ARK-A3001 Design of Structures_Basics

Tension & Compression

Toni Kotnik

Professor of Design of Structures

Aalto University
Department of Architecture
Department of Civil Engineering

- **principle of duality**
  - cable & arch
  - same geometric logic
  - different structural behaviour
- **bracing**
- **design of arches**
- **vault**
- **membrane**

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Principle of Duality

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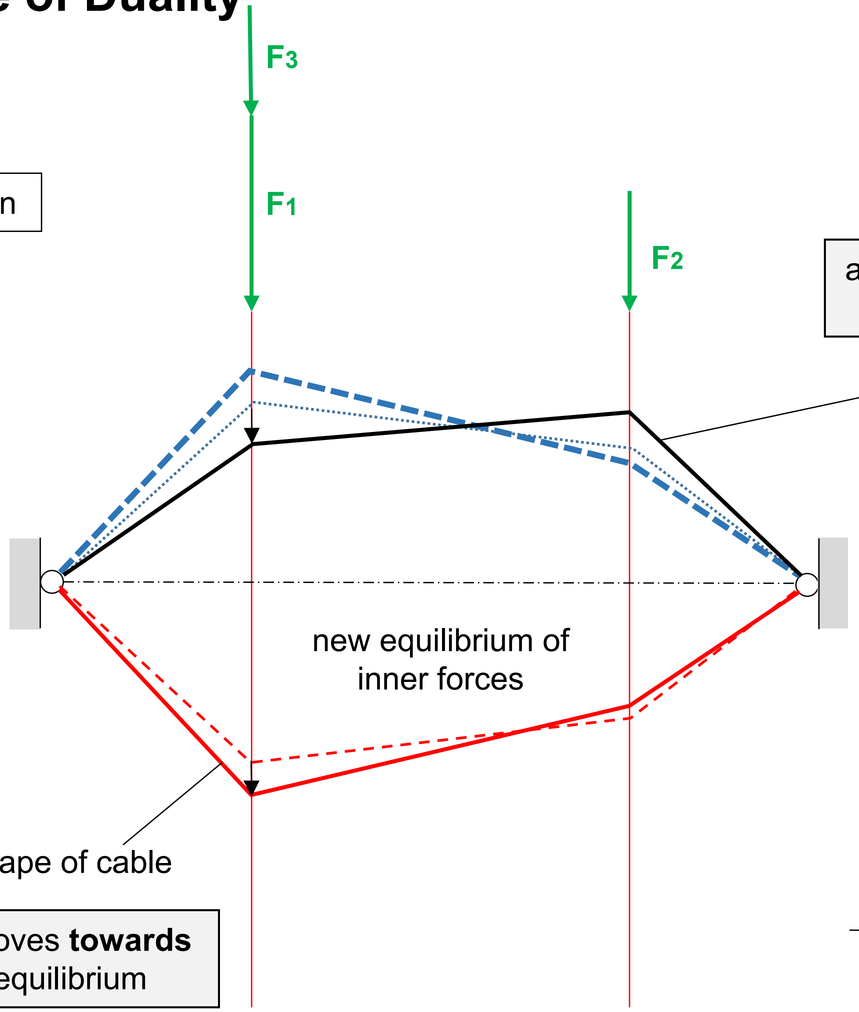
Principle of Duality

location plan



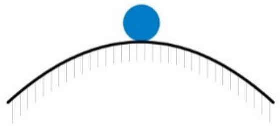
new shape of arch

new equilibrium of inner forces

new shape of cable

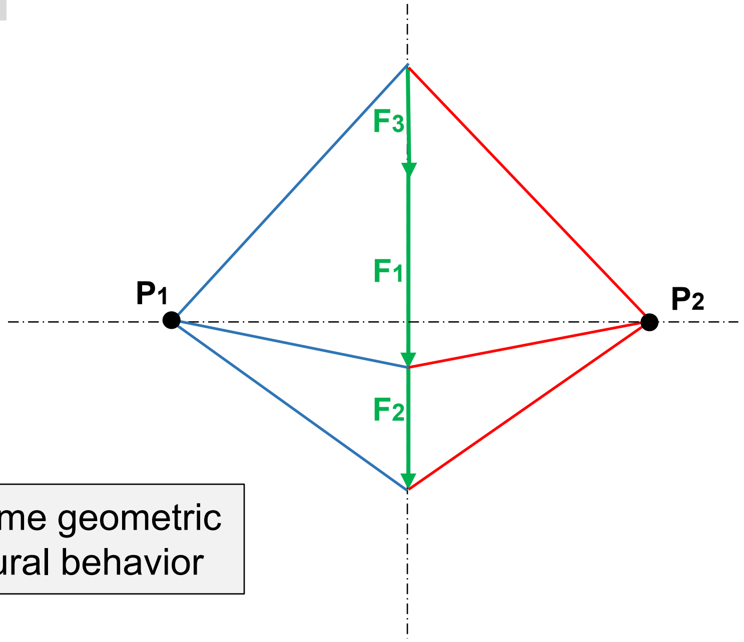
cable moves **towards** new equilibrium

Arch
instable equilibrium

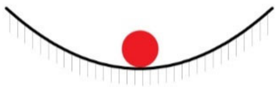


arch moves **away** from new equilibrium

force plan

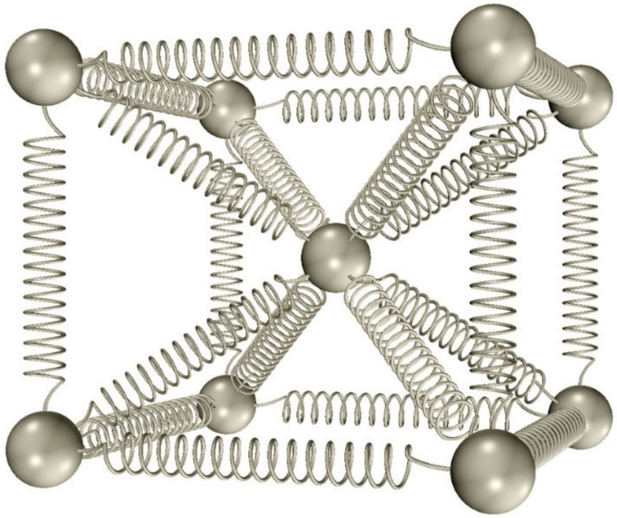


Cable
stable equilibrium

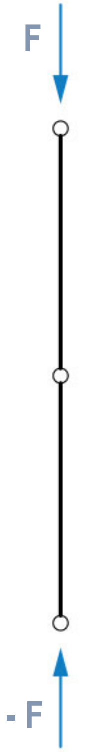


arch & cable have the same geometric logic but different structural behavior

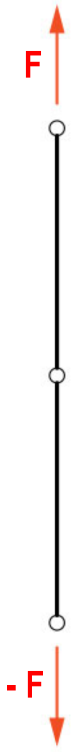
Solid Material



ball-and-spring model of transmission
of forces in solid materials

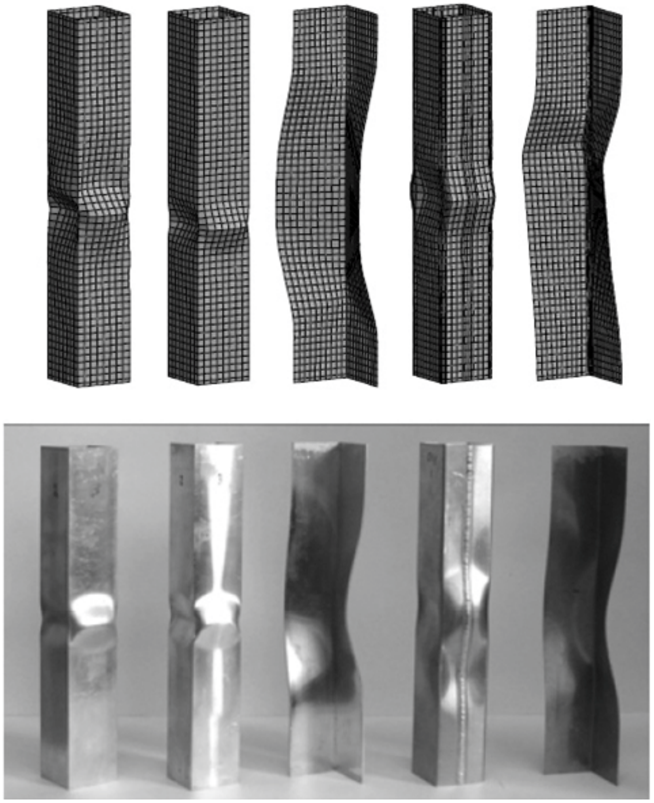


compression

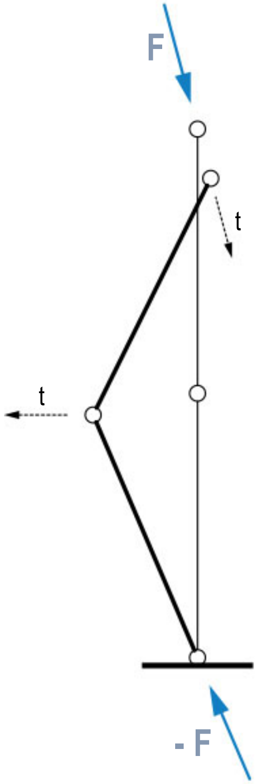


tension

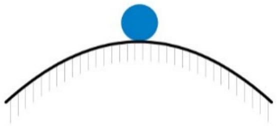
Solid Material

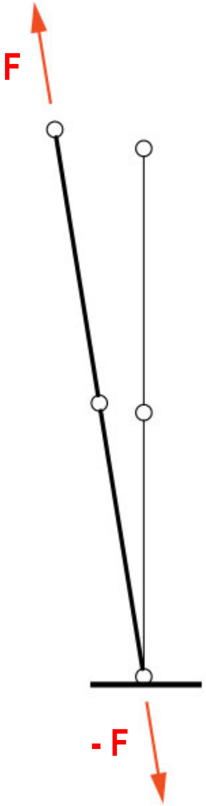


buckling of column

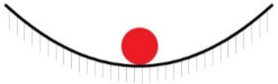


compression
unstable

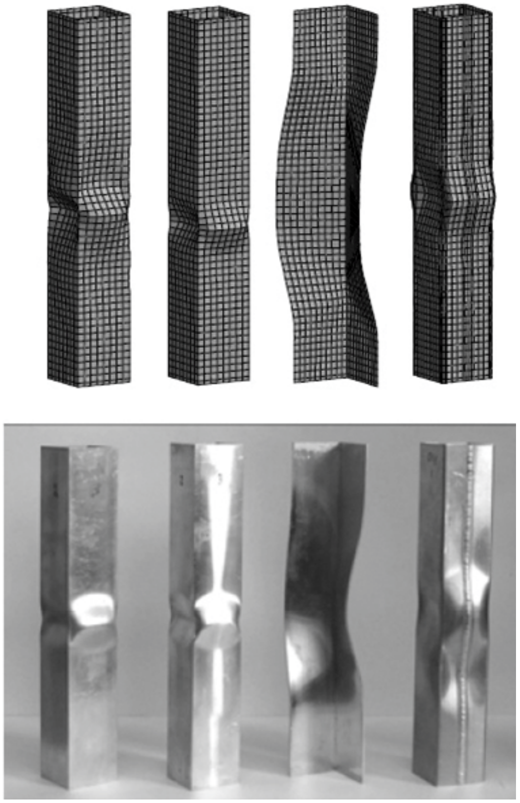




tension
stable

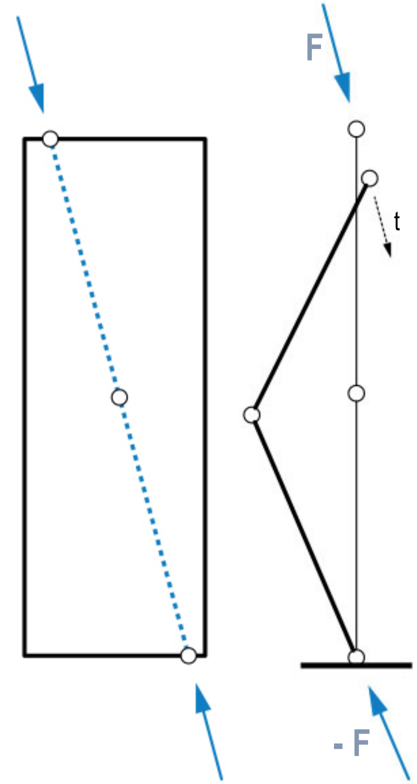


Solid Material

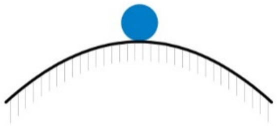


buckling of column

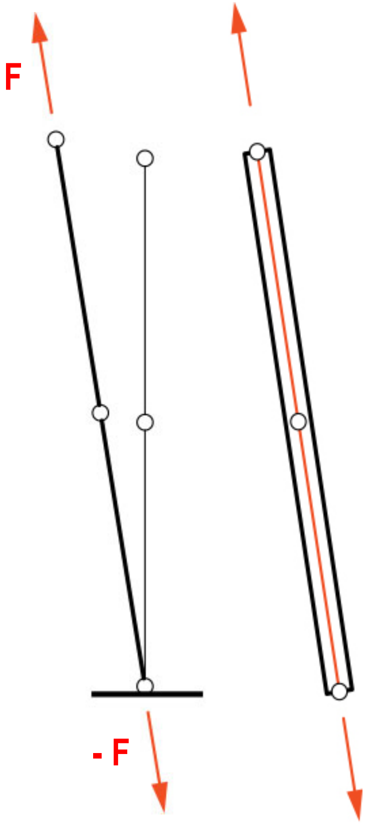
thick



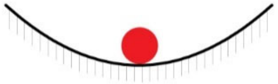
compression
unstable

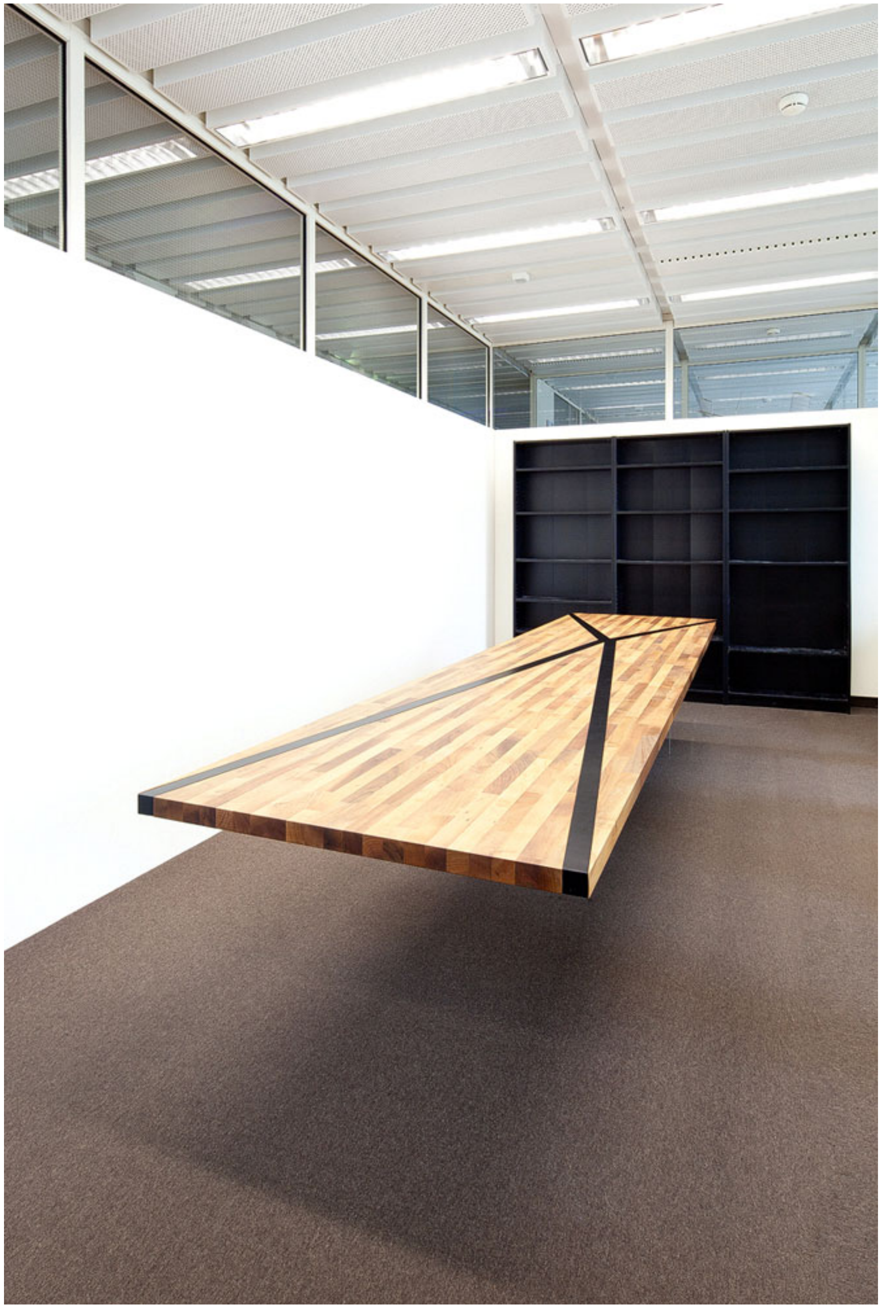


thin

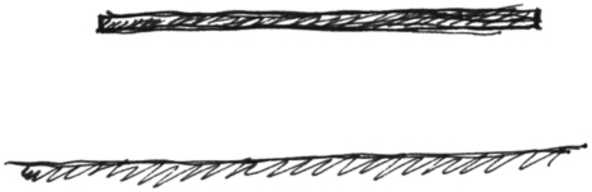


tension
stable





The term table has its etymological roots in the Greek ***dishos***, the disk, and describes a piece of furniture that is characterized by the **horizontality of the tabletop**.



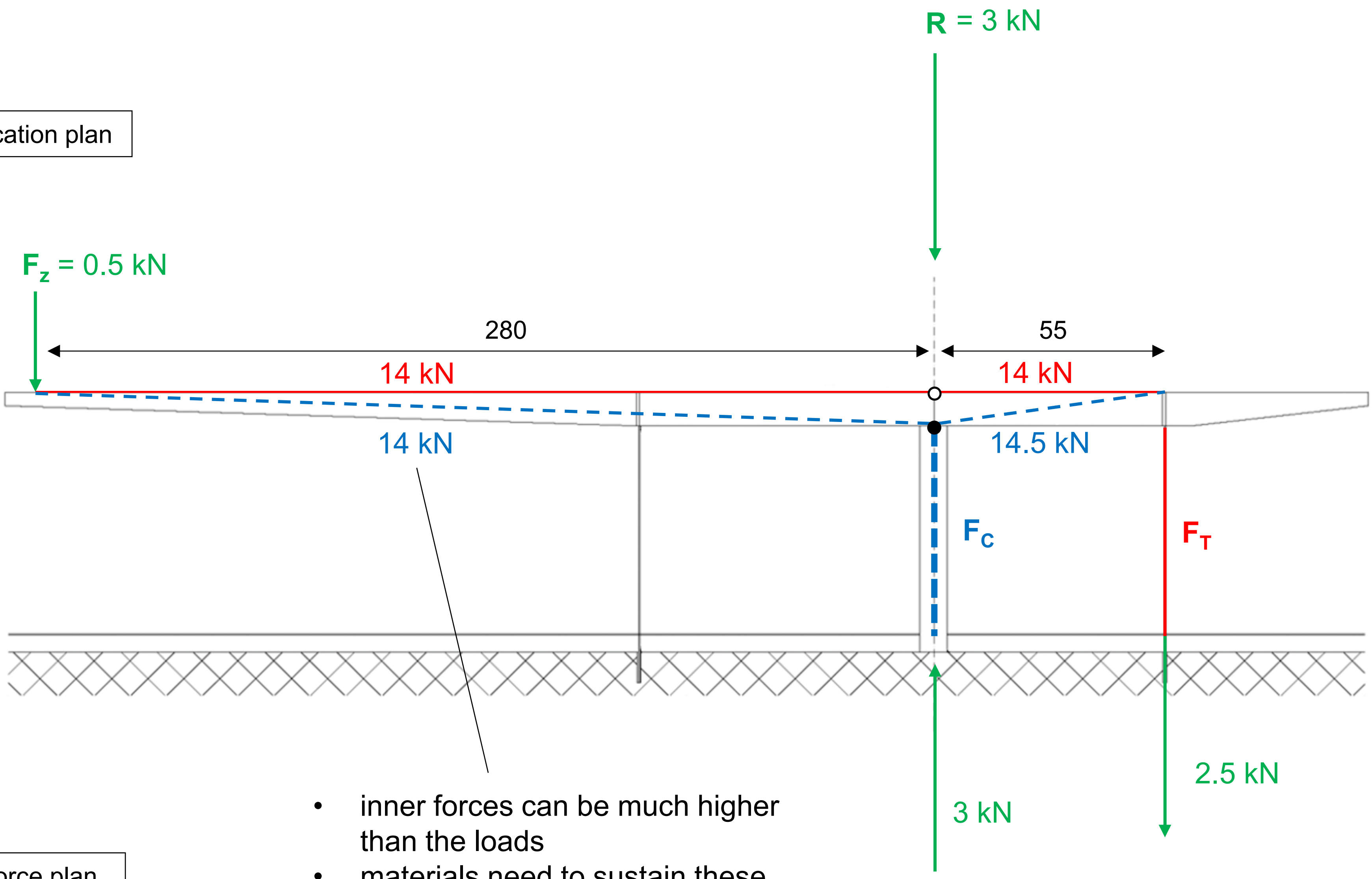
Counterpoise
Conference Table
Zurich, Switzerland, 2010

Counterpoise
Conference Table
Zurich, Switzerland, 2010

Counterpoise
Conference Table
Zurich, Switzerland, 2010

Counterpoise
Conference Table
Zurich, Switzerland, 2010

location plan



force plan

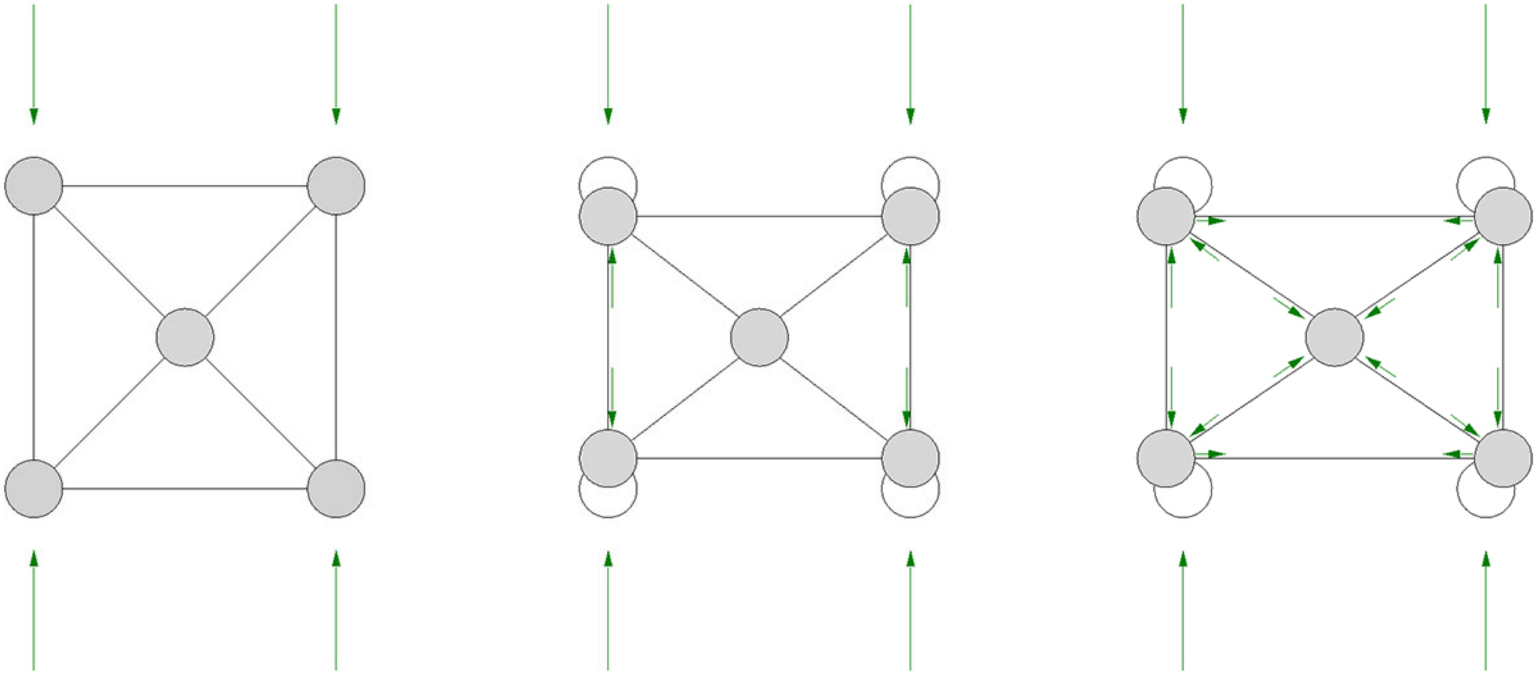
as exercise

- inner forces can be much higher than the loads
- materials need to sustain these high inner forces
- behavior of material under loads is crucial

