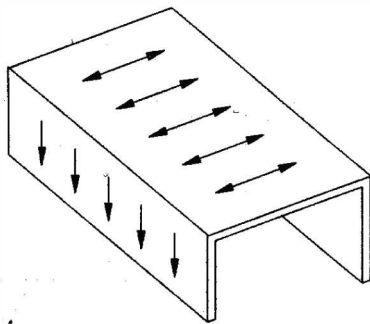
$$P = 2500 \#$$

Soil pressure

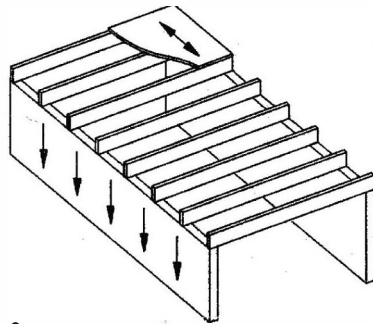
$$f = P/A = 2500 \# / 2'$$

$$f = 1250 \text{ psf}$$

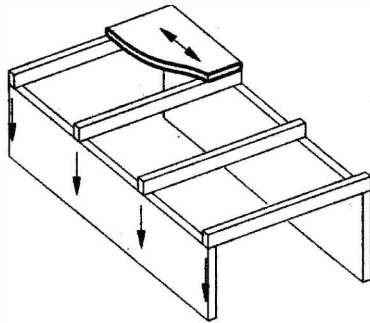
$$1250 < 2000, \text{ OK}$$



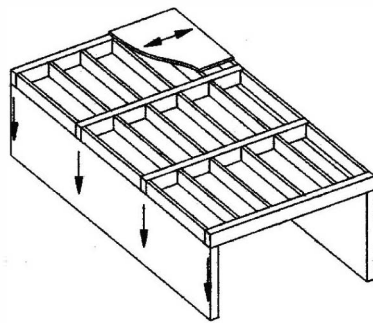
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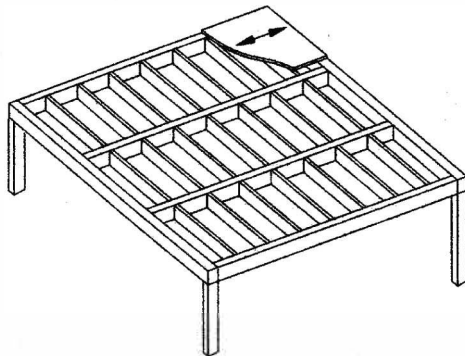
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5

1 Concrete slab / wall

Slab span $L = 20'$, $t = 8''$ thick

Uniform load $\Sigma = LL + DL = 50 \text{ psf} + 120 \text{ psf}$

$\Sigma = 170 \text{ psf}$

Slab load on wall

$w = 170 \text{ psf} \times 20'/2$

$w = 1700 \text{ plf}$

2 Joist roof / wall

2x12 wood joists at 24", span $L = 18'$

Uniform load $\Sigma = LL + DL = 30 \text{ psf} + 20 \text{ psf}$

$\Sigma = 50 \text{ psf}$

Load on wall (per linear foot of wall)