Counterpoise
Conference Table
Zurich, Switzerland, 2010

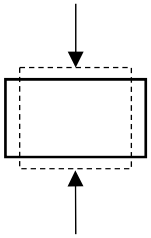
Solid Material

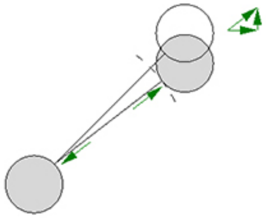
compression



Poisson effect

contraction in one direction is always accompanied by a smaller but proportional expansion in the perpendicular direction

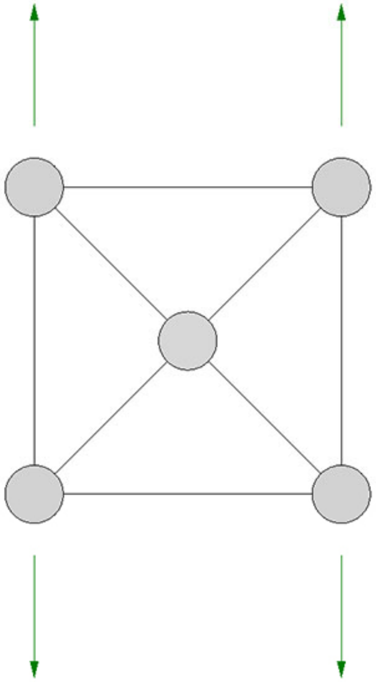


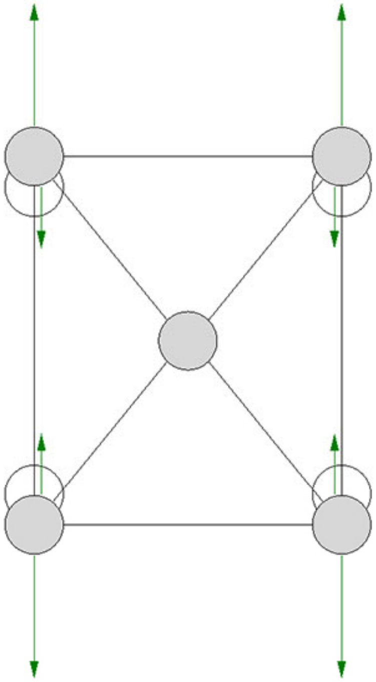


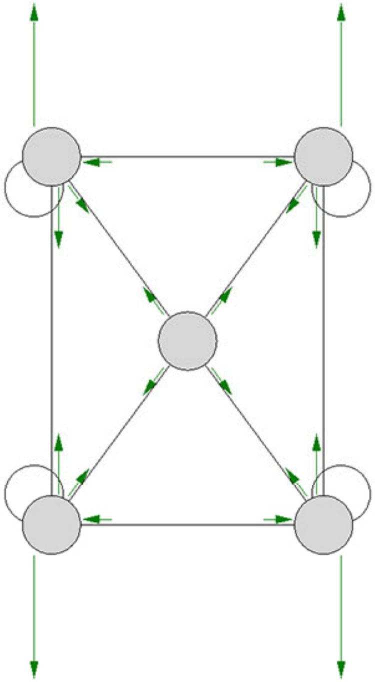
interaction of all atoms

Solid Material

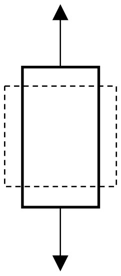
tension

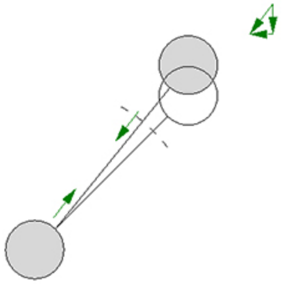






Poisson effect
prolongation in one direction is always accompanied by a smaller but proportional contraction in the perpendicular direction

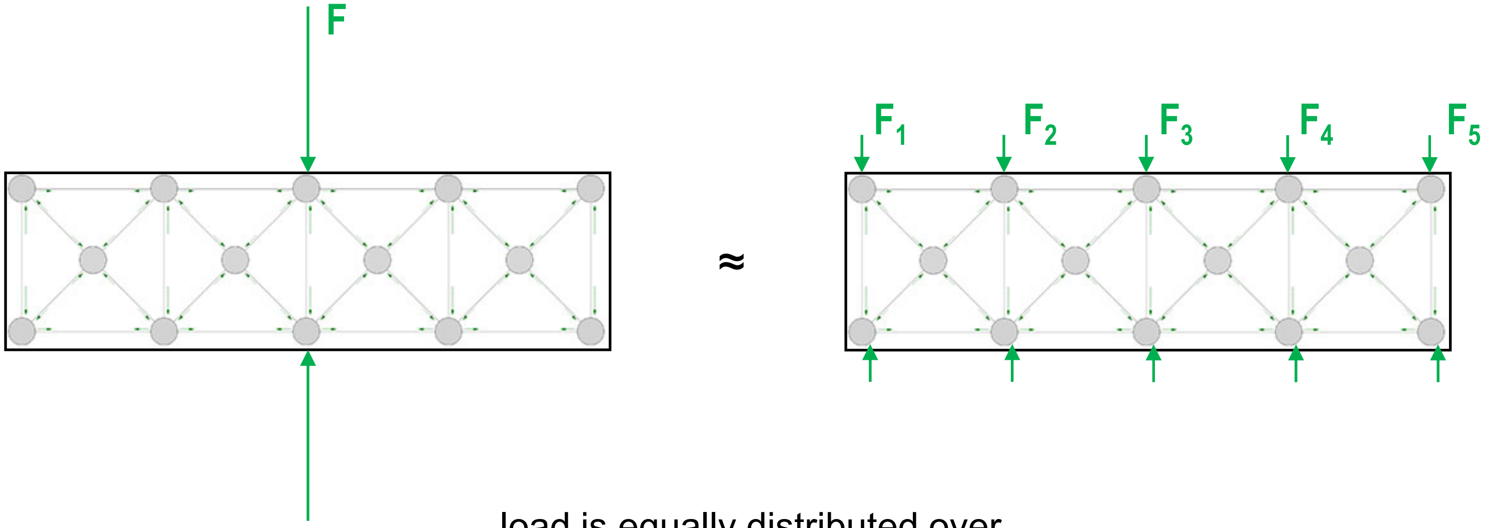




interaction of all atoms

Solid Material

stress



load is equally distributed over
the available cross sectional area

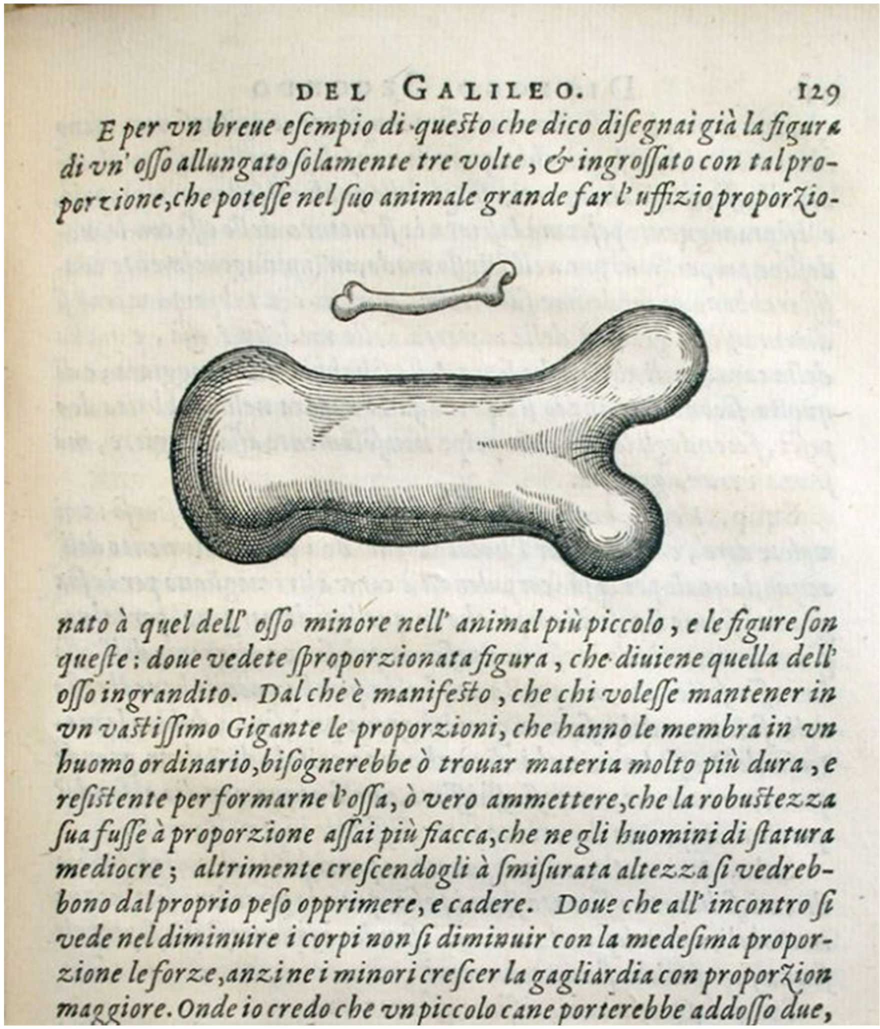
simplified model by Cauchy

stress

$$\boxed{\sigma = \frac{F}{A}}$$

Solid Material

scaling



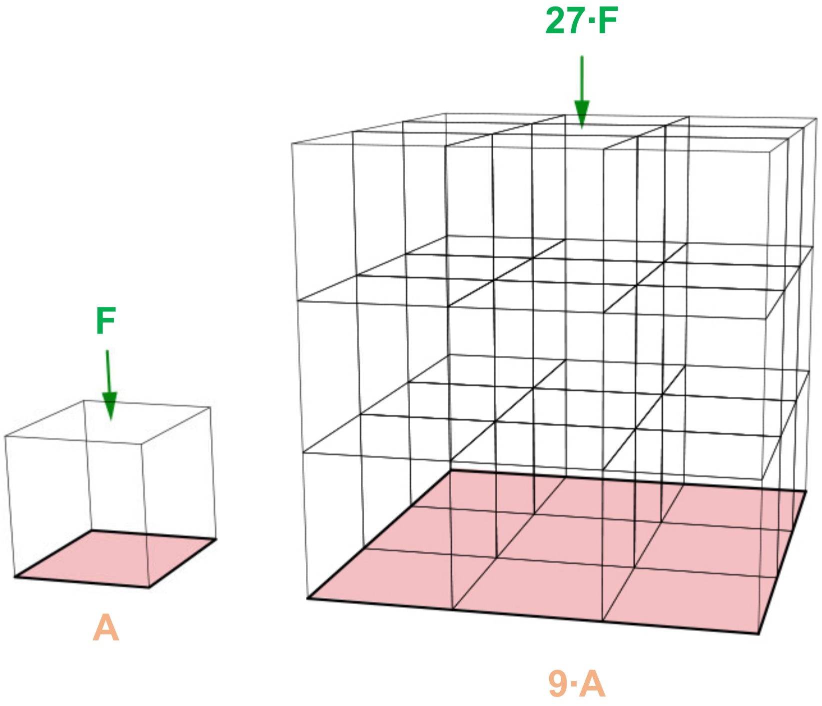
DEL GALILEO. 129

E per vn breue eſempio di queſto che dico diſegnai già la figura di vn' oſſo allungato ſolamente tre volte, & ingroſſato con tal proportione, che poteſſe nel ſuo animale grande far l' uffizio proporzionato à quel dell' oſſo minore nell' animal più piccolo, e le figure ſon queſte: doue vedete ſproporzionata figura, che diuiene quella dell' oſſo ingrandito. Dal che è manifeſto, che chi voleſſe mantener in vn vaſtiſſimo Gigante le proporzioni, che hanno le membra in vn huomo ordinario, biſognerebbe ò trouar materia molto più dura, e reſiſtente per formarne l'oſſa, ò vero ammettere, che la robuſtezza ſua fuſſe à proporzione aſſai più fiacca, che ne gli huomini di ſtatura mediocre; altrimente creſcendogli à ſmiſurata altezza ſi vedrebbono dal proprio peſo opprimere, e cadere. Doue che all' incontro ſi vede nel diminuire i corpi non ſi diminuir con la medeſima proporzione le forze, anzi ne i minori creſcer la gagliardia con proporzion maggiore. Onde io credo che vn piccolo cane porterebbe addoſſo due,

How does the stress in the bone changes if the size of the animal is scaled up by **factor 3**?

$$\boxed{\sigma = \frac{F}{A}}$$

increase by **factor 3**



Solid Material
scaling

How does the stress in the bone changes if the size of the animal is scaled up by **factor 3**?

$$\boxed{\sigma = \frac{F}{A}}$$

increase by
factor 3

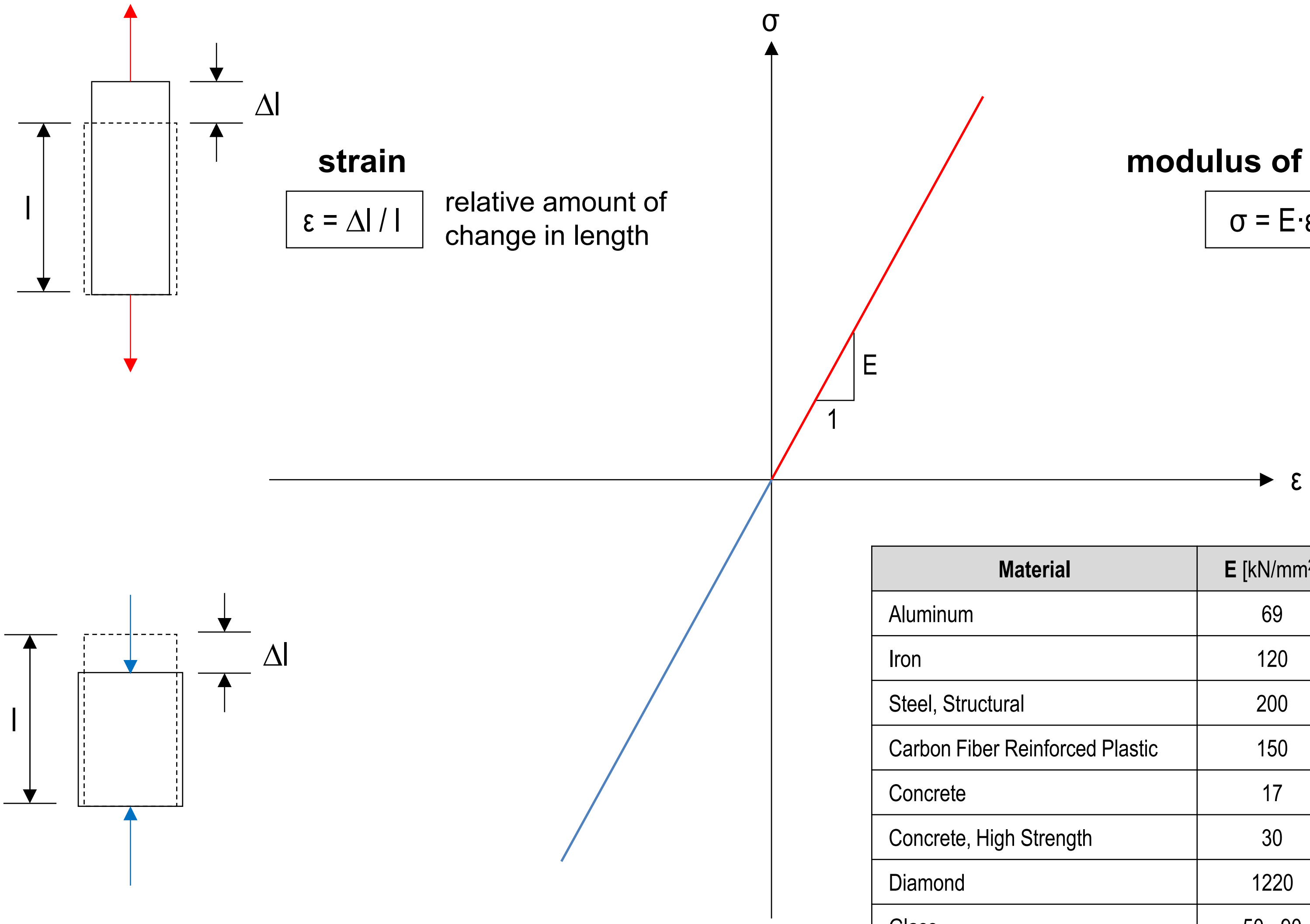
What does this mean for architecture?

a model cannot simply be scaled up!

upscaling requires
- change of dimensions or
- change of material or
- change of form

Solid Material

Modulus of Elasticity



strain

$\boxed{\varepsilon = \Delta l / l}$ relative amount of change in length

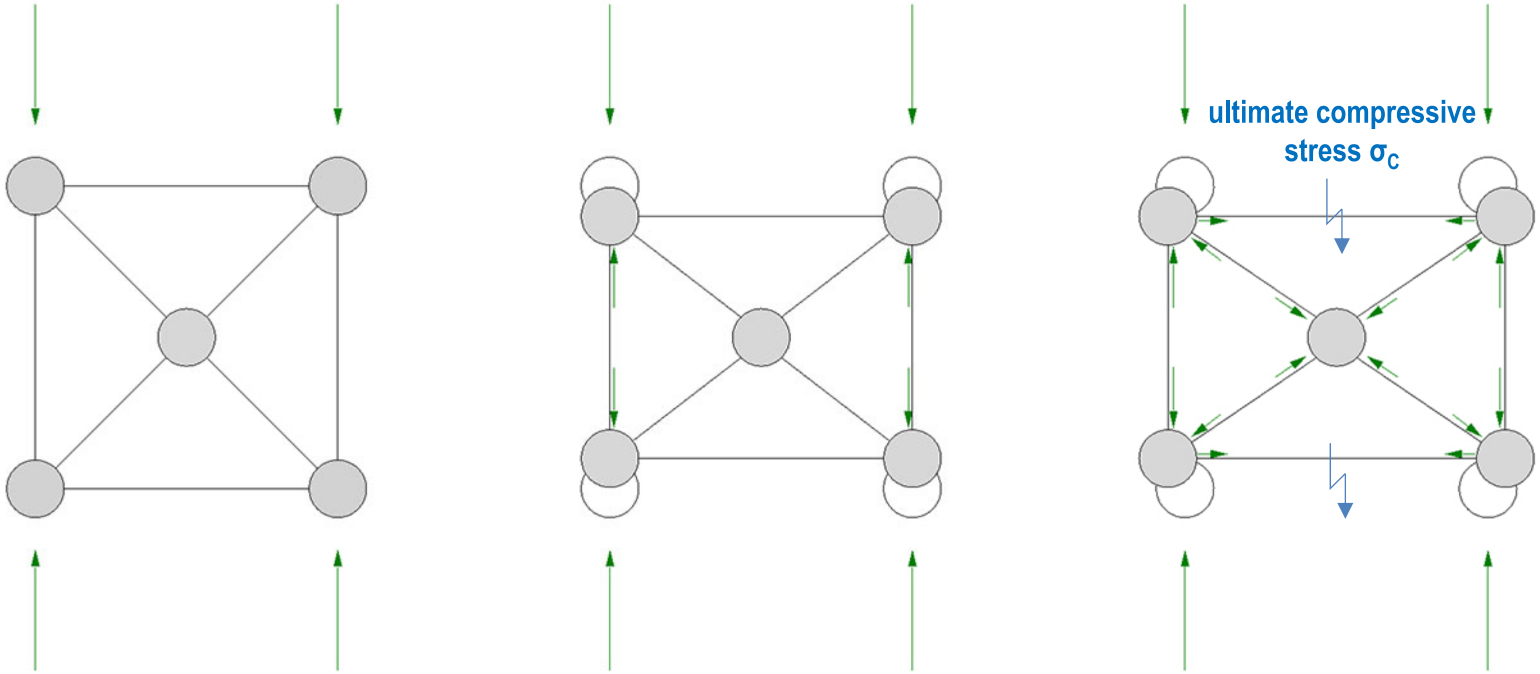
modulus of elasticity

$\boxed{\sigma = E \cdot \varepsilon}$

Material	**E** [kN/mm^2]
Aluminum	69
Iron	120
Steel, Structural	200
Carbon Fiber Reinforced Plastic	150
Concrete	17
Concrete, High Strength	30
Diamond	1220
Glass	50 - 90
Oak Wood (along grain)	11

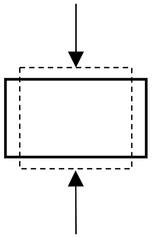
Solid Material

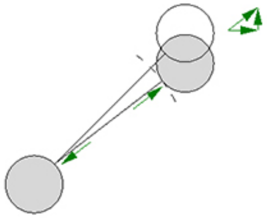
compression



Poisson effect

contraction in one direction is always accompanied by a smaller but proportional expansion in the perpendicular direction

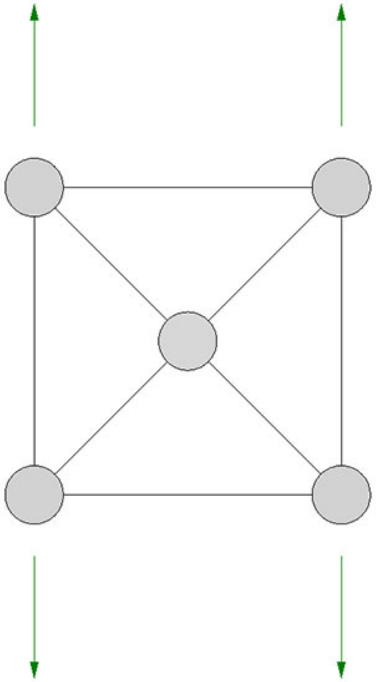




interaction of all atoms

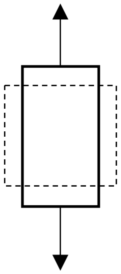
Solid Material

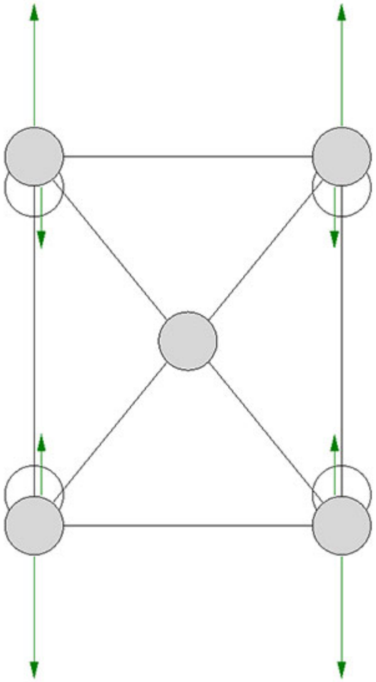
tension

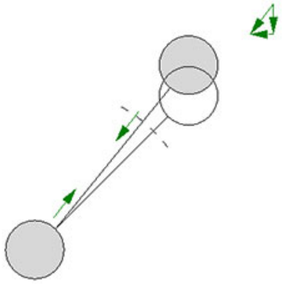


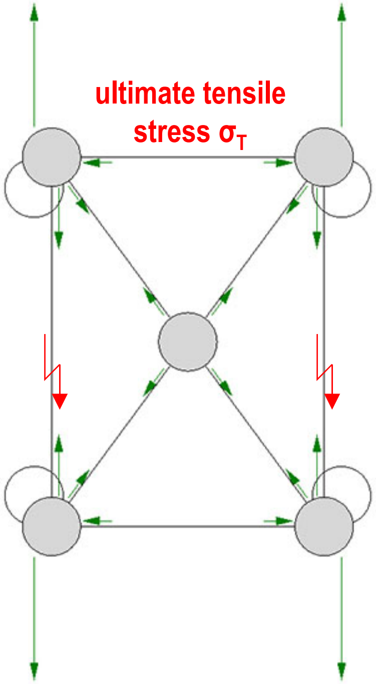
Poisson effect

prolongation in one direction is always accompanied by a smaller but proportional contraction in the perpendicular direction





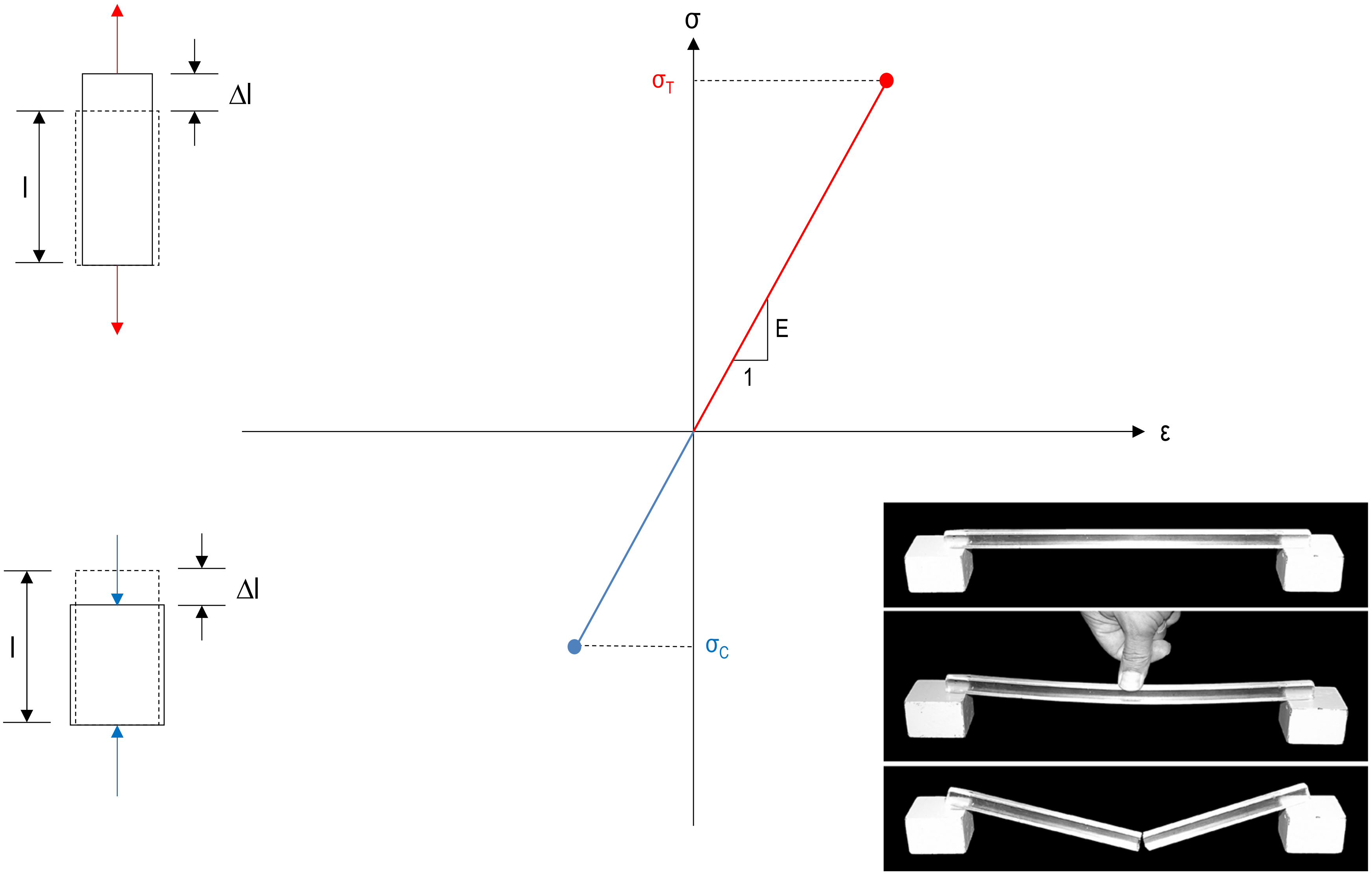




interaction of all atoms

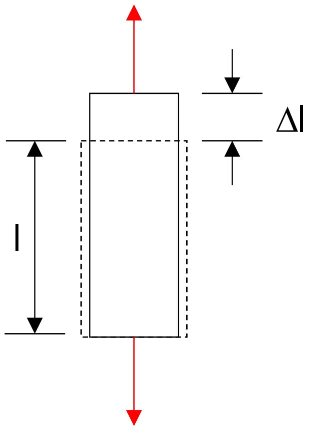
Solid Material

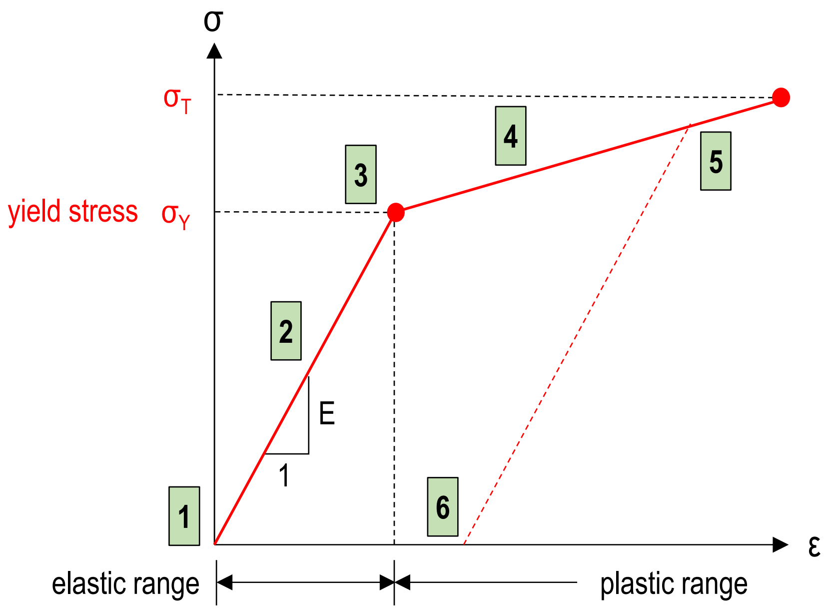
ultimate stress

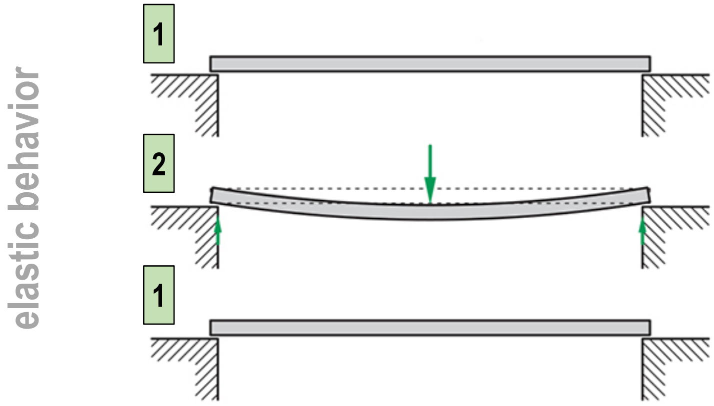


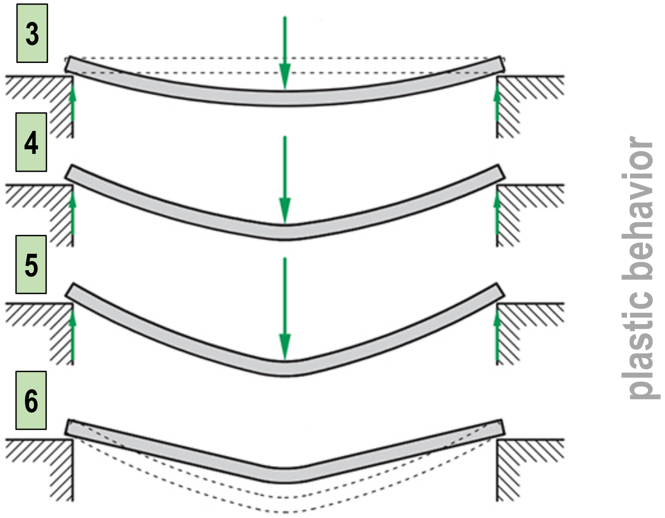
Solid Material

elastic and plastic range



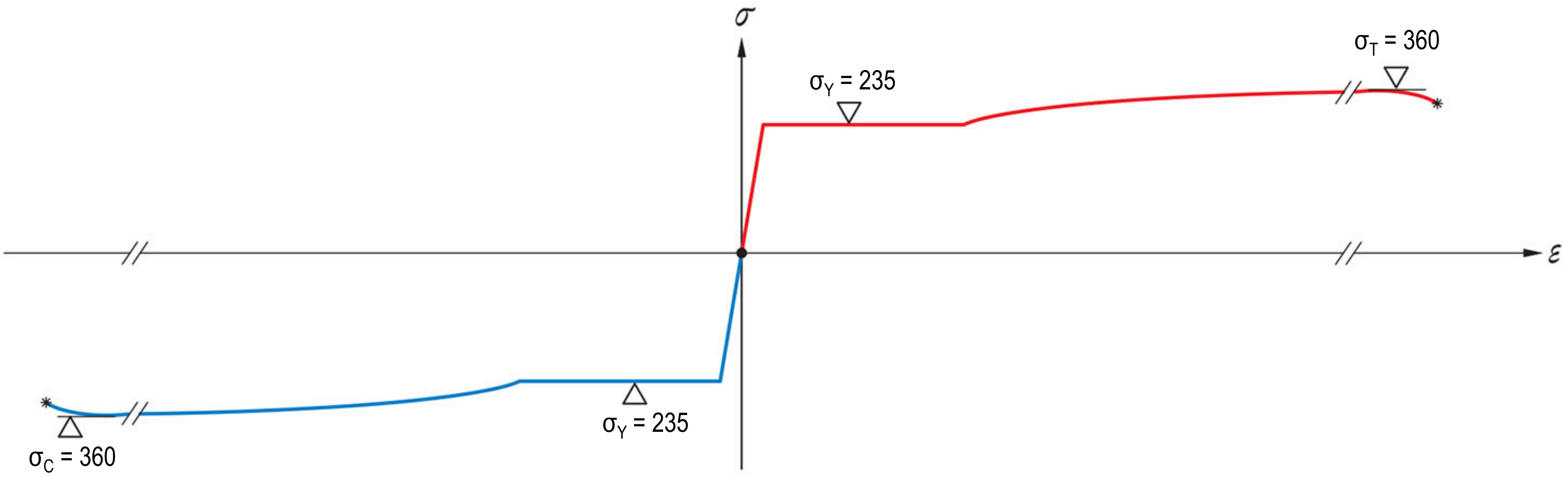






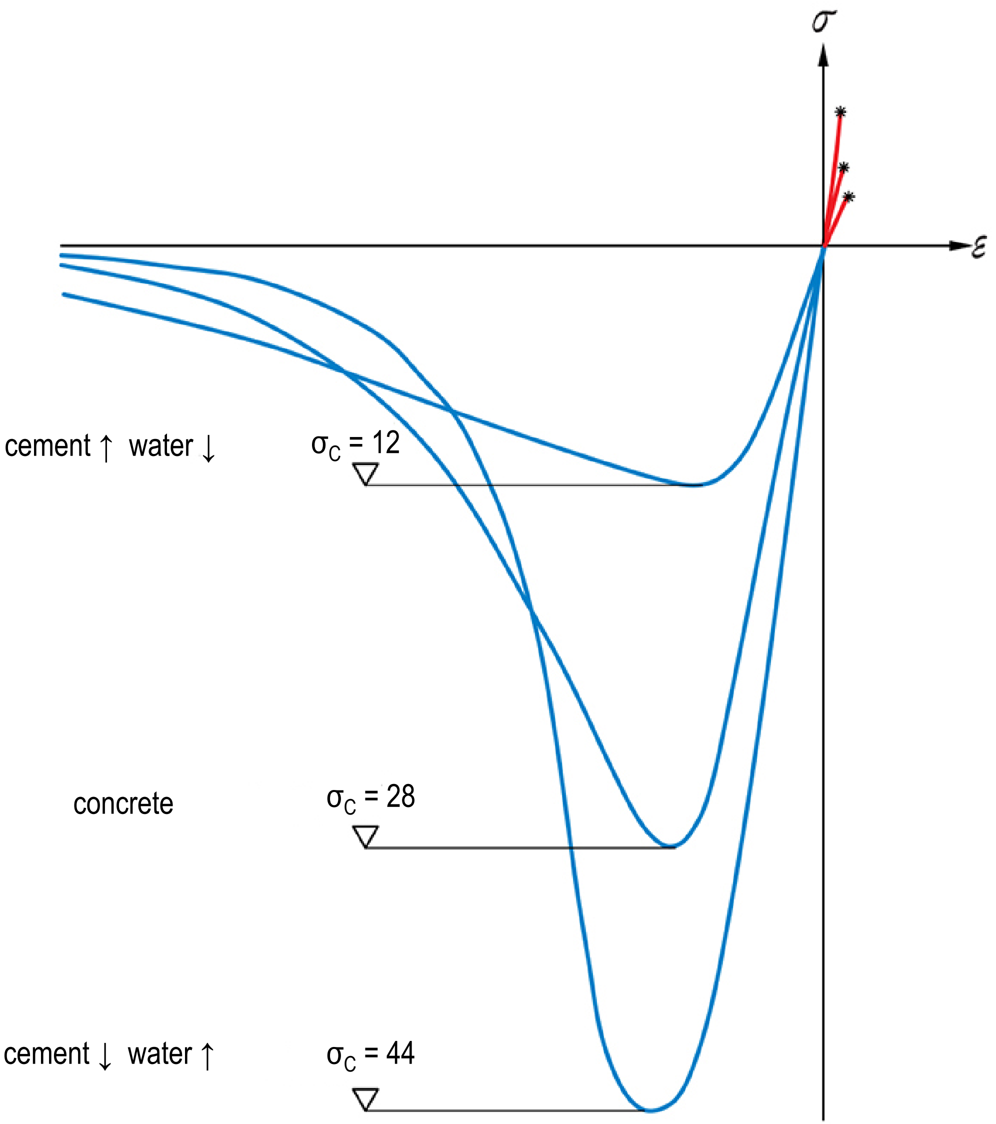
Solid Material

steel



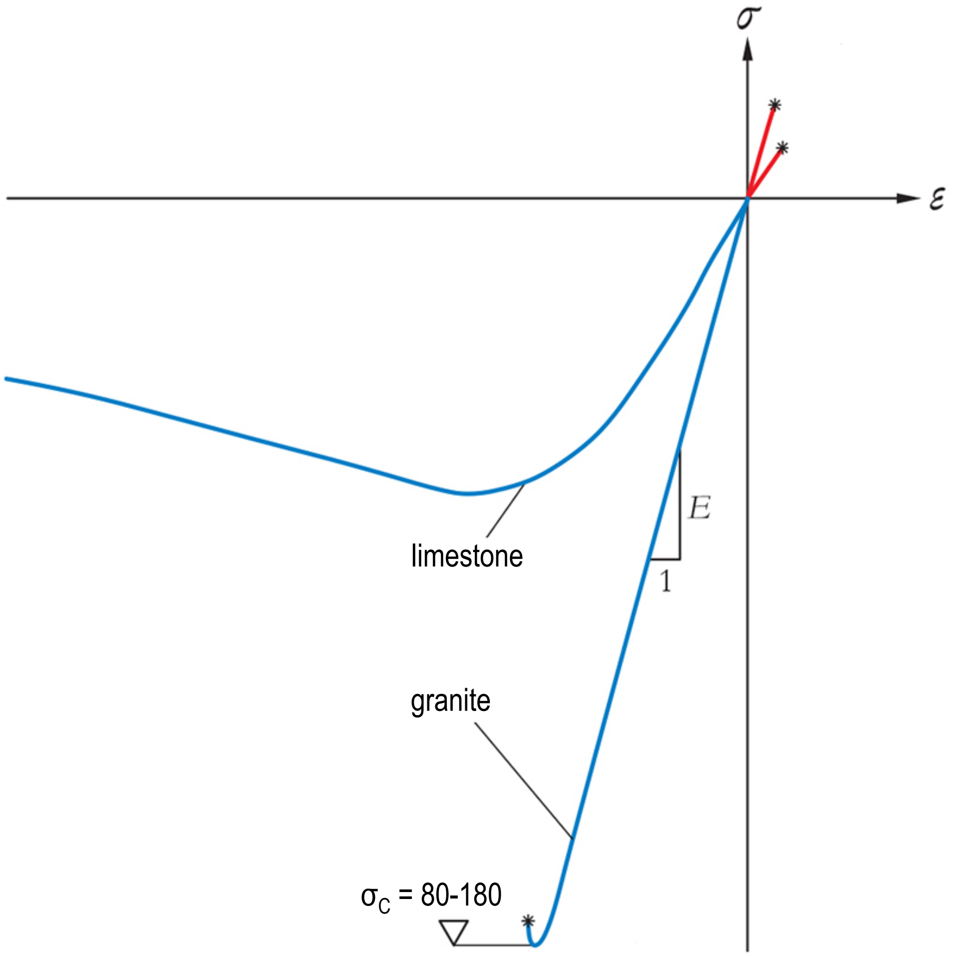
Solid Material

concrete



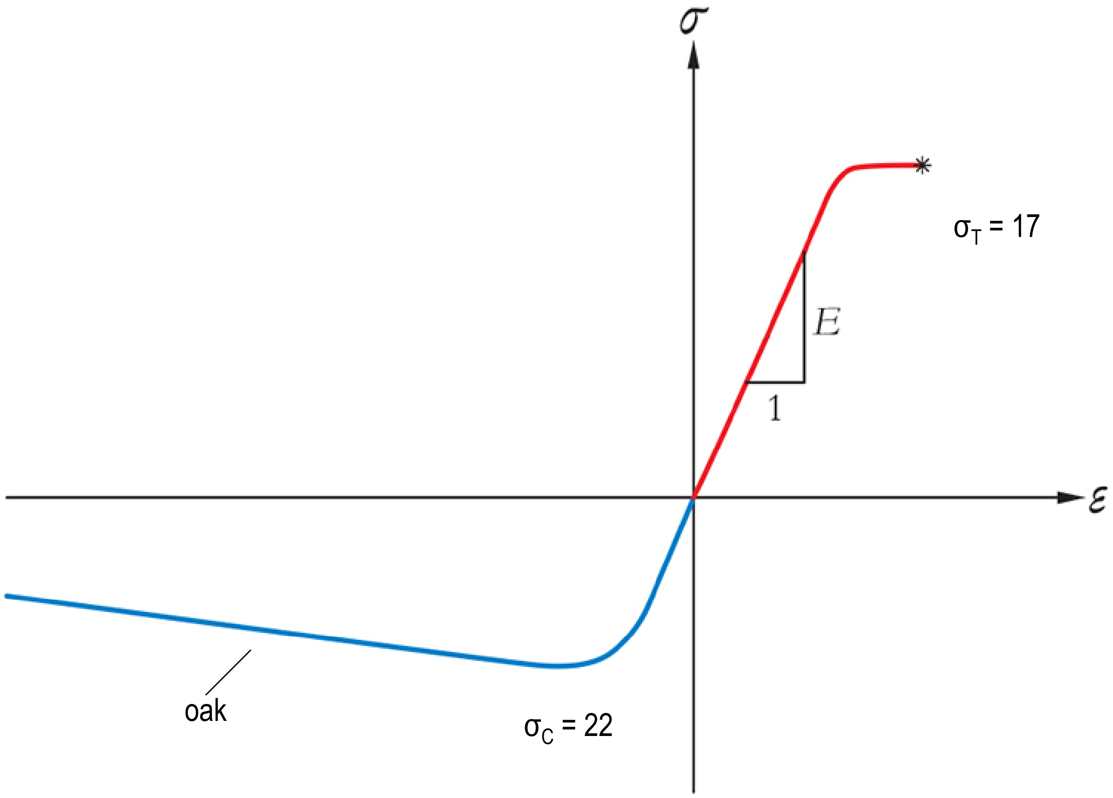
Solid Material

stone



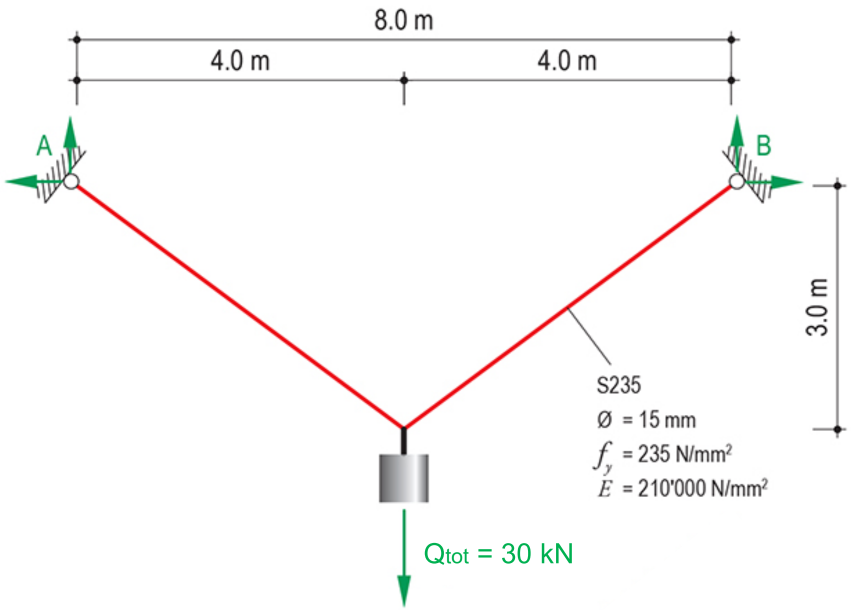
Solid Material

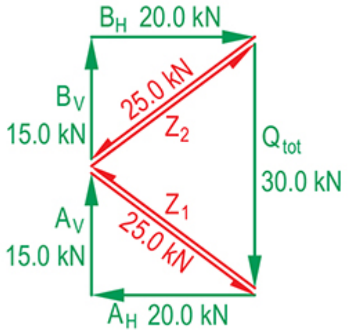
wood



Solid Material

dimensioning





$$\sigma = \frac{F}{A} = \frac{25\text{kN}}{176.71\ \text{mm}^2} = 141.47\ \text{N/mm}^2$$

$\sigma = E \cdot \varepsilon$ implies $\varepsilon = \sigma / E = 141.47\ \text{N/mm}^2 / 210´000\ \text{N/mm}^2 = 0.0672\ \%$

with $\varepsilon = \Delta l / l$ it follows $\Delta l = 5\ \text{m} \cdot 0.0672\ \% = 3.36\ \text{mm}$

$\boxed{\sigma = \frac{F}{A}}$ **stress**

$\boxed{\sigma = E \cdot \varepsilon}$ **stress**

$\boxed{\varepsilon = \Delta l / l}$ **strain**

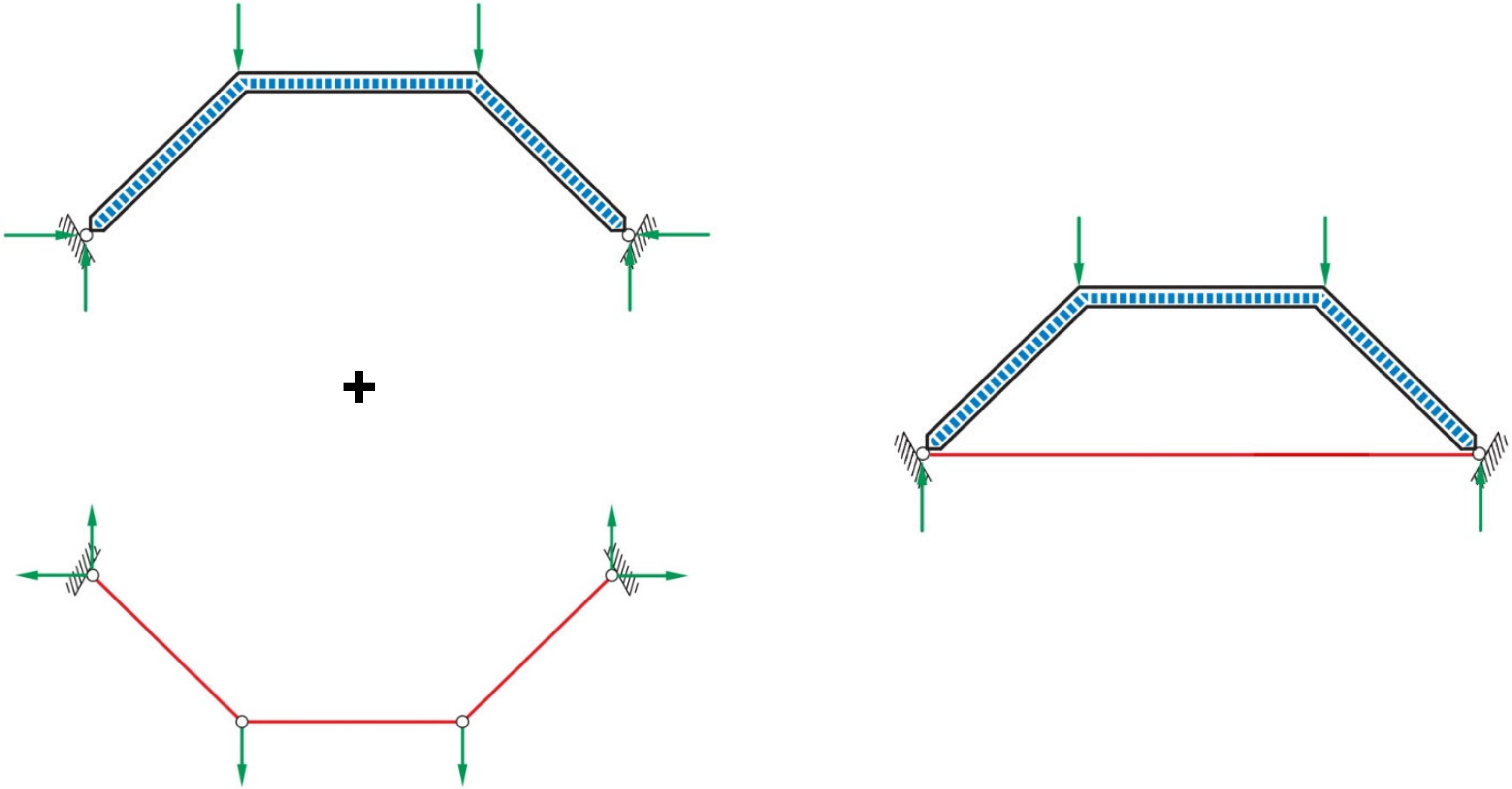
Tension + Compression

arch

only compression as inner foces

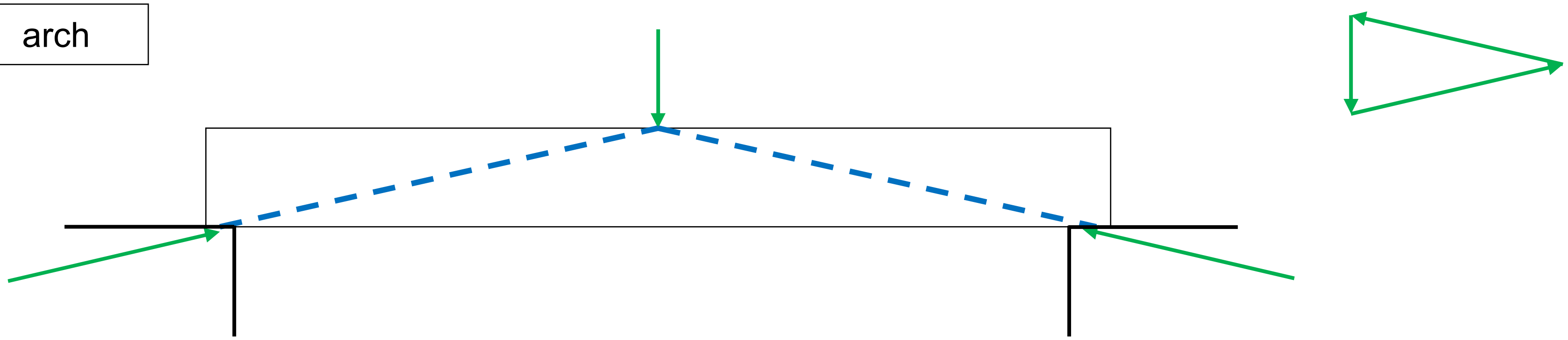
cable

only tension as inner foces



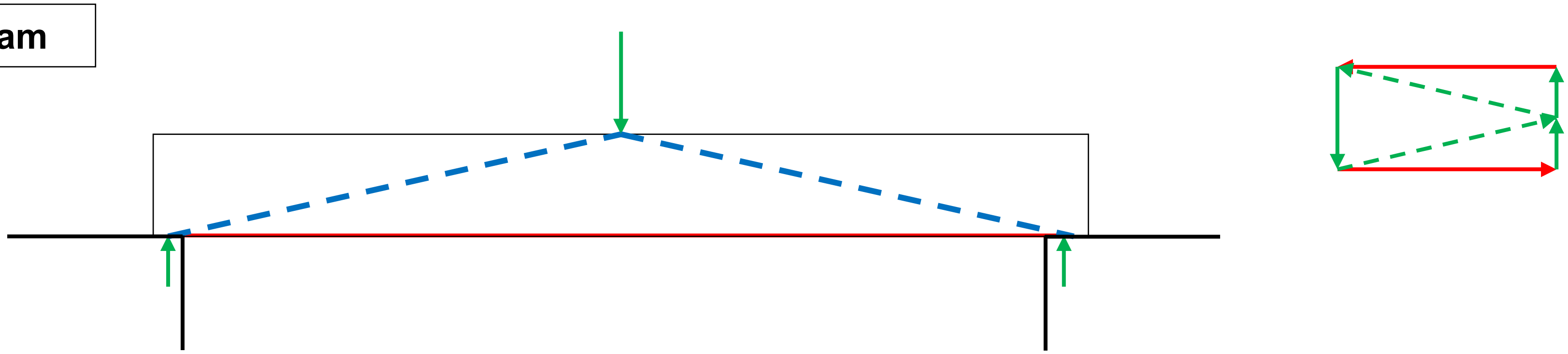
inner force if beam can take **compression**