$w = 50 \text{ psf} \times 18'/2$

$w = 450 \text{ plf}$

3 Concrete slab / beam / wall

Beams at 10', span $L = 30'$

Uniform load $\Sigma = LL + DL = 20 \text{ psf} + 70 \text{ psf}$

$\Sigma = 90 \text{ psf}$

Beam load $w = 90 \text{ psf} \times 10' / 1000$

$w = 0.9 \text{ klf}$

Beam reaction $R = 0.9 \text{ klf} \times 30' / 2$

$R = 13.5 \text{ k}$

4 Concrete slab on metal deck / joist/ beam

Spans: deck $L = 8'$, joist $L = 20'$, beam $L=40'$

Uniform load $\Sigma = LL + DL = 40 \text{ psf} + 60 \text{ psf}$

$\Sigma = 100 \text{ psf}$

Joist load $w = 100 \text{ psf} \times 8' / 1000$

$w = 0.8 \text{ klf}$

Beam point loads $P = 0.8 \text{ klf} \times 20'$

$P = 16 \text{ k}$

Beam reaction $R = 4 P / 2 = 4 \times 16 \text{ k} / 2$

$R = 32 \text{ k}$

5 Concrete slab on metal deck / joist/ beam / girder

Spans: deck $L = 5'$, joist $L = 20'$, beam $L = 40'$, girder $L = 60'$

Uniform load $\Sigma = LL + DL = 50 \text{ psf} + 50 \text{ psf}$

$\Sigma = 100 \text{ psf}$

Uniform joist load $w = 100 \text{ psf} \times 5' / 1000$

$w = 0.5 \text{ klf}$

Beam point loads $P = 0.5 \text{ klf} \times 20'$

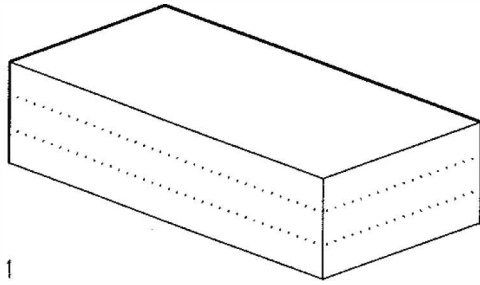
$P = 10 \text{ k}$

Girder point loads $P = 7 \times 10 \text{ k} / 2$

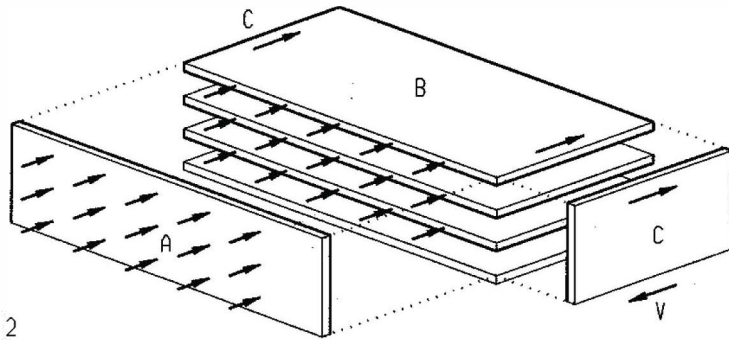
$P = 35 \text{ k}$

Column reaction $R = (100 \text{ psf} / 1000) \times 40' \times 60' / 4$

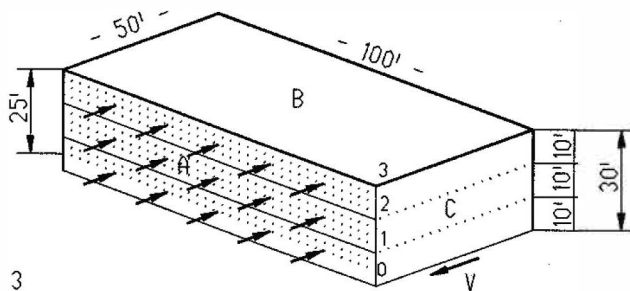
$R = 60 \text{ k}$



1



2



3

Wind load resisted by shear wall

- 1 Three-story building
 - 2 Exploded visualization
 - 3 Building dimensions
- A Wind Wall
B Roof and floor diaphragms
C Shear walls

Assume:

Wind pressure $P = 20$ psf

Load path

Wind wall > diaphragms > shear walls > footings

Force per level

Roof force F_3

$$F_3 = 20 \text{ psf} \times 100' \times 5' / 1000$$

$$F_3 = 10 \text{ k}$$

Level 2 force F_2

$$F_2 = 20 \text{ psf} \times 100' \times 10' / 1000$$

$$F_2 = 20 \text{ k}$$

Level 1 force F_1

$$F_1 = 20 \text{ psf} \times 100' \times 10' / 1000$$

$$F_1 = 20 \text{ k}$$

Shear per wall (2 shear walls)

Level 2

$$V_2 = (F_3) / 2 = (10 \text{ k}) / 2$$

$$V_2 = 5 \text{ k}$$

Level 1

$$V_1 = (F_3 + F_2) / 2 = (10 \text{ k} + 20 \text{ k}) / 2$$

$$V_1 = 15 \text{ k}$$

Level 0

$$V_0 = (F_2 + F_1 + F_0) / 2 = (10 \text{ k} + 20 \text{ k} + 20 \text{ k}) / 2$$

$$V_0 = 25 \text{ k}$$

Note:

- Diaphragms resist half the load from above and below
- Diaphragms transfer load from wind wall to shear walls