arch



inner force if beam can take **compression & tension**

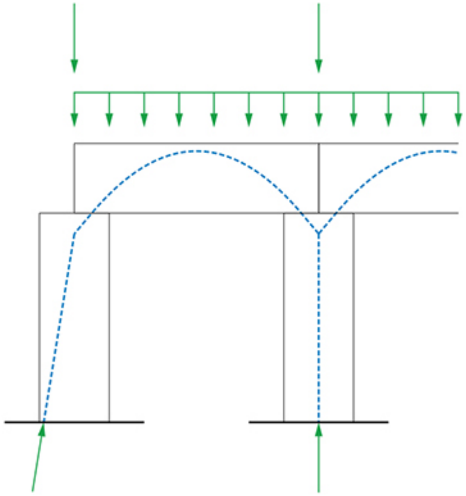
beam

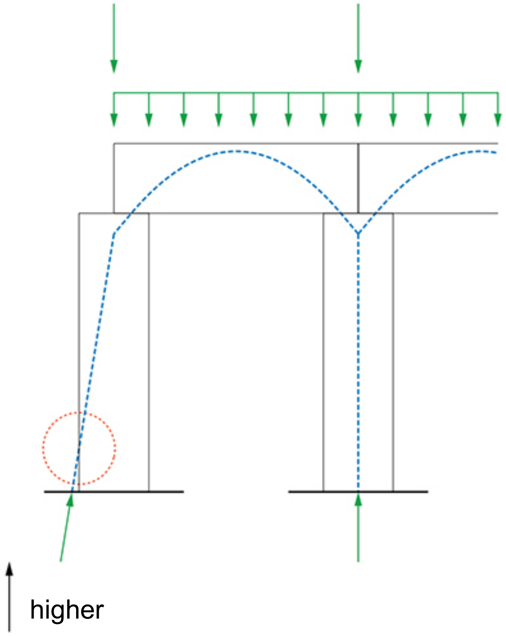


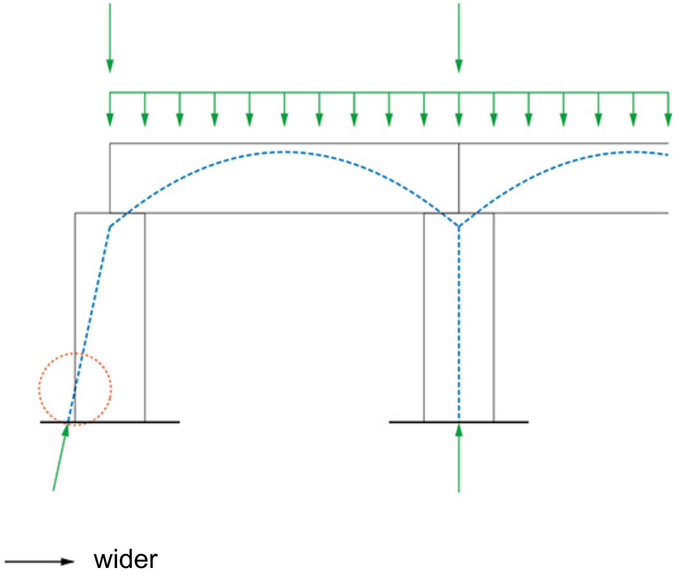
Column & Beam

Temple E,Selinunt
Italy, around 460-450 BC

Column & Beam



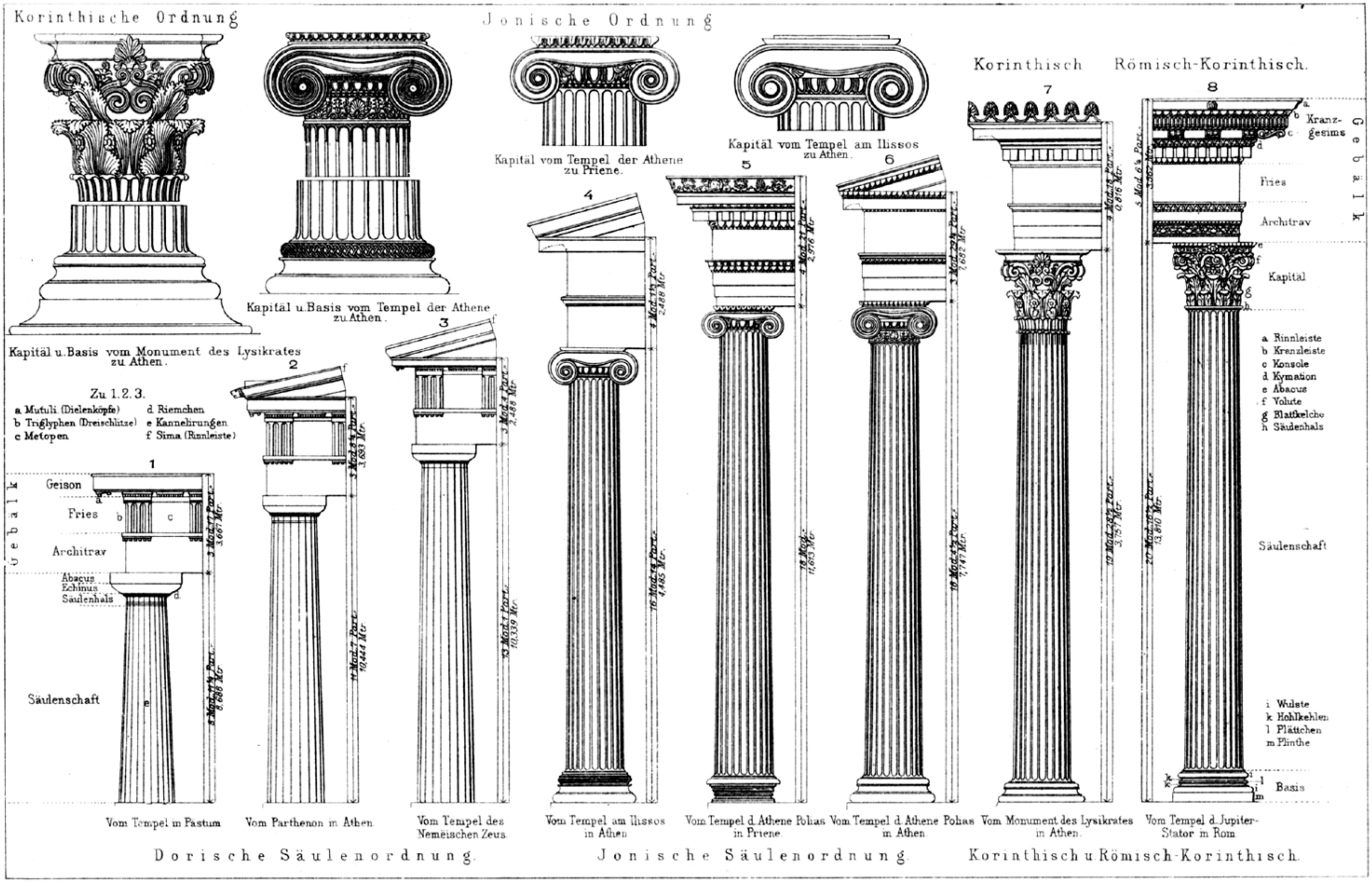




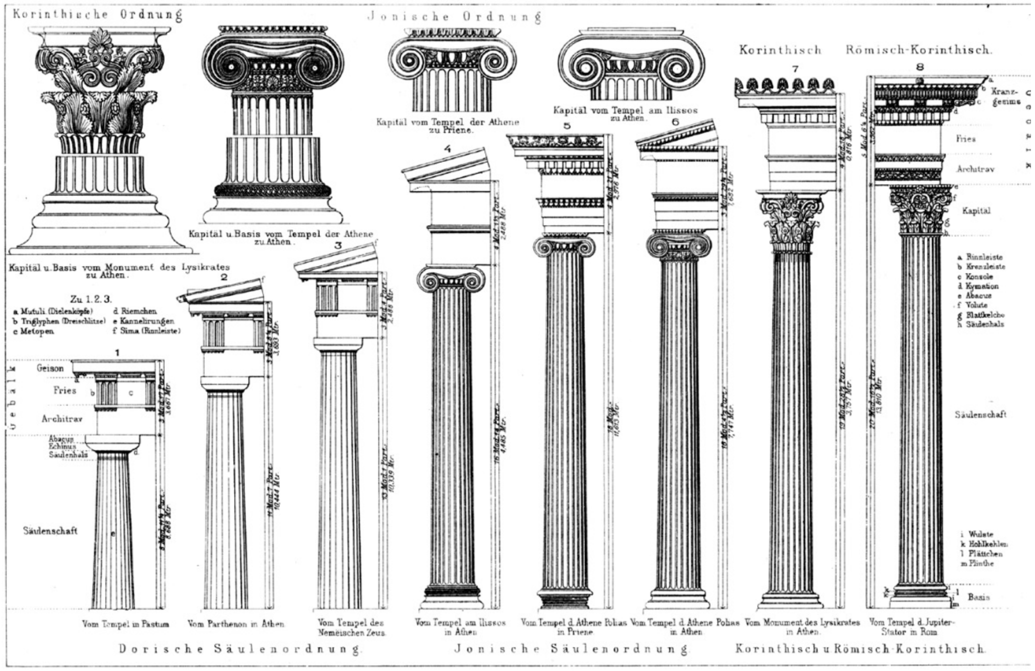
stone
dimensions of column and beam are
dependent on each other

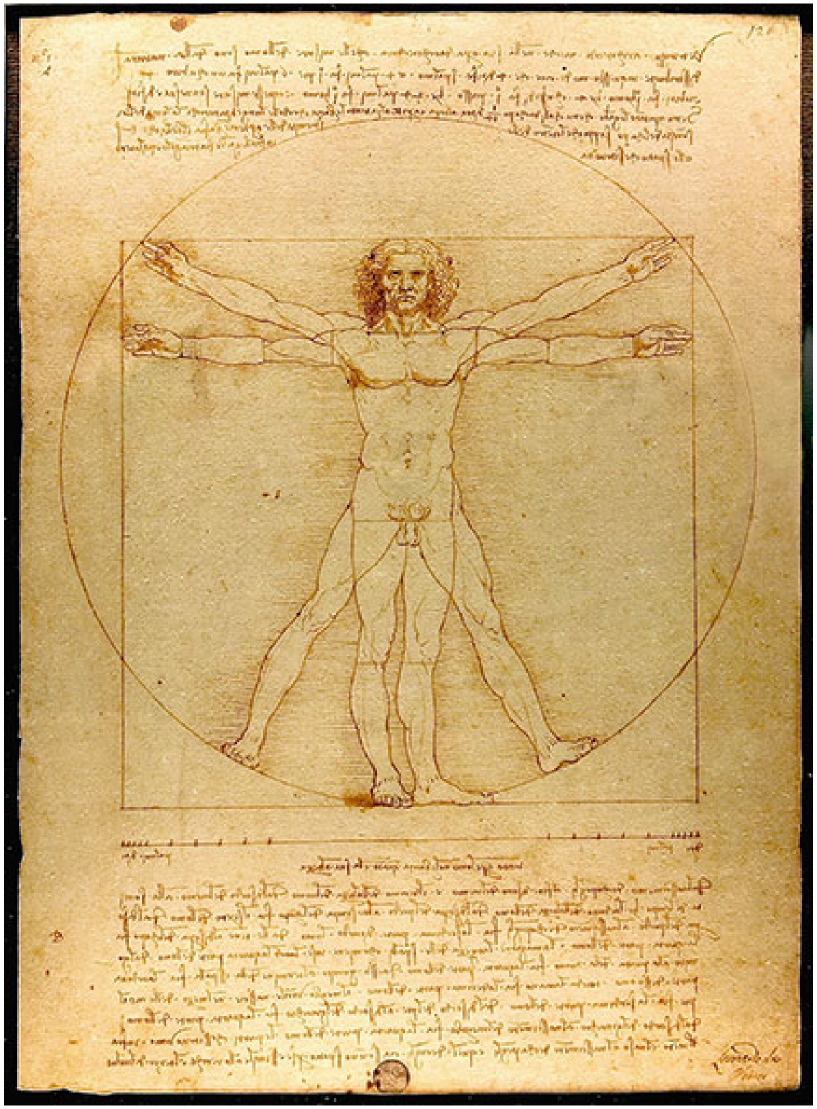
Column & Beam

proportion system



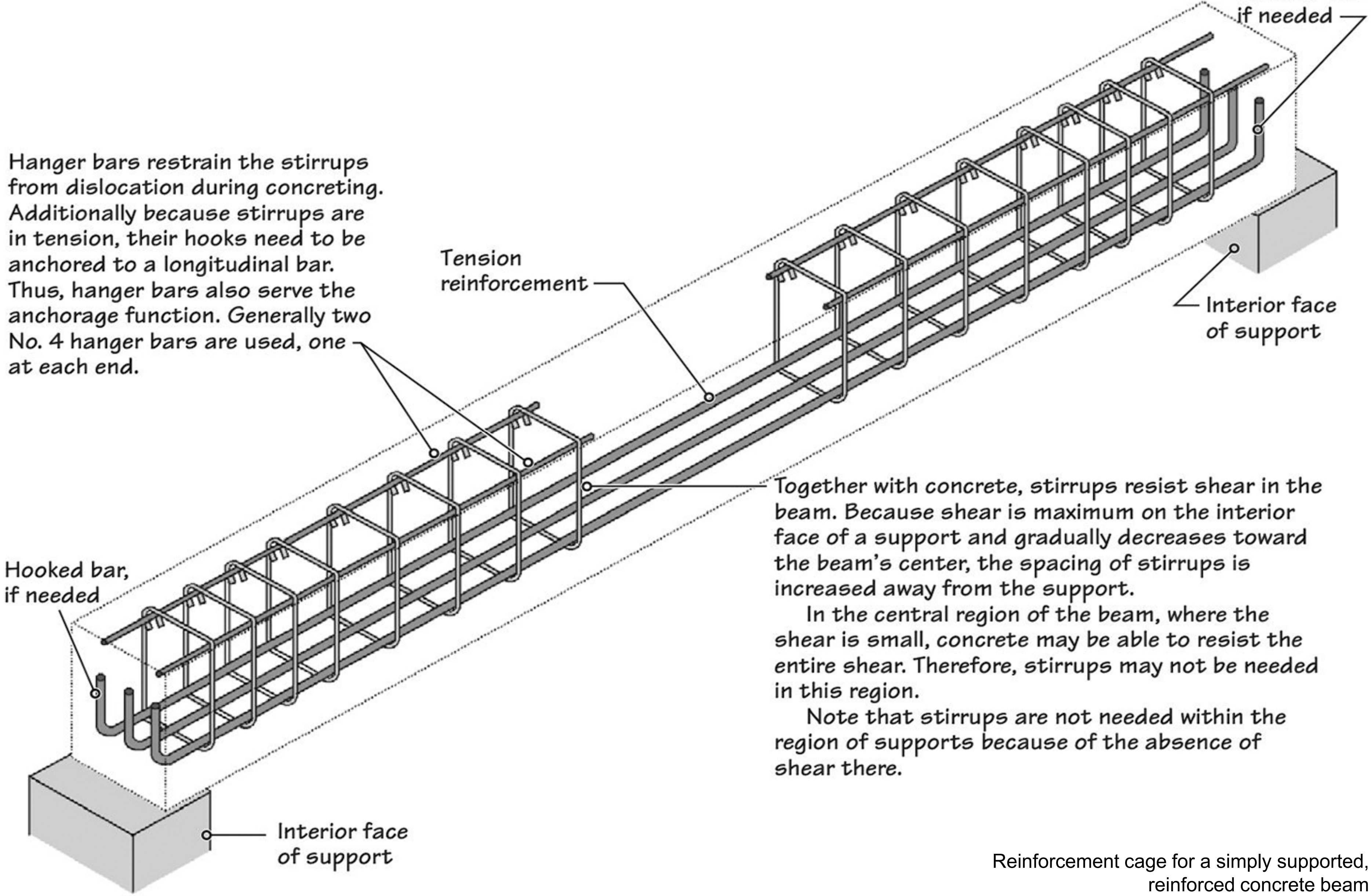
Column & Beam
proportion system





Leonardo da Vinci: Vitruvian Man
Italy, around 1490

Beam



Hanger bars restrain the stirrups from dislocation during concreting. Additionally because stirrups are in tension, their hooks need to be anchored to a longitudinal bar. Thus, hanger bars also serve the anchorage function. Generally two No. 4 hanger bars are used, one at each end.

Tension reinforcement

Hooked bar, if needed

Interior face of support

Together with concrete, stirrups resist shear in the beam. Because shear is maximum on the interior face of a support and gradually decreases toward the beam's center, the spacing of stirrups is increased away from the support.

In the central region of the beam, where the shear is small, concrete may be able to resist the entire shear. Therefore, stirrups may not be needed in this region.

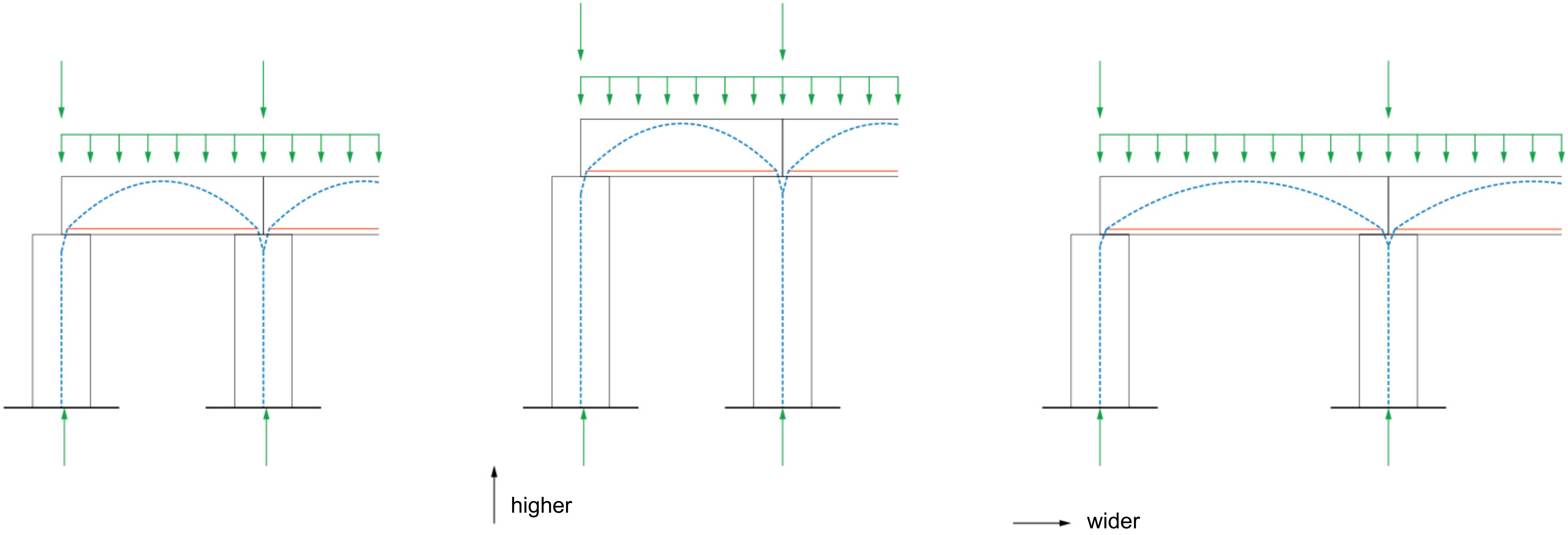
Note that stirrups are not needed within the region of supports because of the absence of shear there.

Hooked bar, if needed

Interior face of support

Reinforcement cage for a simply supported, reinforced concrete beam

Column & Beam



(reinforced) concrete
dimensions of column and beam are
independent of each other

Column & Beam

> *„For us [as architects], it is fortunate that with scientific progress construction methods and techniques are changing over the course of time. Due to this change of construction methods the appearance of buildings is changing, too. That is the development of construction methods drives the evolution of architecture.“*
>
> Livio Vacchini

Livio Vacchini: Sport Centre Mühlimatt
Windisch, Switzerland, 2010

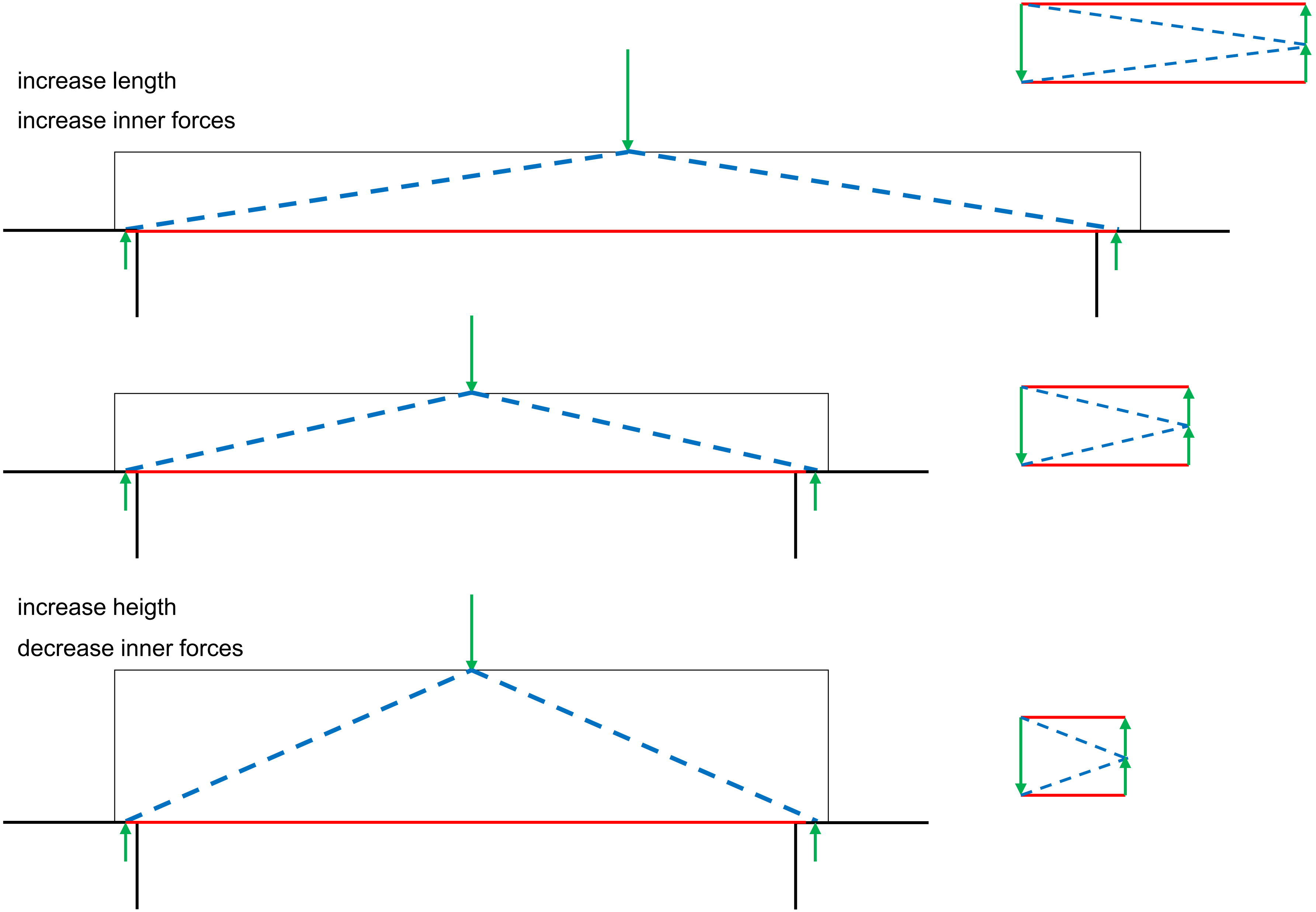
Beam

↑ increase length

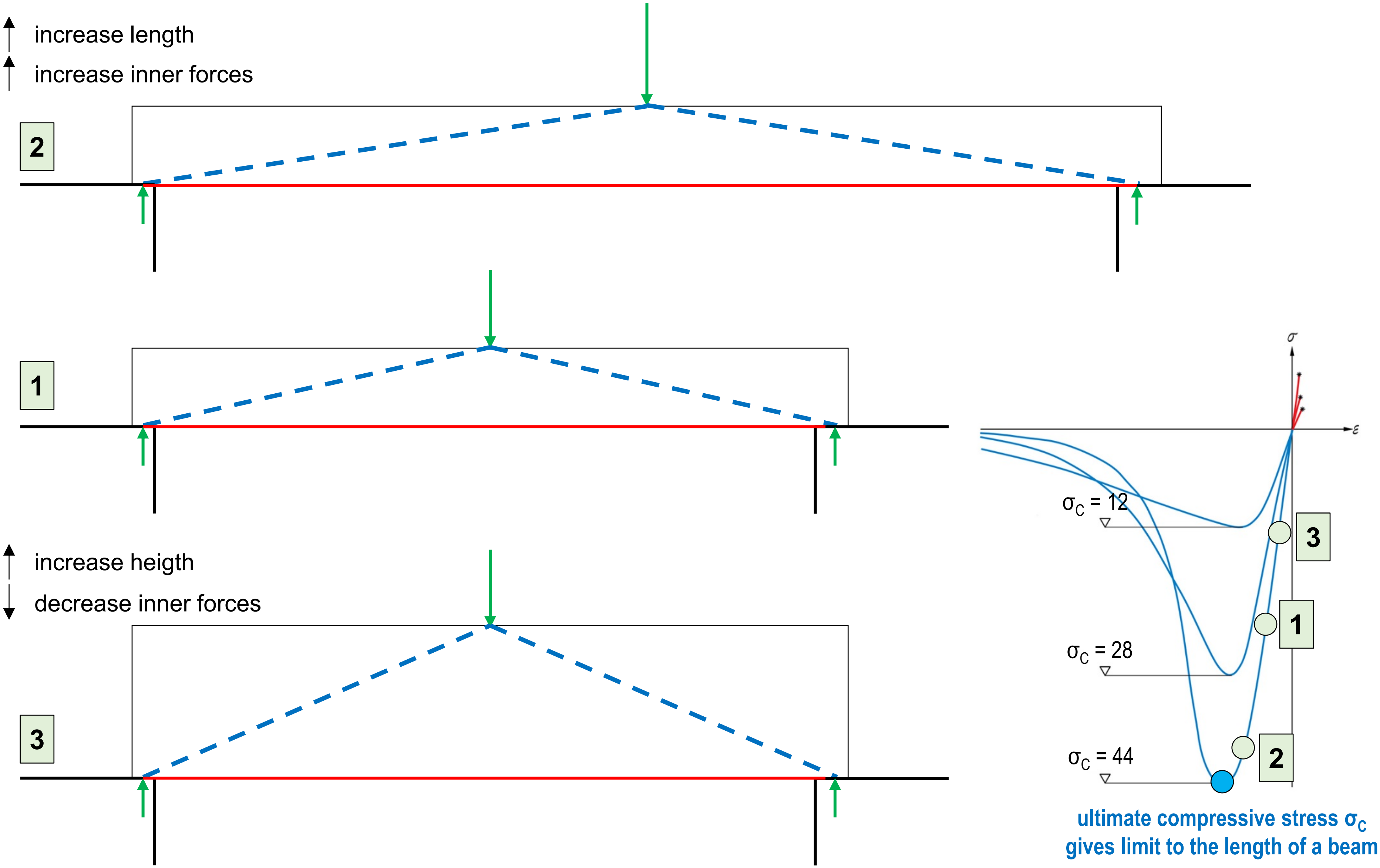
↑ increase inner forces

↑ increase heigth

↓ decrease inner forces



Beam

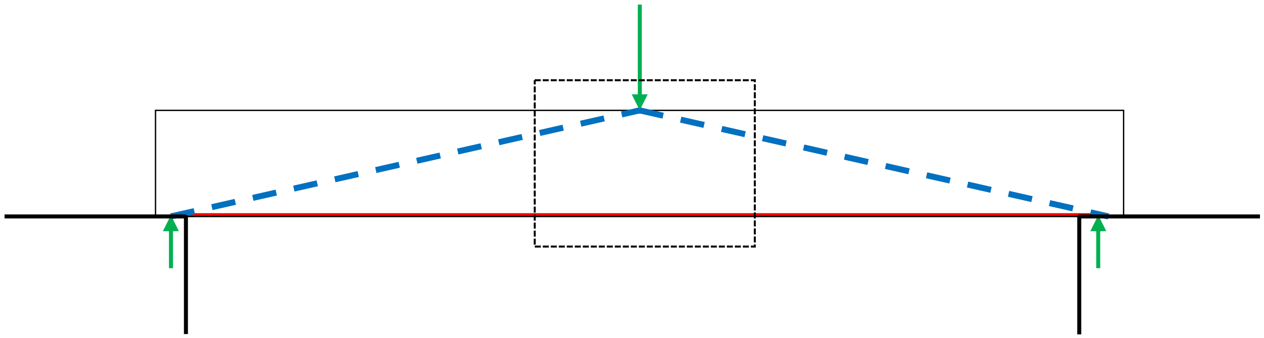


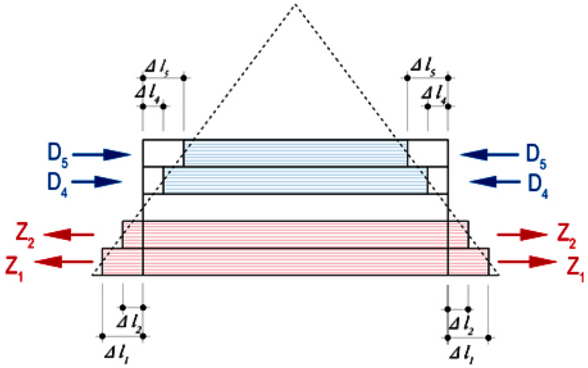
↑ increase length
↑ increase inner forces

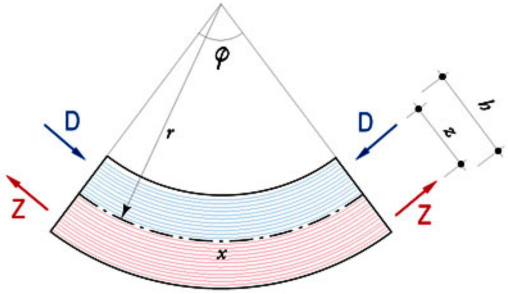
↑ increase heigth
↓ decrease inner forces

ultimate compressive stress σ_C gives limit to the length of a beam

Bending

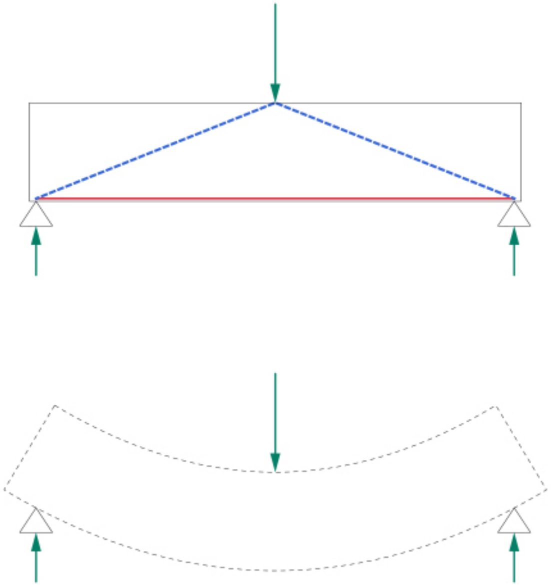




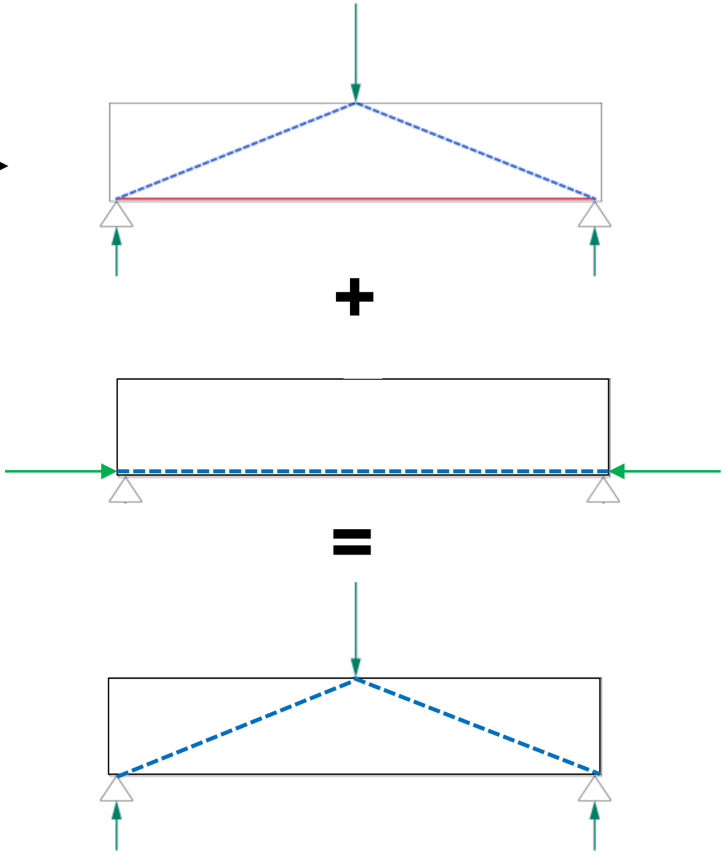


compression and tension in the same section results in **bending**

Post-Tensioned Beam



strategy against bending

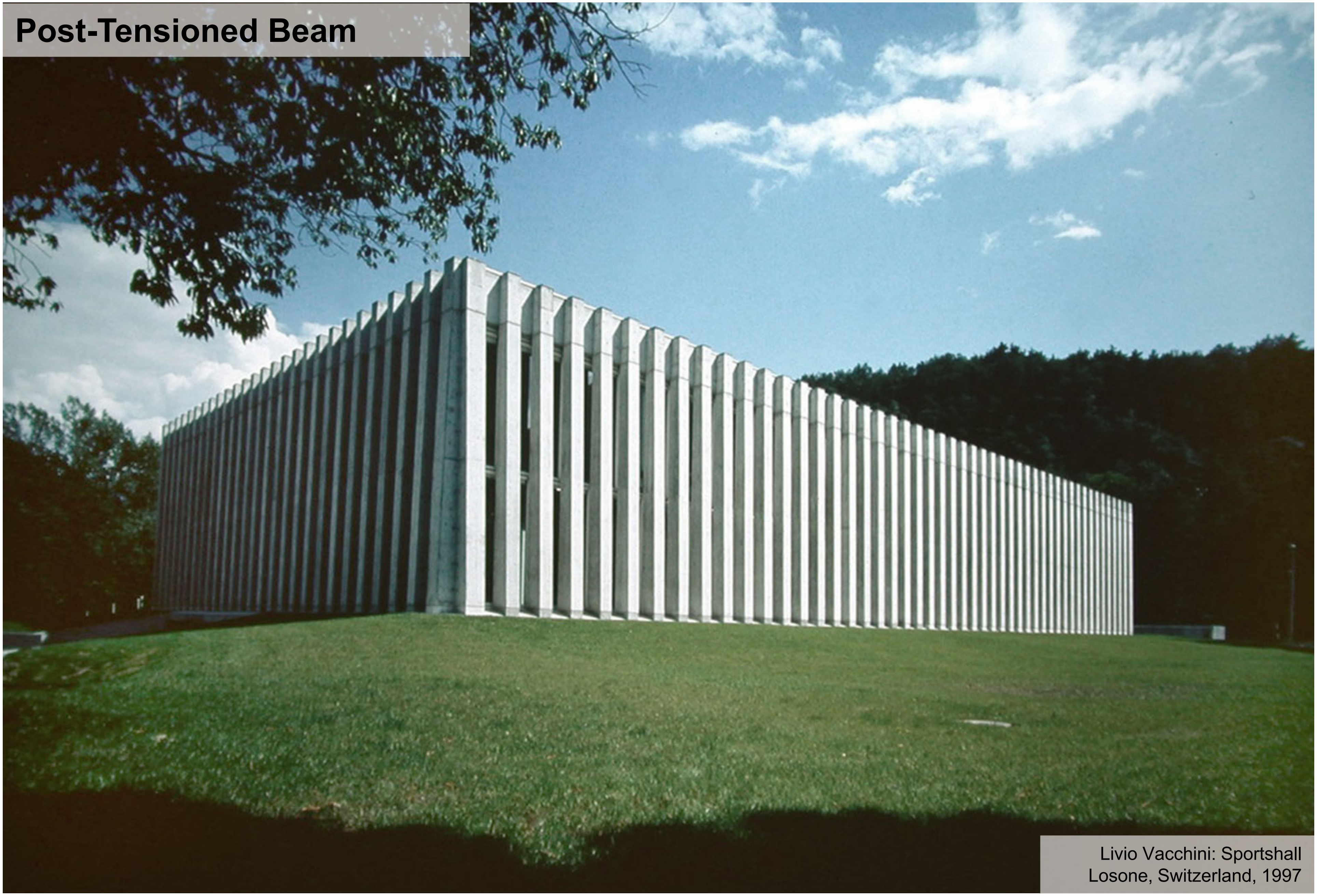


tension cable
to press both ends of
beam together

compression and tension in the same section results in **bending**

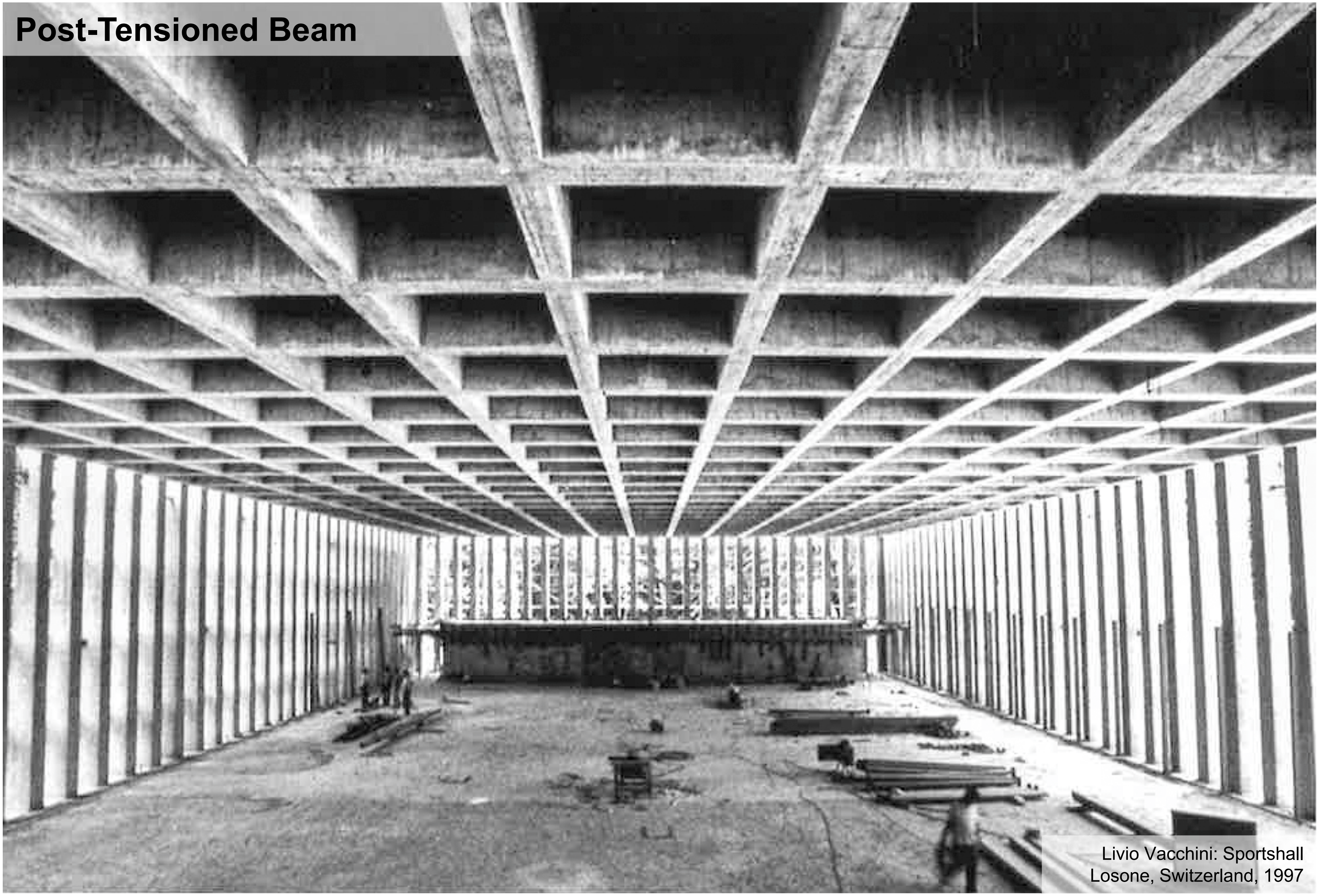
compensate tension by additional compression

Post-Tensioned Beam



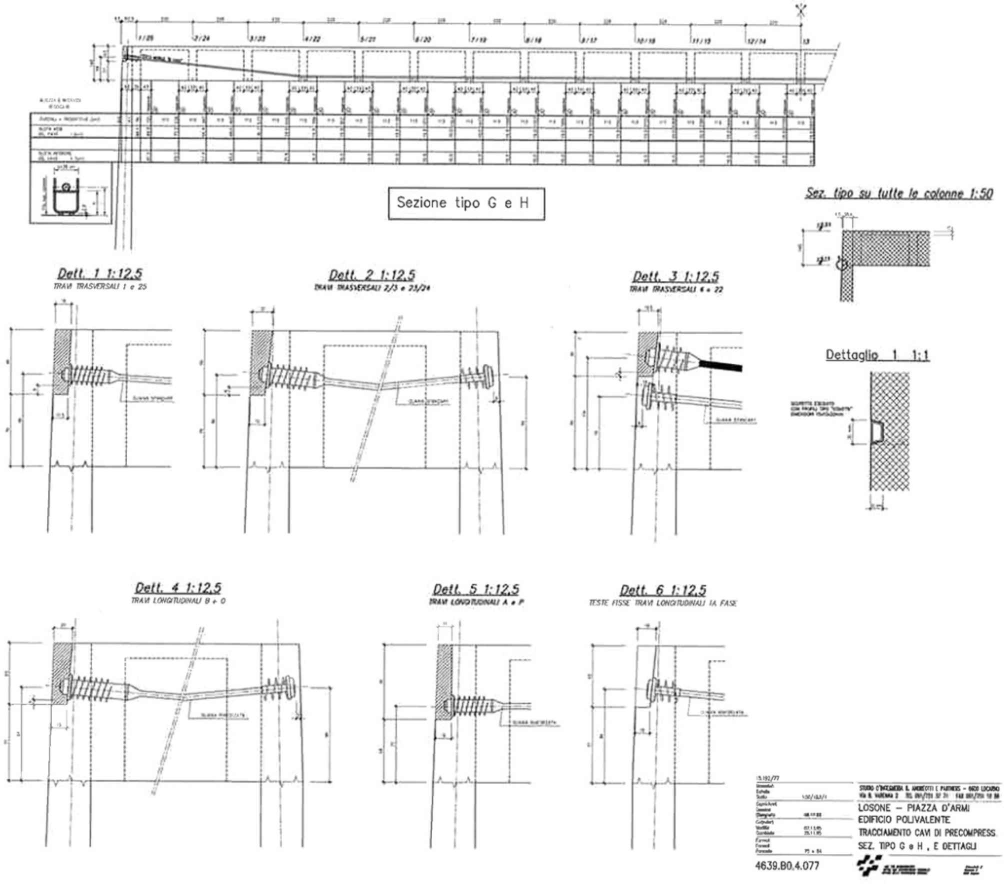
Livio Vacchini: Sportshall
Losone, Switzerland, 1997

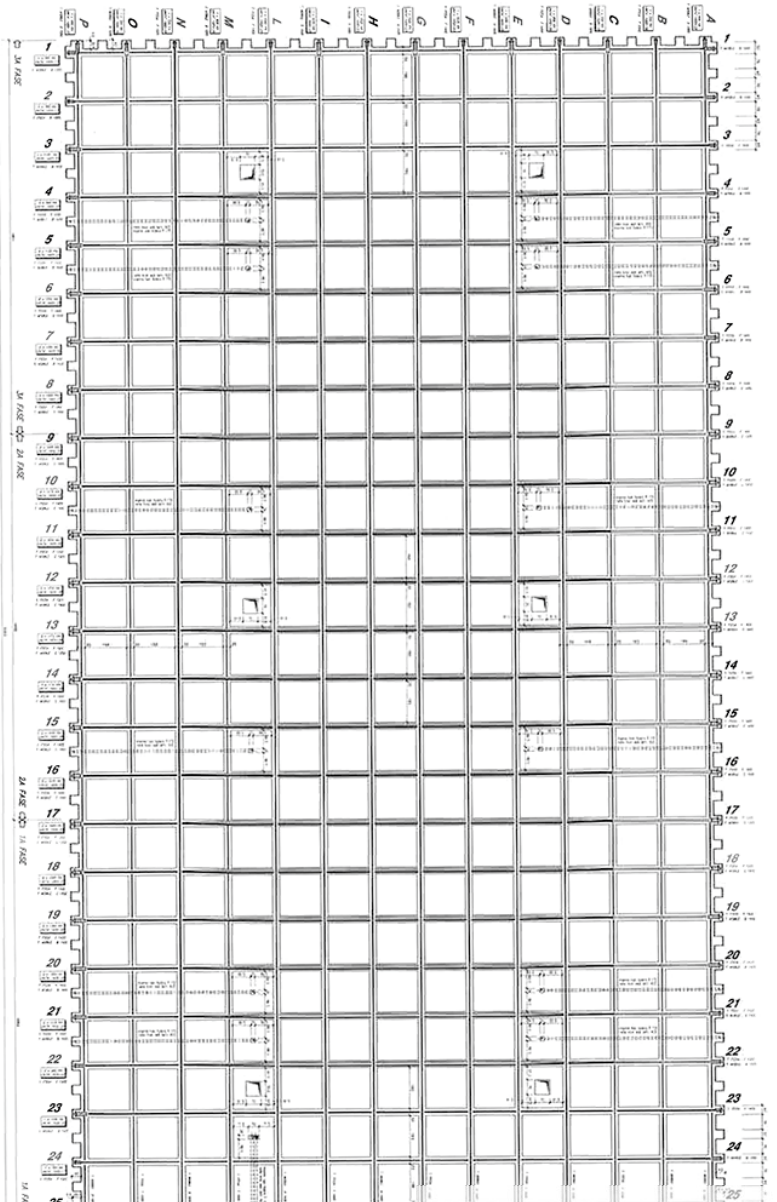
Post-Tensioned Beam



Livio Vacchini: Sportshall
Losone, Switzerland, 1997

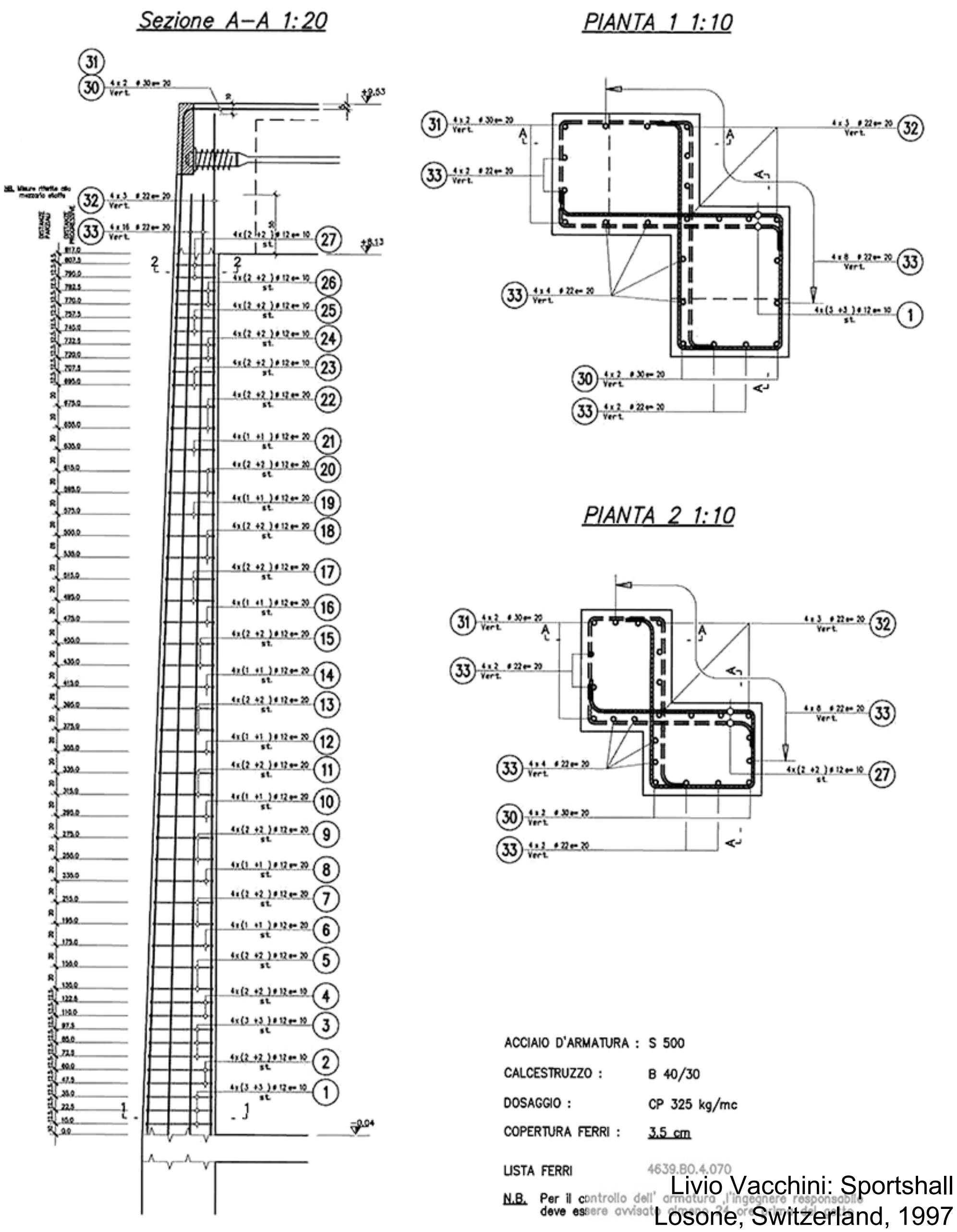
Post-Tensioned Beam





Livio Vacchini: Sportshall
Losone, Switzerland, 1997

Post-Tensioned Beam



ACCIAIO D'ARMATURA : S 500

CALCESTRUZZO : B 40/30

DOSAGGIO : CP 325 kg/mc

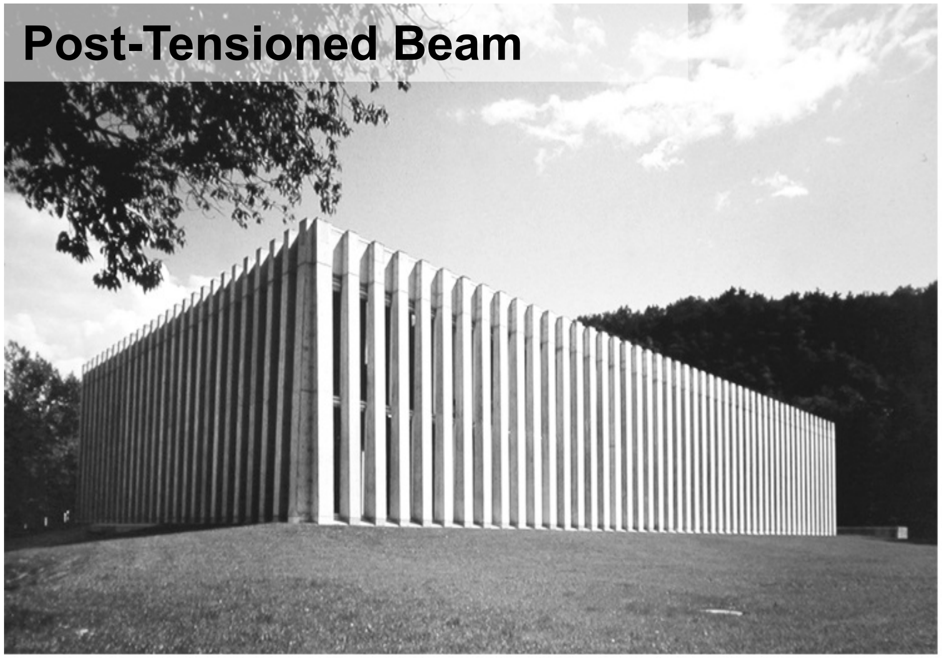
COPERTURA FERRI : 3.5 cm

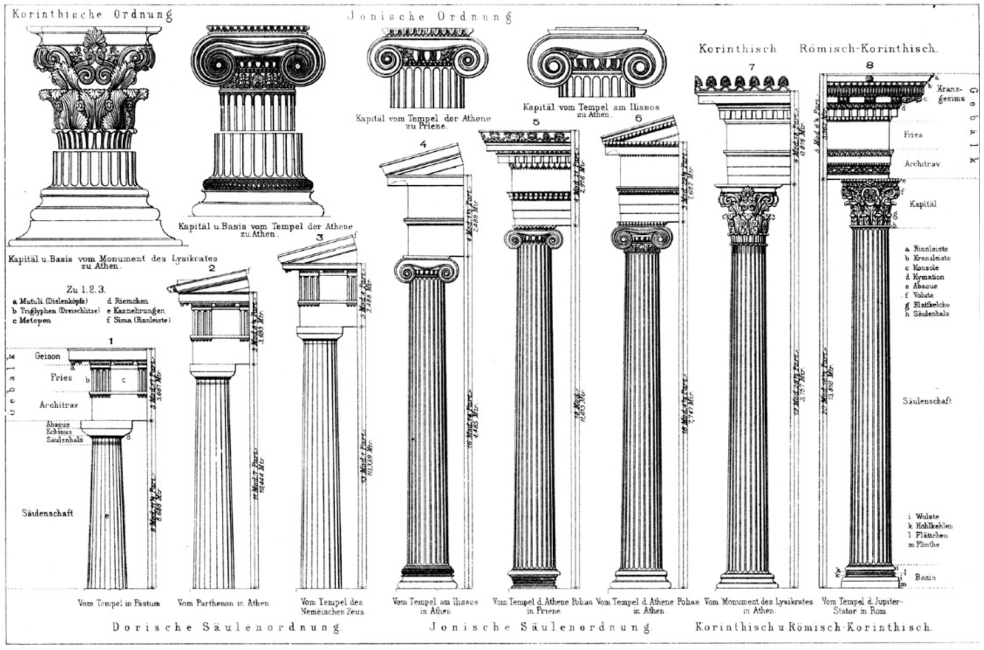
LISTA FERRI 4639.B0.4.070

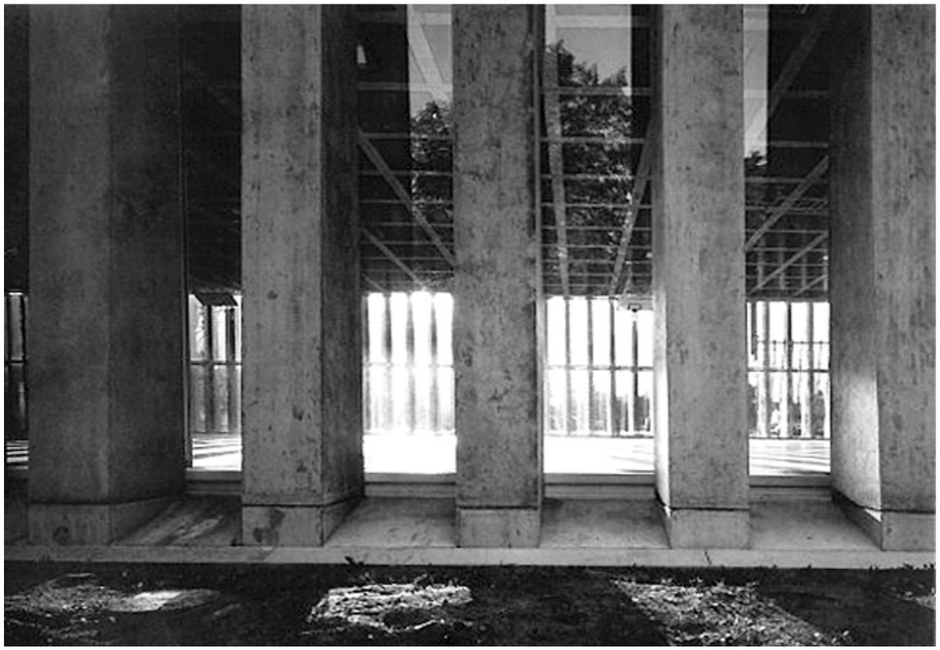
N.B. Per il controllo dell' armatura ,l'ingegnere responsabile deve essere avvisato almeno 24 ore prima del getto.

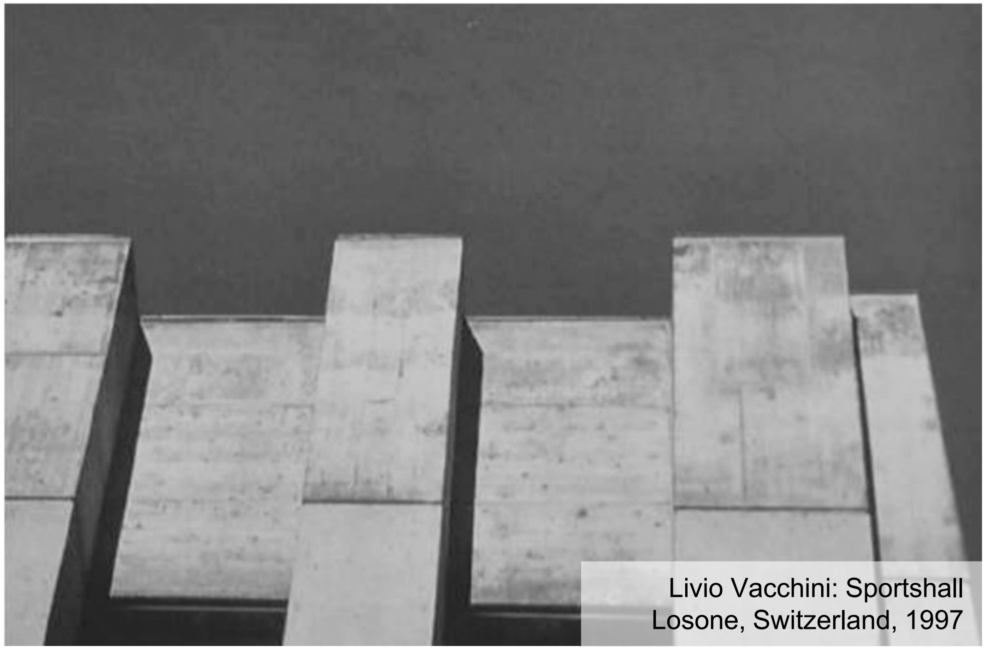
Livio Vacchini: Sportshall
Losone, Switzerland, 1997

Post-Tensioned Beam





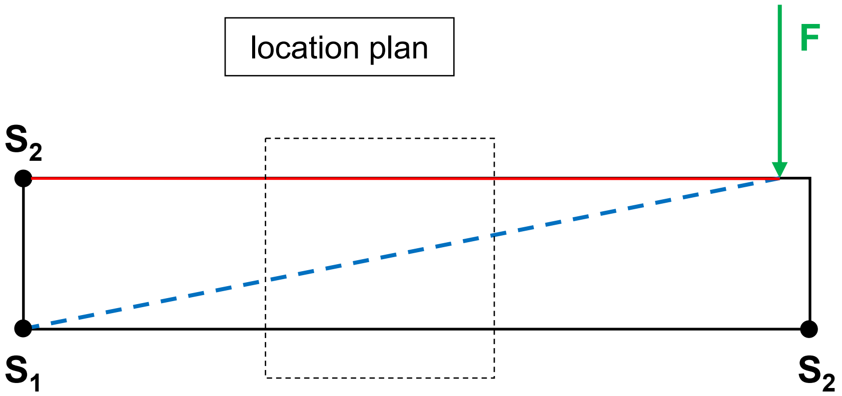




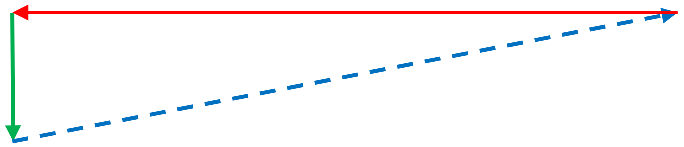
Livio Vacchini: Sportshall
Losone, Switzerland, 1997

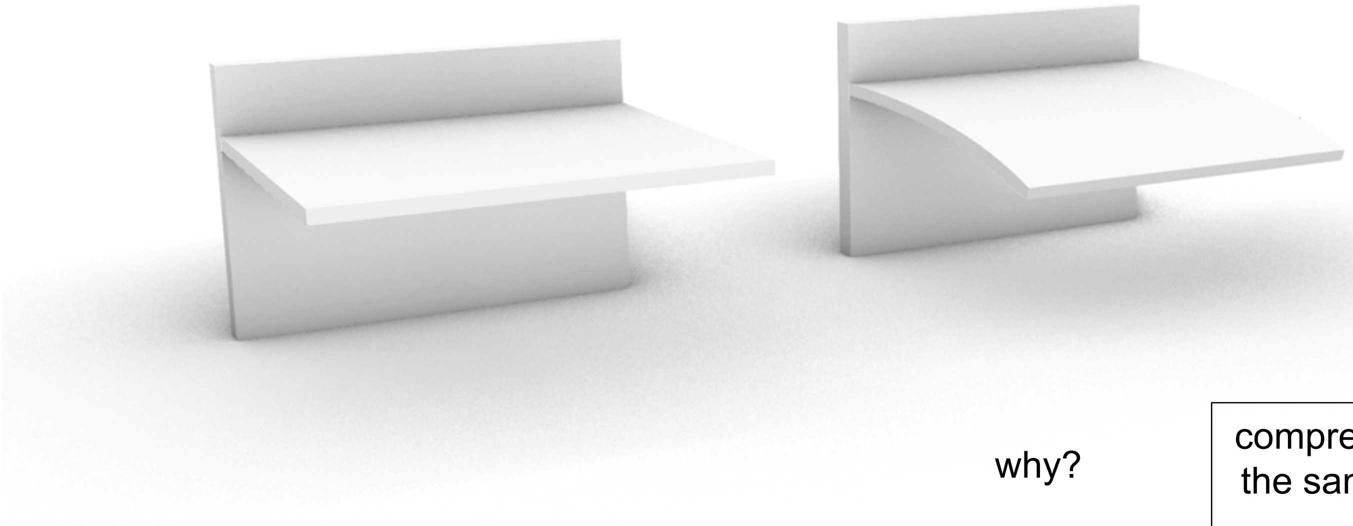
Cantilever

location plan



force plan



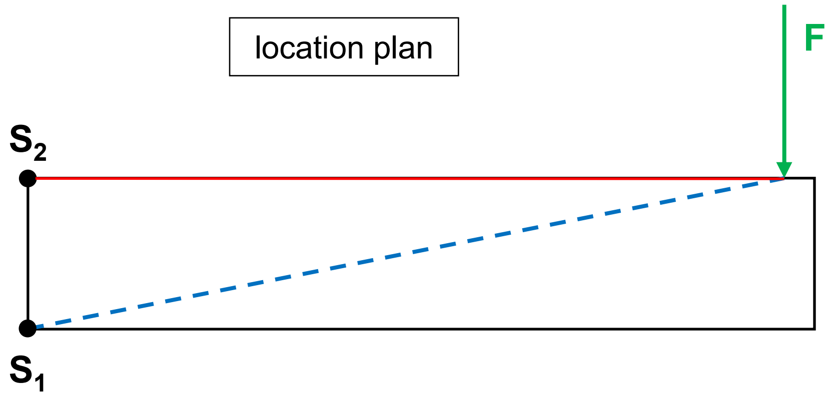


why?

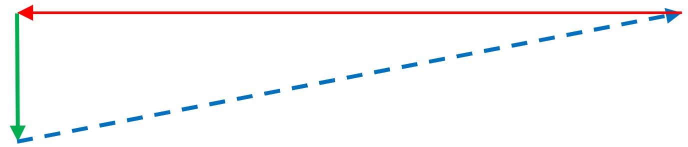
compression and tension in the same section results in **bending**

Cantilever

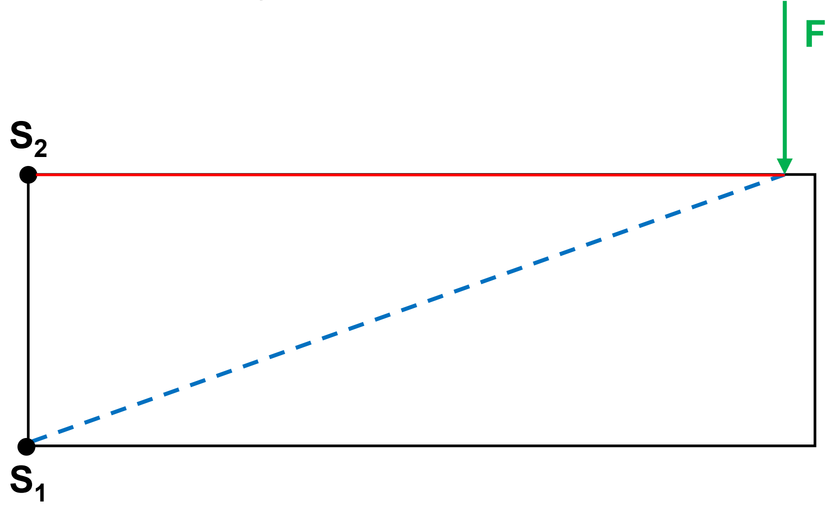
location plan

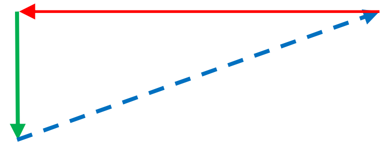


force plan



reduce bending by reducing
magnitude of inner forces



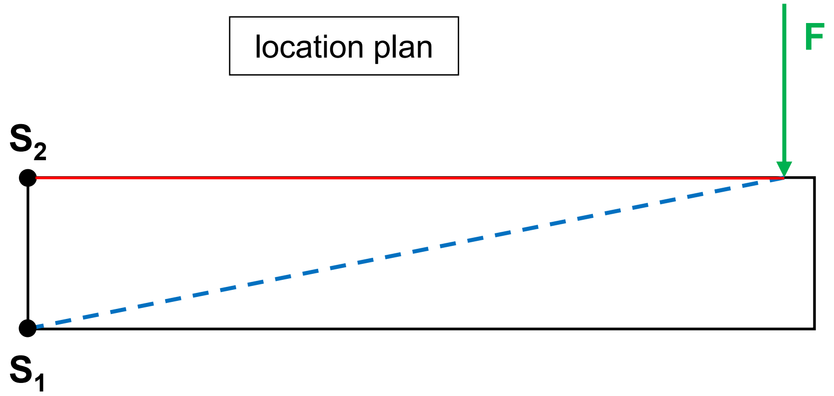


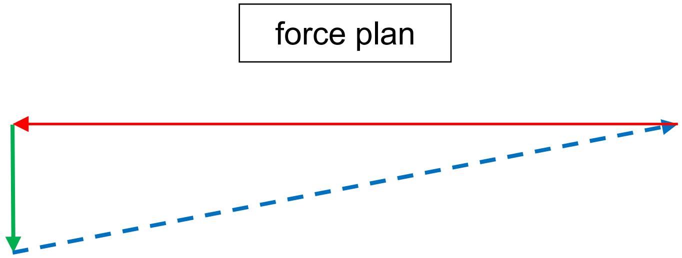
increase height of cantilever

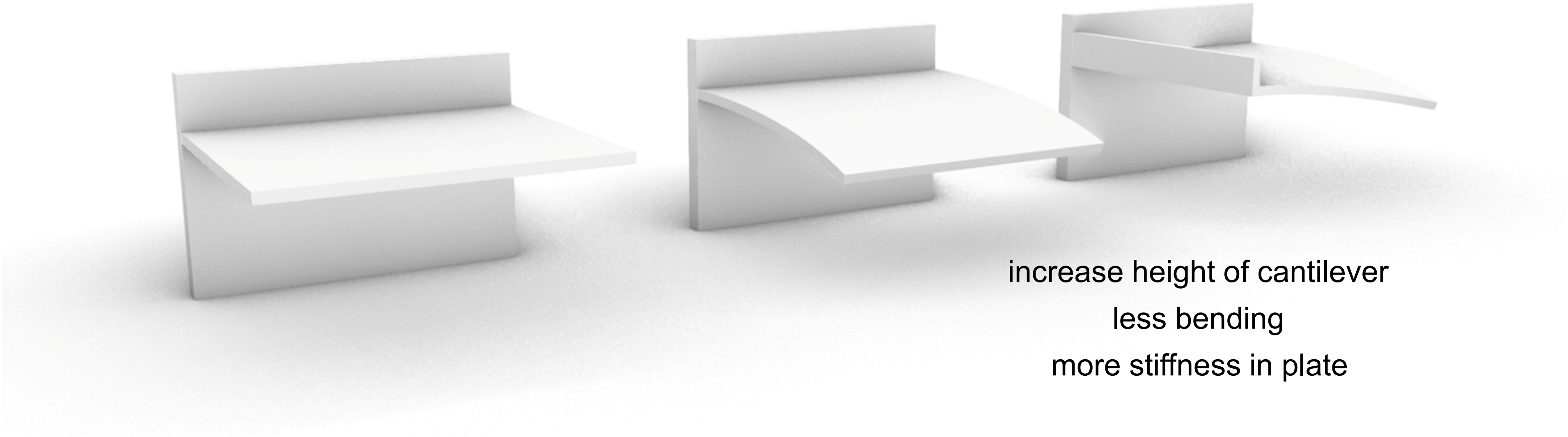
less inner forces

less bending

Cantilever







increase height of cantilever

less bending

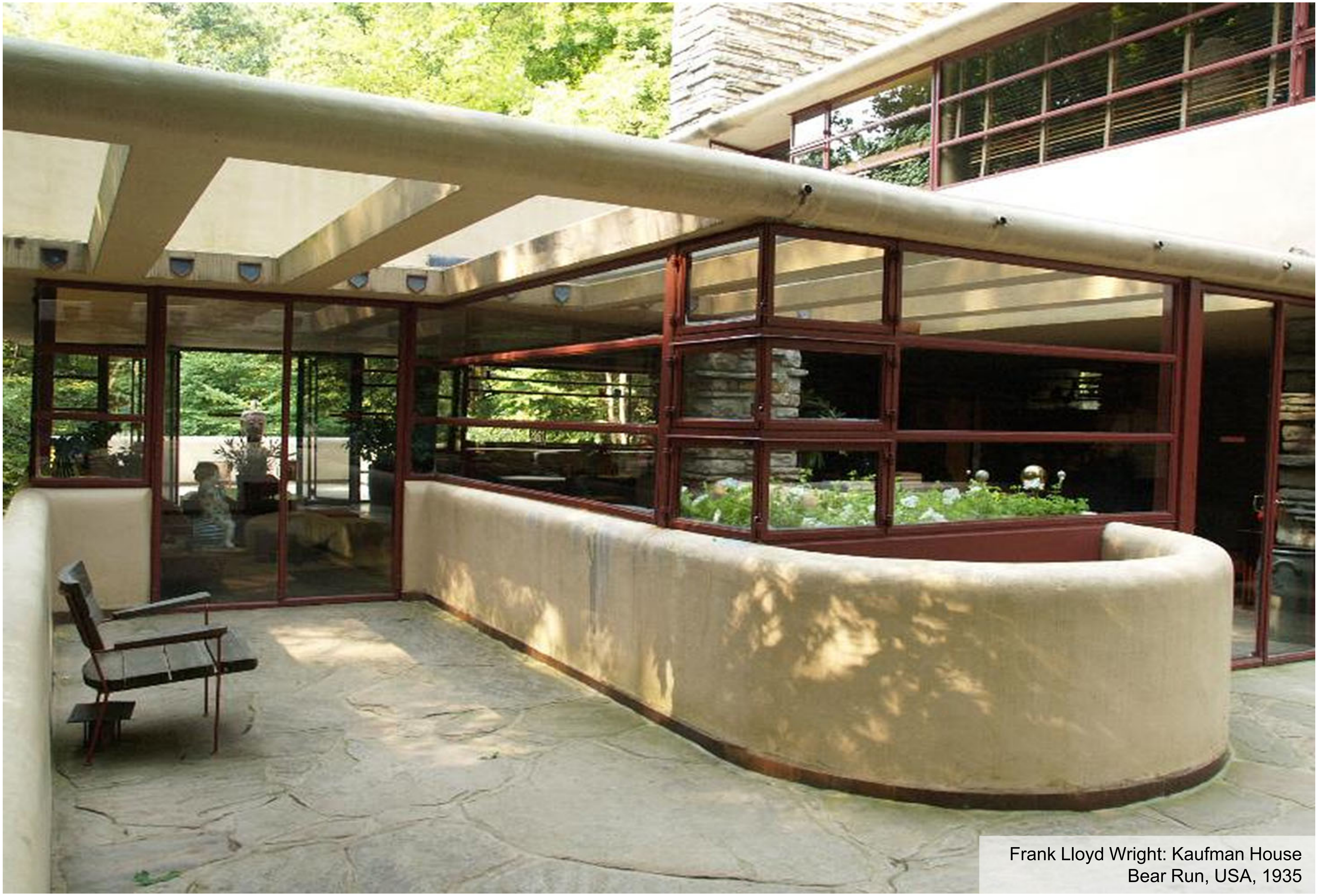
more stiffness in plate

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

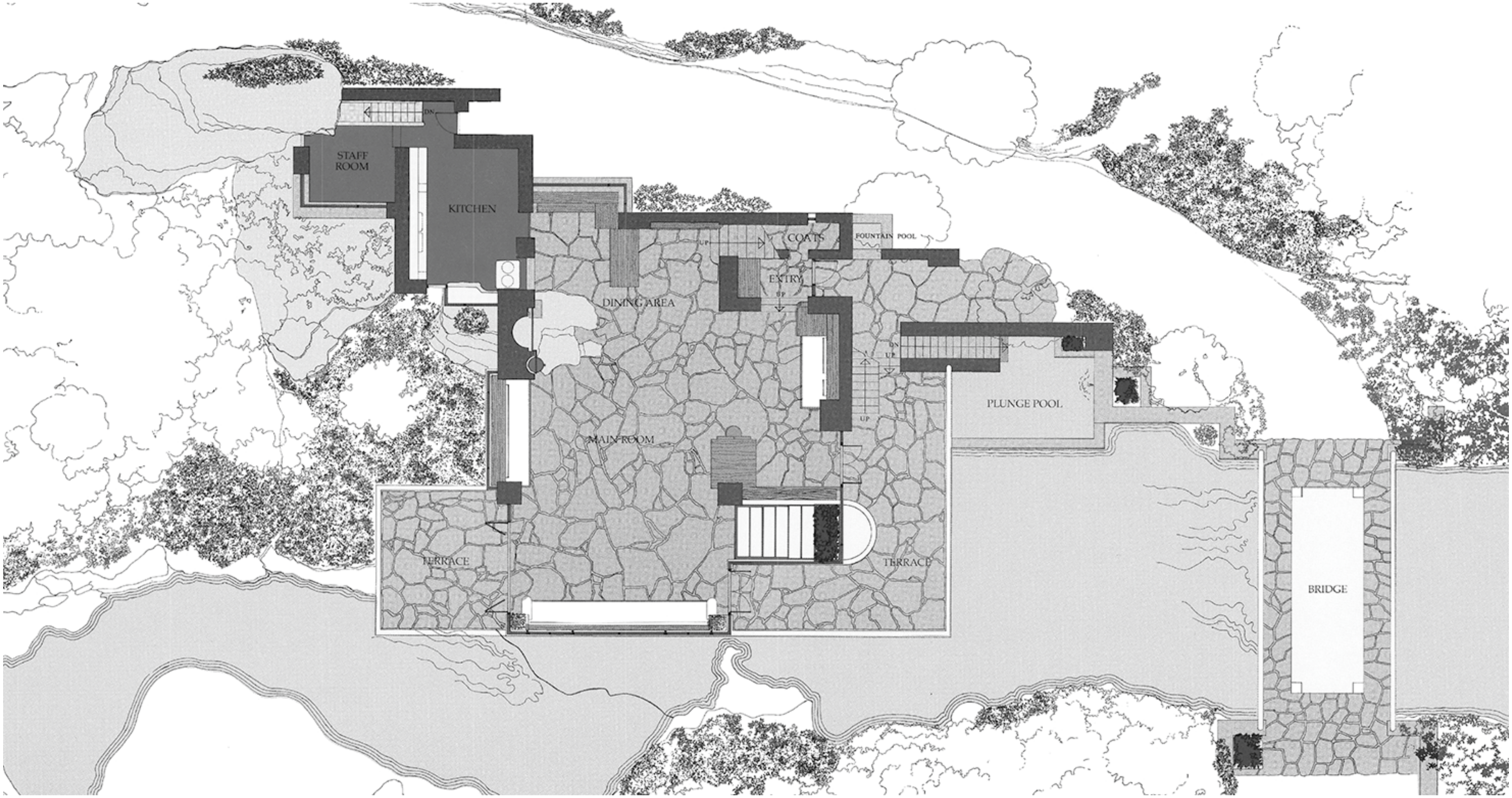
Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935



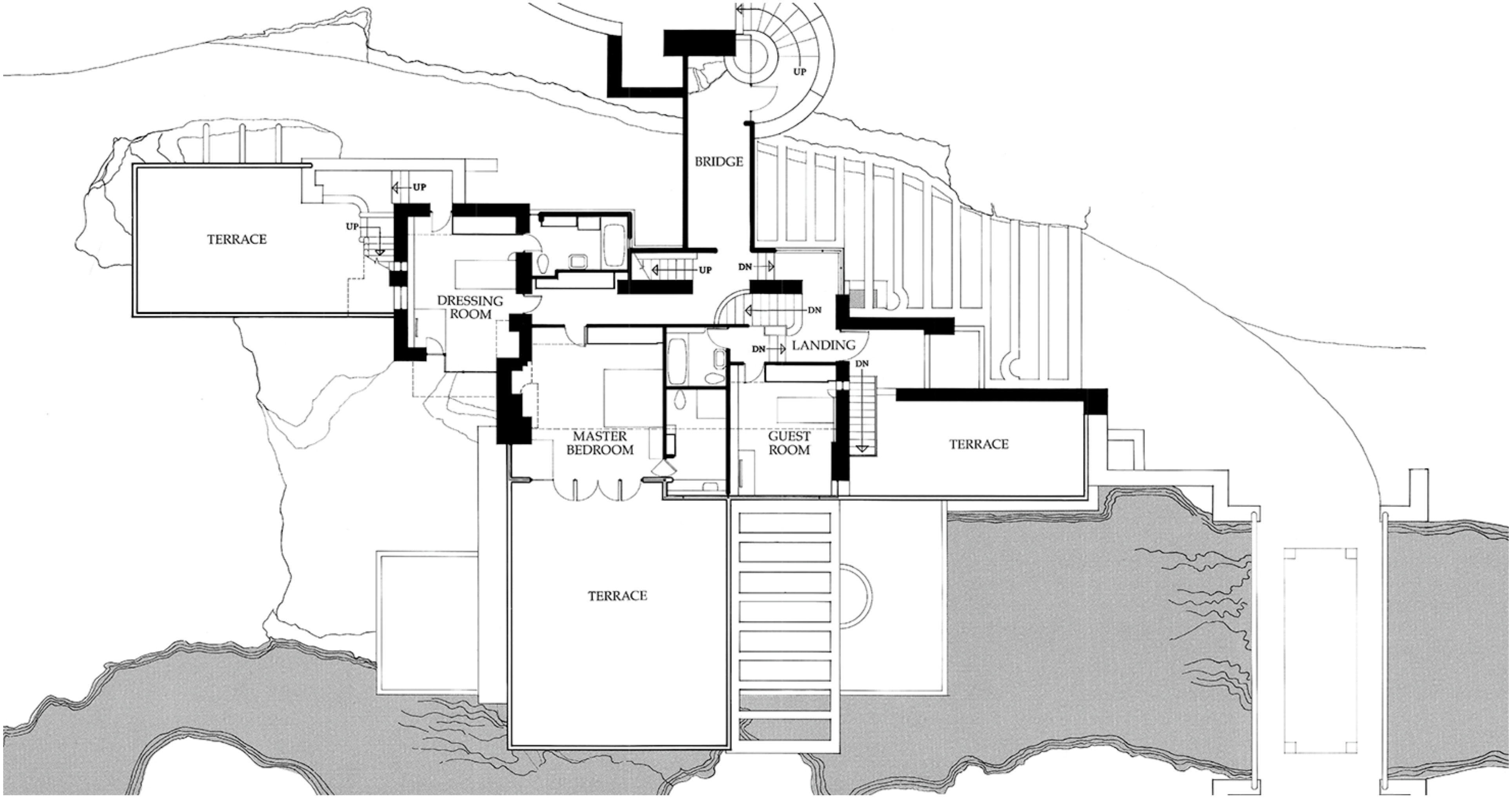
Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

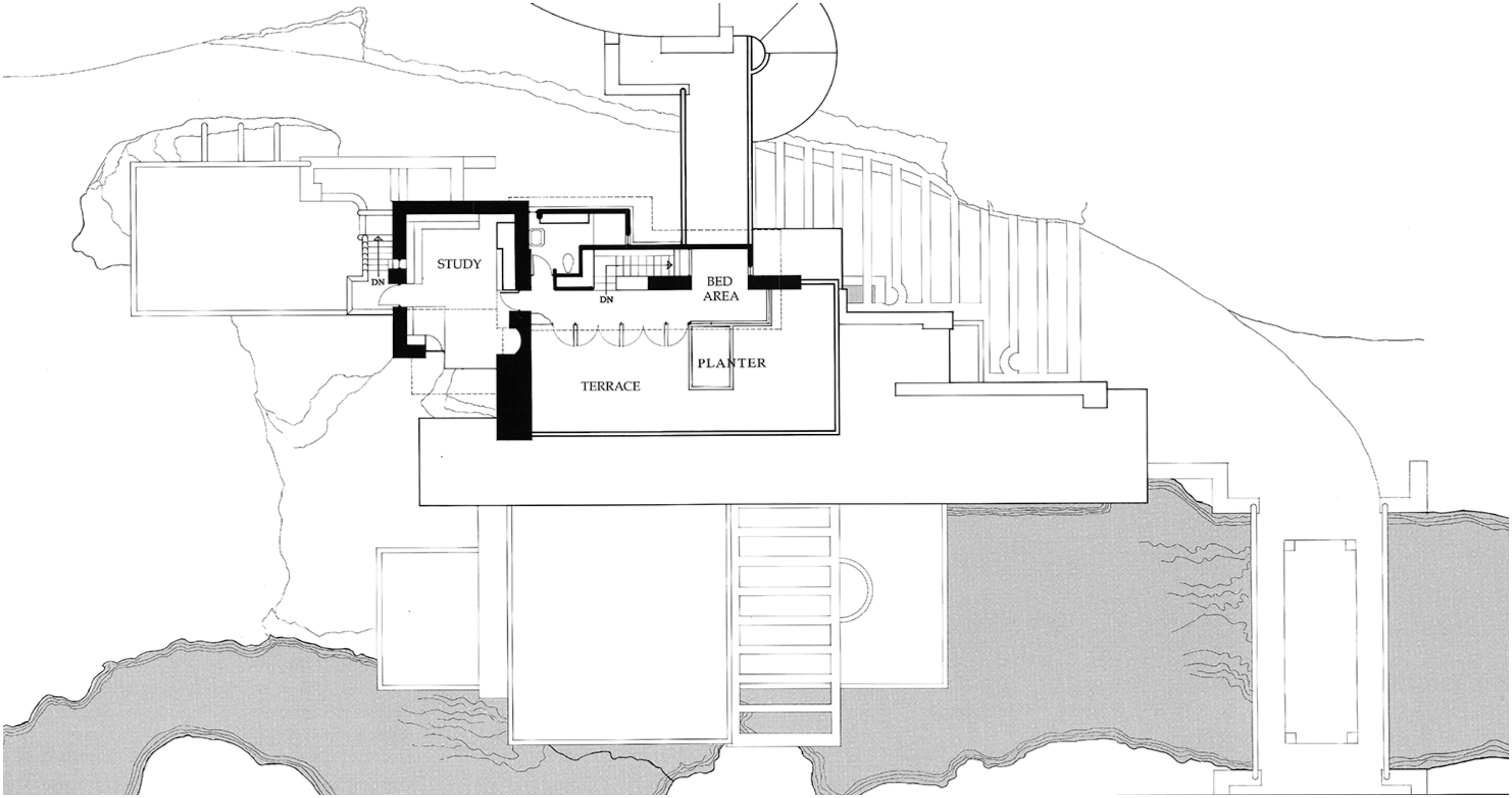


Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935



Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

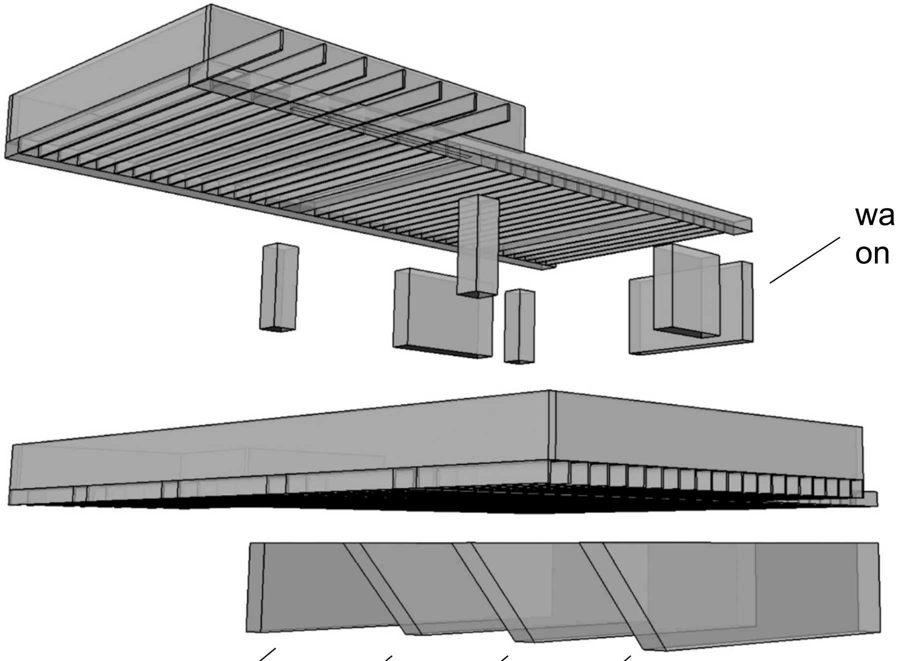


Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

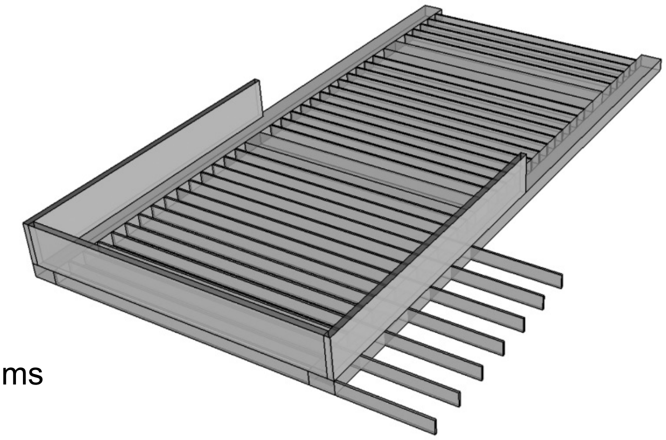
https://vimeo.com/802540

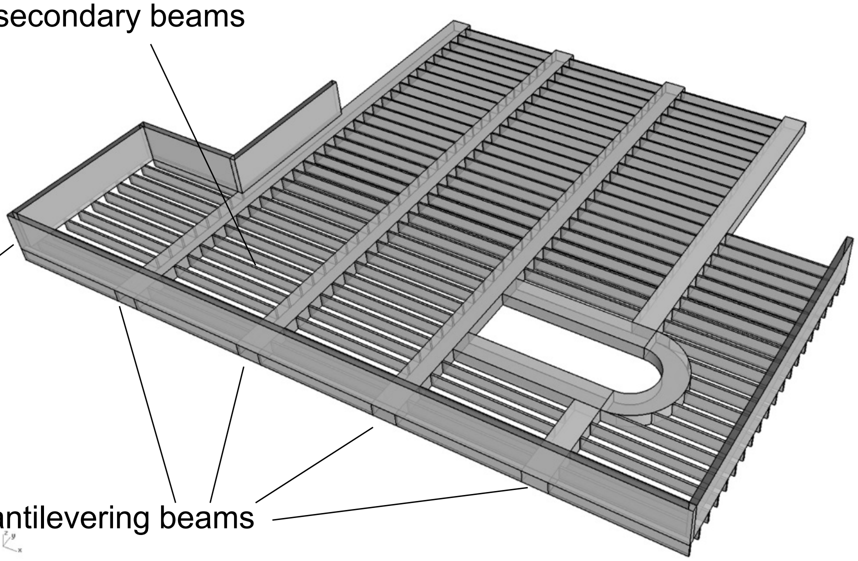
Cantilever



walls and columns
on top of main beams

four walls in riverbed



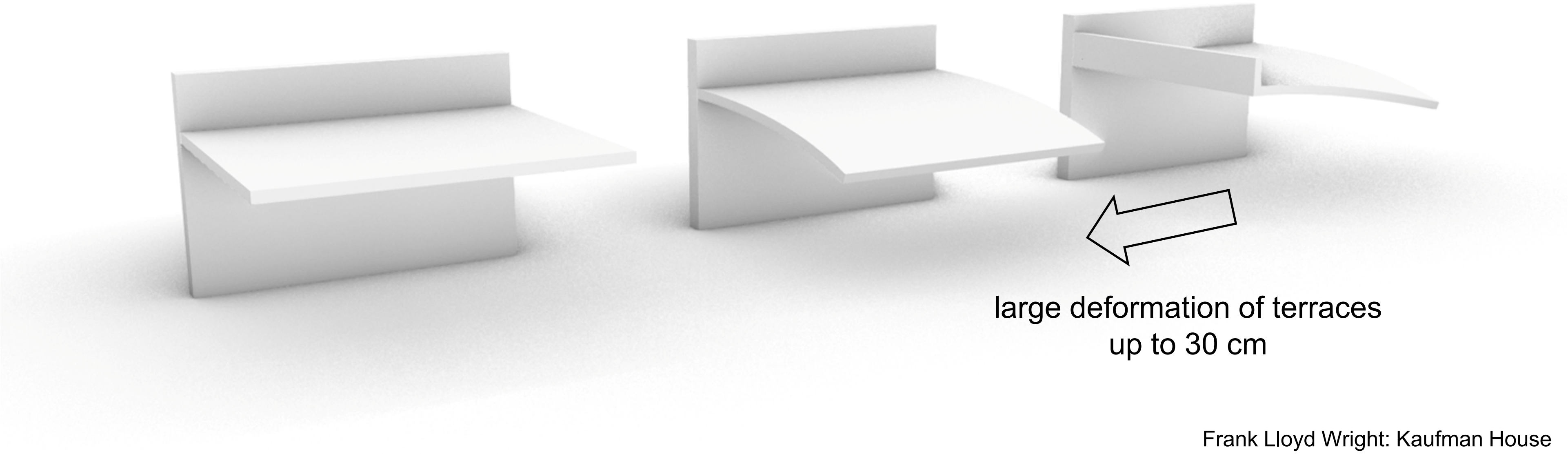


secondary beams

stiffening railing

main cantilevering beams

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

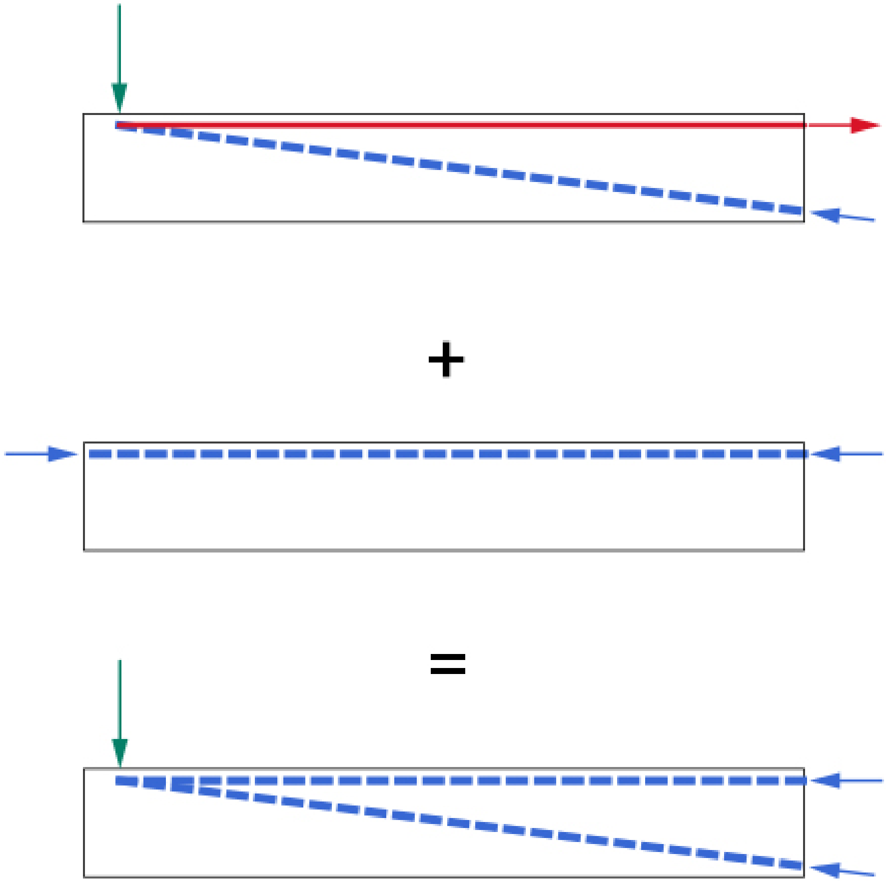


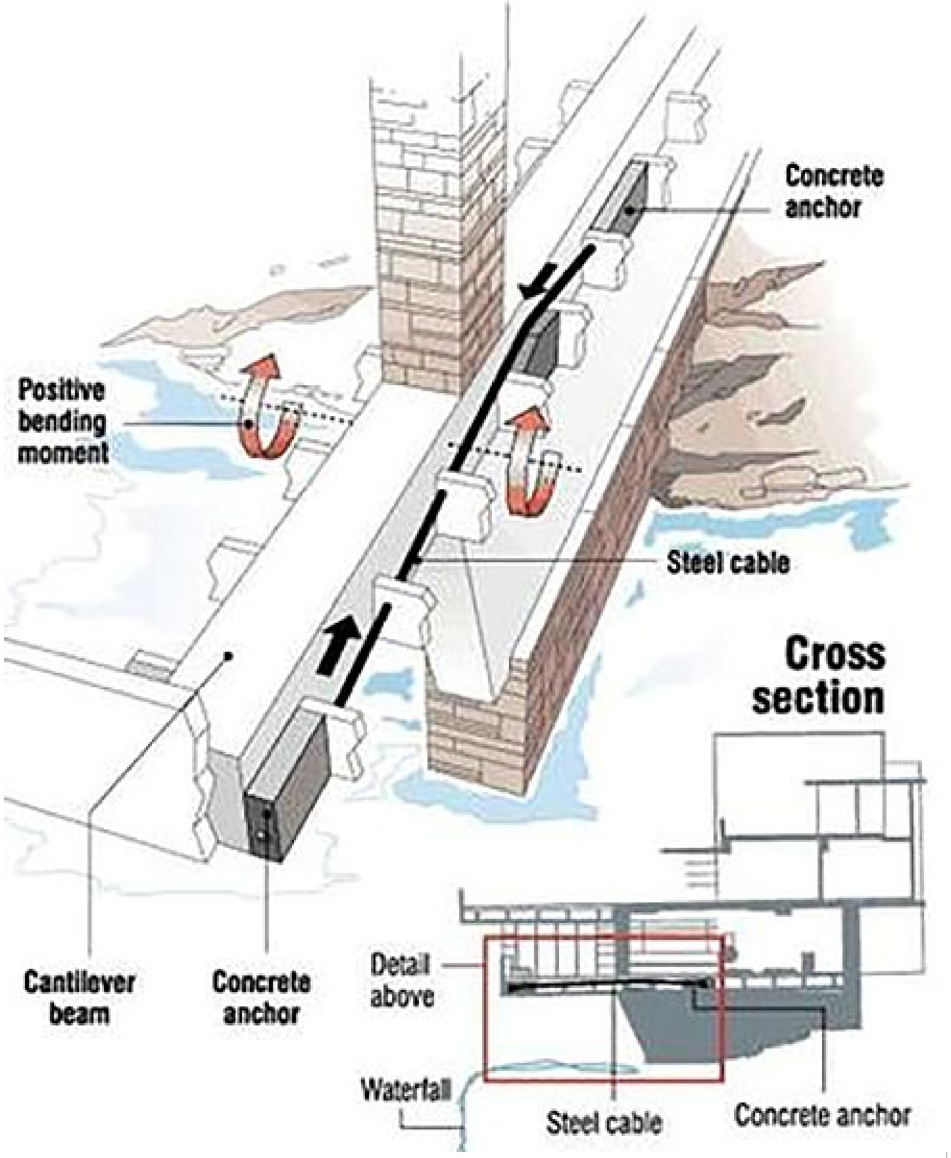
large deformation of terraces
up to 30 cm

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Cantilever

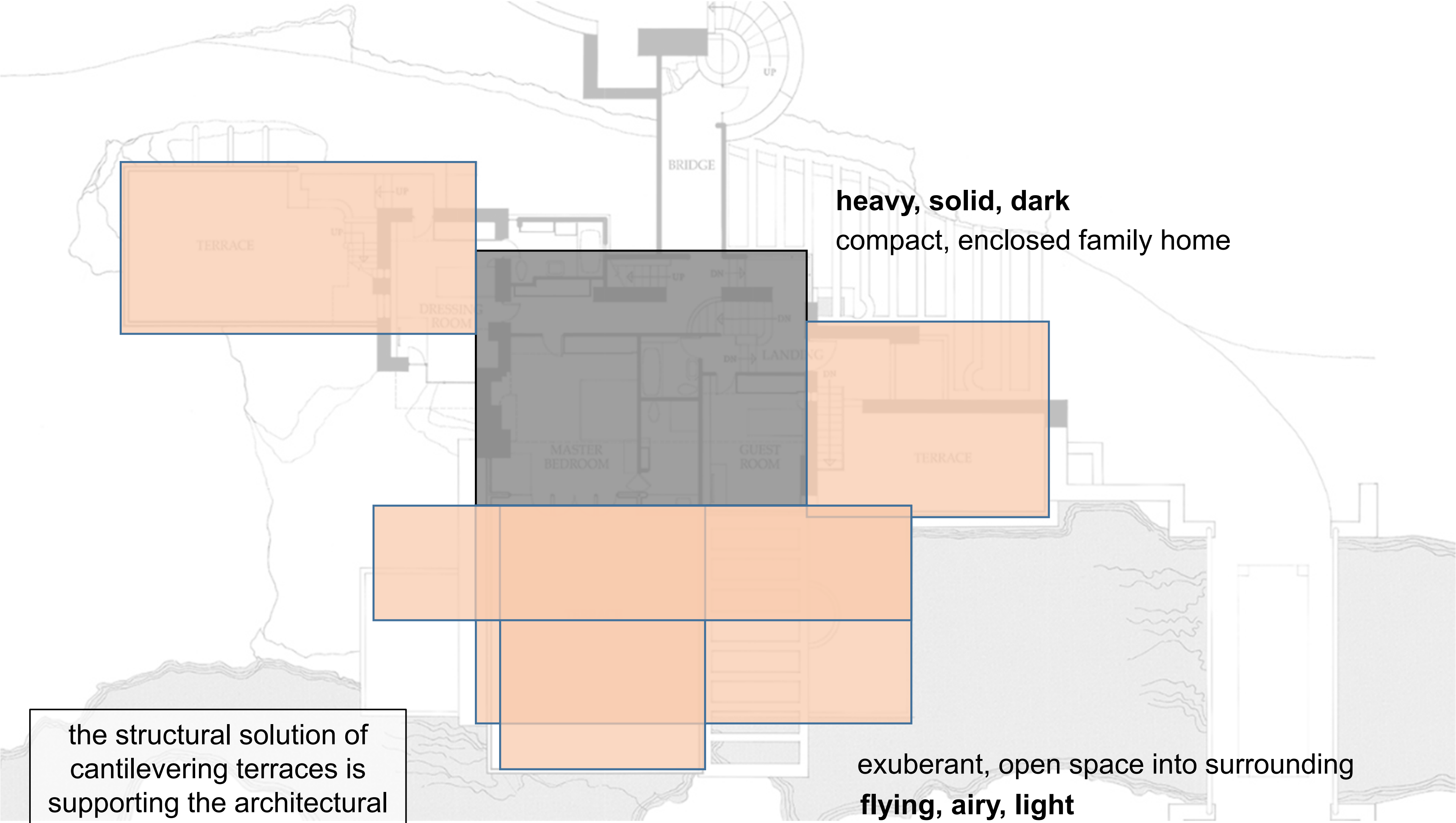
Post-tensioning of beams





Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935



heavy, solid, dark
compact, enclosed family home

exuberant, open space into surrounding
flying, airy, light

the structural solution of cantilevering terraces is supporting the architectural conception

Frank Lloyd Wright: Kaufman House
Bear Run, USA, 1935

Poisson-effect

stress

stress-strain diagram

beam

cantilever

structure & architectural concept

ARK-A3001 Design of Structures_Basics

Tension & Compression

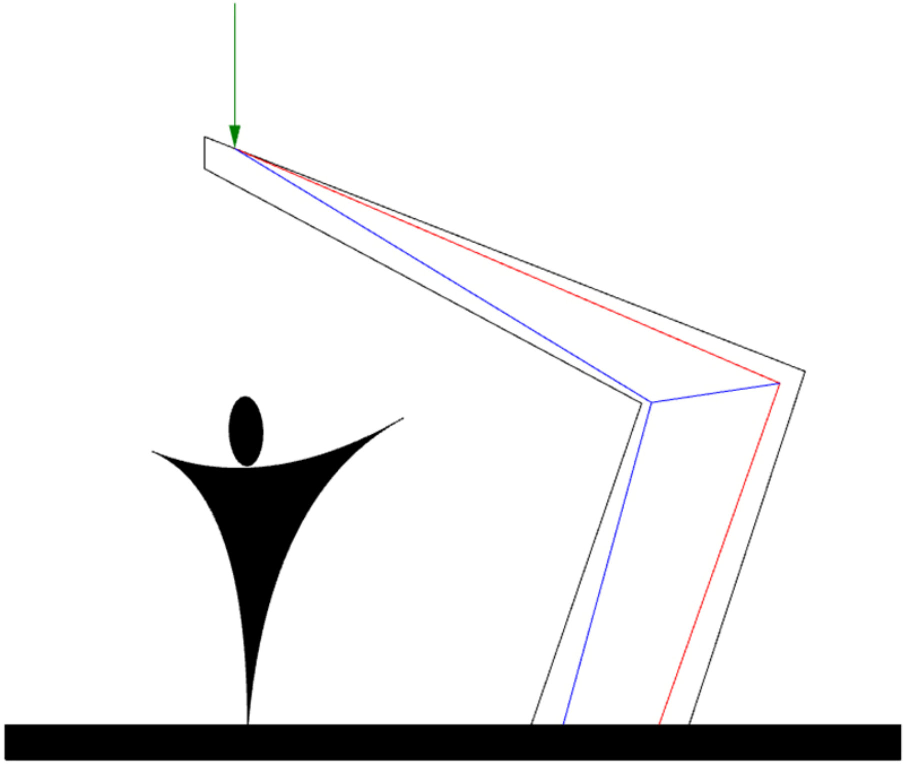
Toni Kotnik

Professor of Design of Structures

Aalto University
Department of Architecture
Department of Civil Engineering

Exercise 4.1

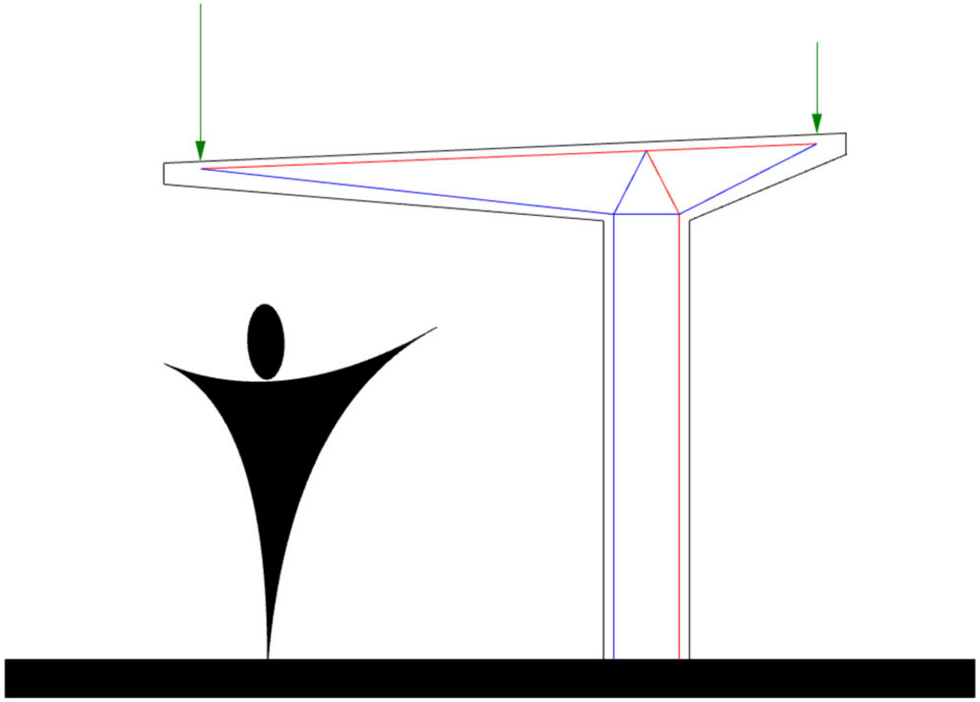
Given is the location plan for a bus stop together with the inner forces. Construct the force plan and sketch the deformation of the bus stop under the load.



Bus stop in former Soviet Union from Peter Ortner: *Back in the USSR: Soviet Roadside Architecture from Samarkand to Yerevan*, 2016

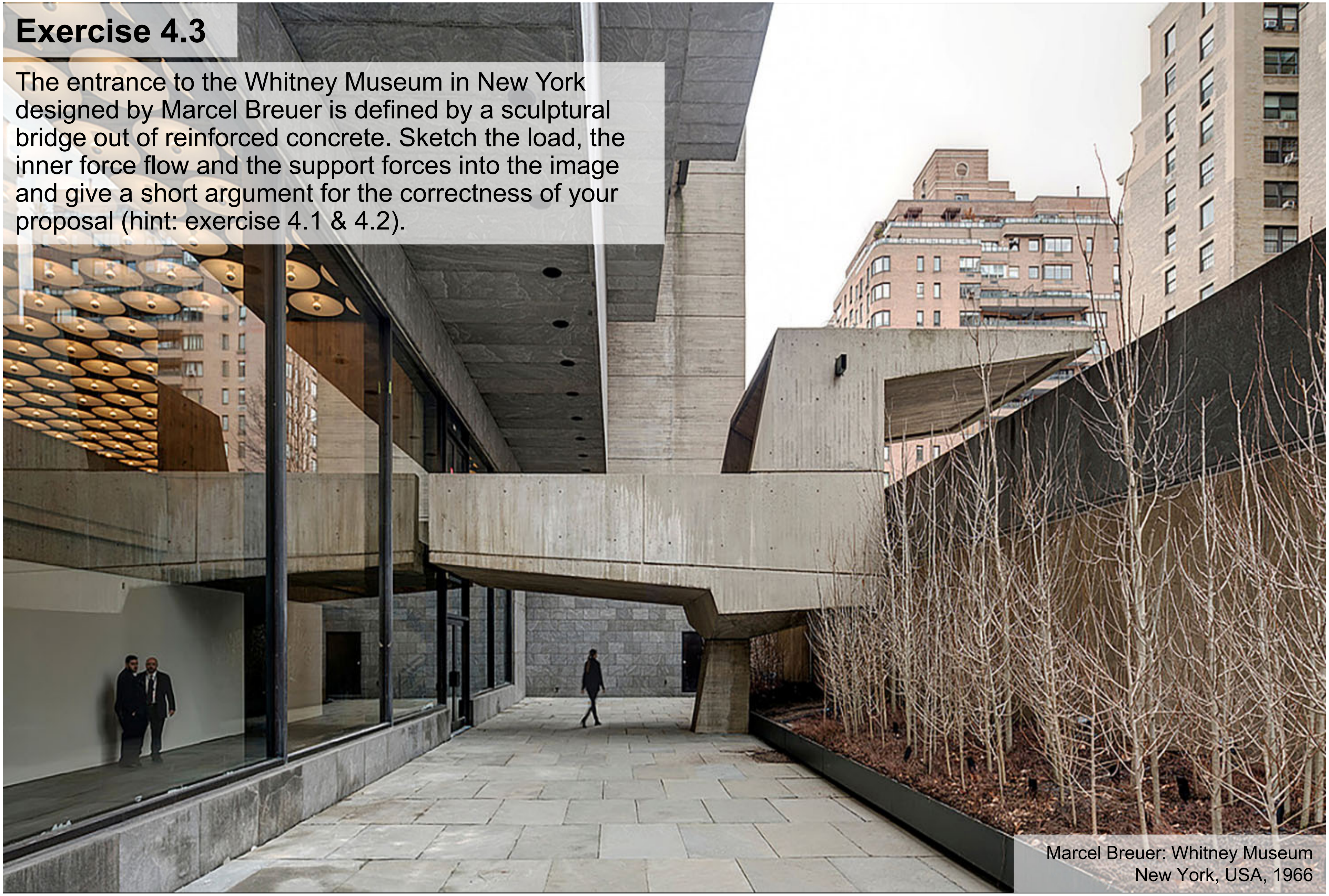
Exercise 4.2

Given is the location plan for a canopy together with the inner forces. Construct the force plan.



Exercise 4.3

The entrance to the Whitney Museum in New York designed by Marcel Breuer is defined by a sculptural bridge out of reinforced concrete. Sketch the load, the inner force flow and the support forces into the image and give a short argument for the correctness of your proposal (hint: exercise 4.1 & 4.2).



Marcel Breuer: Whitney Museum
New York, USA, 1966

The Plan to Save Fallingwater

This breathtaking house designed by Frank Lloyd Wright was in danger of collapse until an engineering firm found a way to stop it from falling down

A firsthand account
by renowned engineer

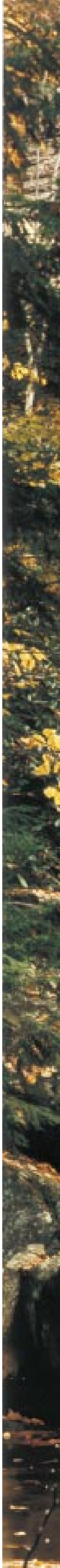
Robert Silman

Perched on a hillside in southwestern Pennsylvania, about 72 miles from Pittsburgh, is one of the world's most famous houses. Fallingwater, the stunning creation of architect Frank Lloyd Wright, has been an American icon since its construction in 1937. More than two million tourists have visited the site and stared in awe at the building's concrete terraces hanging over a clear, swift-running stream. Architecture critics have extolled Fallingwater as Wright's greatest achievement. In fact, in 1991 the American Institute of Architects voted it the best work ever produced by an American architect.

Yet this incomparable structure has a critical flaw. Wright's design did not provide enough support for the portion of the house that hangs over the stream. As a result, Fallingwater's famed terraces began to droop as soon as they were built, causing large cracks to appear in the concrete. What is more, the sagging gradually increased over the next six decades. In 1995 the Western Pennsylvania Conservancy, which owns Fallingwater, was concerned enough to hire our engineering firm, Robert Silman Associates in New York City, to examine the house's structural problems. The results of our investigation indicated that the beams supporting the house were continuing to bend and that the building would eventually collapse into the stream below if nothing was done.

In 1996 the conservancy prudently decided to shore up Fallingwater with temporary steel beams and columns. At the same time, our office began to draw up a plan to permanently repair the house. We had previously worked on two other buildings designed by Wright—the Darwin D. Martin House in Buffalo, N.Y., and Wingspread in Racine, Wis.—but Fallingwater posed a unique challenge. To determine how to relieve the stresses that were threatening the house, our engineers probed the building with radar and ultrasonic pulses, then performed a rigorous structural analysis. Along the way we also tried to retrace the thinking of Wright and his apprentices. We now have a plausible theory to explain how the design of Fallingwater went awry.

The story of Fallingwater begins with Edgar Kaufmann, Sr., who owned a successful department store in Pittsburgh in the 1930s. His son, Edgar Kaufmann, jr. (he always spelled "junior" with a lowercase "j"), spent a short time as an apprentice in Wright's studio at Taliesin, the architect's estate in Spring Green, Wis. Kaufmann, jr., convinced his father to retain Wright to do some work at the store and later to design a weekend house for the family on a site that had formerly been



ROBERT P. RUSCHAK/COURTESY OF WESTERN PENNSYLVANIA CONSERVANCY

a summer recreation camp for the store's employees.

The wooded property features a small stream known as Bear Run that cascades over a series of rocky ledges. The Kaufmanns had always assumed that their house would be located downstream from the ledges, at a point where the waterfalls could be viewed from below. But it was Wright's genius to site the house *above* the falls, on top of a large sandstone ledge that overlooks the stream. The building was designed in 1935, and construction started in 1936. The design work was conducted at the Taliesin studio, with Wright's apprentices Bob Mosher and Edgar Tafel participating significantly. The structural calculations for Fallingwater were done in the same studio by engineers Mendel Glickman and William Wesley Peters.

Wright and his apprentices designed the house so that the section over Bear Run acts as a cantilever. Like a diving board, it has a fixed end and a free end. The fixed end consists of four large bolsters, three of reinforced concrete (that is, concrete with steel bars embedded in it) and one of stone masonry. These bolsters rise from the sandstone ledge to the building's first floor [*see illustration on pages 92 and 93*]. Each one supports a horizontal reinforced-concrete beam that extends some 4.42 meters (14.5 feet) beyond the bolster, jutting southward over the stream. The beams are connected to one another by concrete joists, each 100 millimeters (four inches) wide. Together the beams and joists create a rectilinear grid. Above this grid are wooden two-by-fours and planking, which support the stone floor of the house's living room and the first-floor terraces.

Beneath the joists and cantilever beams is a concrete slab that serves as the finished underside of the structure. Wright chose this design to give the house's exterior a monolithic look, but it also had a structural purpose. In engineering terms, a cantilever has a negative bending moment—the load at the free end of the horizontal beam is resisted by tension in the beam's upper side and by compression in the lower side. (In contrast, a bookshelf has a positive bending moment—the weight of the books is resisted by compression in the shelf's upper side and by tension in the lower side.) Wright's decision to put the concrete slab under the cantilever beams turned them into inverted tee beams—each shaped like an upside-down T—thereby raising their resistance to compression and enabling them to support a greater load.

Fallingwater has more than one cantilever, though. Terraces extend from

INTERIOR VIEW of Fallingwater's living room shows the stone floor that rests on the house's cantilever beams. The windows at the south end of the room are divided by four steel mullions that help support the weight of the second floor.

the east and west sides of the first floor, supported by concrete joists under their floors and by edge beams in their parapets. And on the building's second floor, directly above the living room, the master bedroom terrace juts farther out than the first floor does, extending an additional 1.83 meters (six feet) southward [*see left illustration below*]. Four T-shaped window mullions rise from the south edge of the living room to the terrace above. At first glance these steel mullions appear to be merely decorative, but we would eventually learn that they, too, play a key role in Fallingwater's structure.

Concerns about the soundness of Wright's design arose even before construction started. Metzger-Richardson, the Pittsburgh engineering firm that supplied the steel bars for the reinforced concrete, insisted that there were not enough bars in the cantilever beams below the living room. To make the beams strong enough to resist bending under their load, the firm doubled the number of one-inch-square bars in each beam from eight to 16. Wright was furious when he learned about the change. He believed that the additional steel bars would increase the weight of the beams too much and thus weaken the structure. In an angry letter to Kaufmann, Sr., he wrote: "I have put so much more into this house than you or any other client has a right to expect, that if I don't have your confidence—to hell with the whole thing."

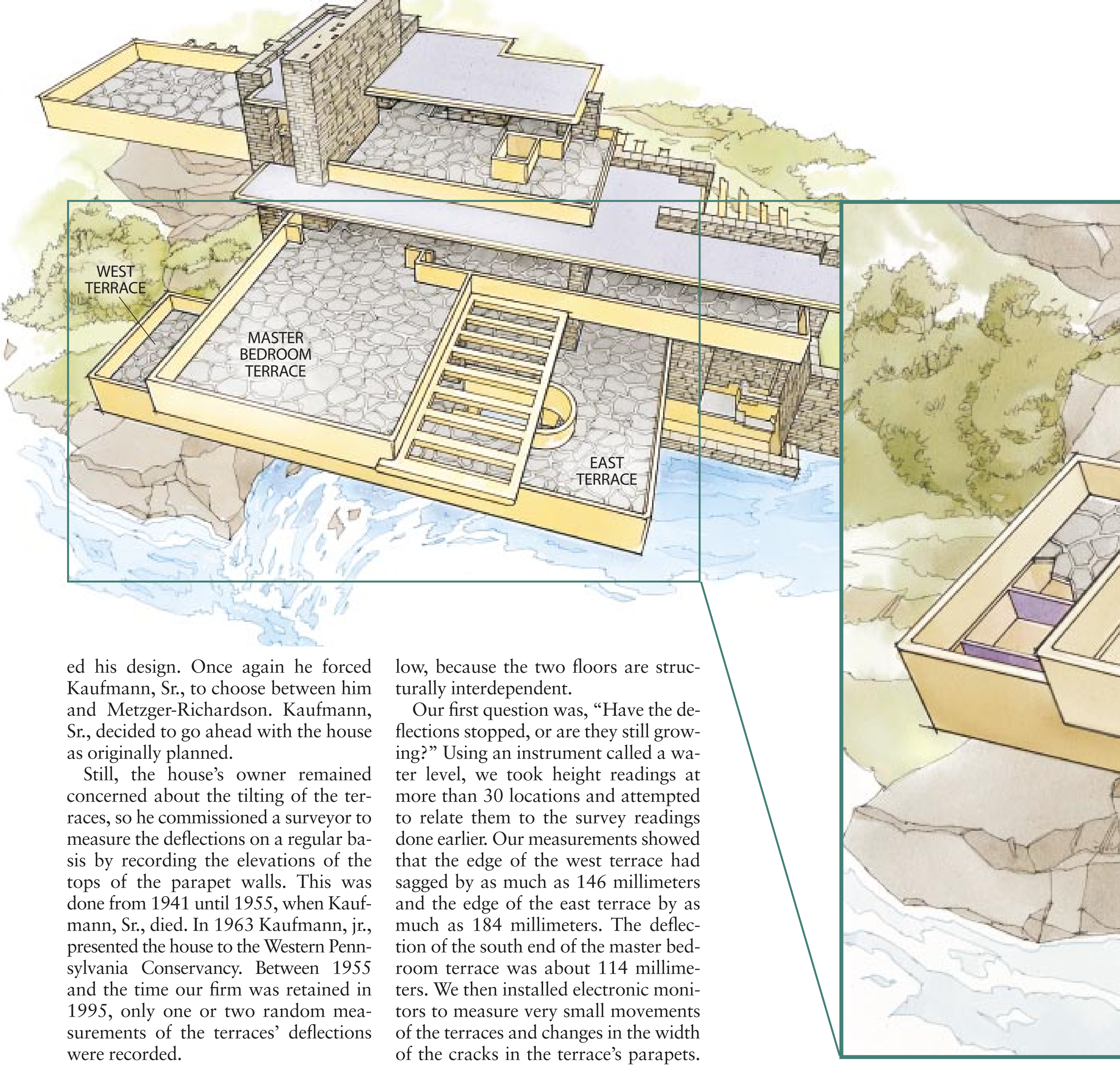
Kaufmann, Sr., appeased his architect by asserting his confidence in him. But Wright was clearly wrong about the cantilever beams: if Metzger-Richardson had not slipped in the extra steel bars, the beams surely would have failed. Even the greater amount of reinforcement was not enough, as the builders discovered during Fallingwater's construction. When workers removed the wooden formwork from beneath the concrete of the first floor, they recorded an instantaneous downward movement of 44.5 millimeters. It is not unusual for a small amount of deflection to occur when the scaffolding is removed from a concrete structure, but in this case the bending was especially pronounced. Mosher, the apprentice on site, telephoned Glickman at the studio in Taliesin. After a quick check of his calculations Glickman is reported to have exclaimed, "Oh my God, I forgot the negative reinforcement!"

Glickman was referring to the reinforcement needed to balance the negative bending moment, which causes compression in the lower part of each cantilever beam and tension in the upper part. In any beam made of reinforced concrete, the concrete resists the compression on the beam and the steel bars in the concrete resist the tension. Fallingwater's cantilever beams could handle the compression caused by the negative moment, but there were not enough steel bars in the upper parts of the beams to balance the tension.

The problem became even more apparent after the completion of the second floor. Soon after workers removed the formwork from the concrete of the master bedroom terrace, two cracks appeared in the terrace's parapets. In 1937 Metzger-Richardson conducted load tests of the structure and calculated that the stresses in the cantilever beams were near or even exceeded the margins of safety. The engineering firm recommended placing permanent props in the streambed to support the first floor and thus reduce the length of the cantilevers. But Wright stubbornly defend-

ROBERT P. RUSCHAK/COURTESY OF WESTERN PENNSYLVANIA CONSERVANCY (*top and bottom left*); COURTESY OF WESTERN PENNSYLVANIA CONSERVANCY (*bottom right*)

CRACKS IN THE PARAPETS of the second-floor terrace appeared as a result of the stresses in the concrete structure (*left*). Electronic monitors attached to the parapets measured changes in the width of the cracks over 18 months and confirmed that they were growing (*below*).



BARRY ROSS

ed his design. Once again he forced Kaufmann, Sr., to choose between him and Metzger-Richardson. Kaufmann, Sr., decided to go ahead with the house as originally planned.

Still, the house's owner remained concerned about the tilting of the terraces, so he commissioned a surveyor to measure the deflections on a regular basis by recording the elevations of the tops of the parapet walls. This was done from 1941 until 1955, when Kaufmann, Sr., died. In 1963 Kaufmann, jr., presented the house to the Western Pennsylvania Conservancy. Between 1955 and the time our firm was retained in 1995, only one or two random measurements of the terraces' deflections were recorded.

Engineers as Detectives

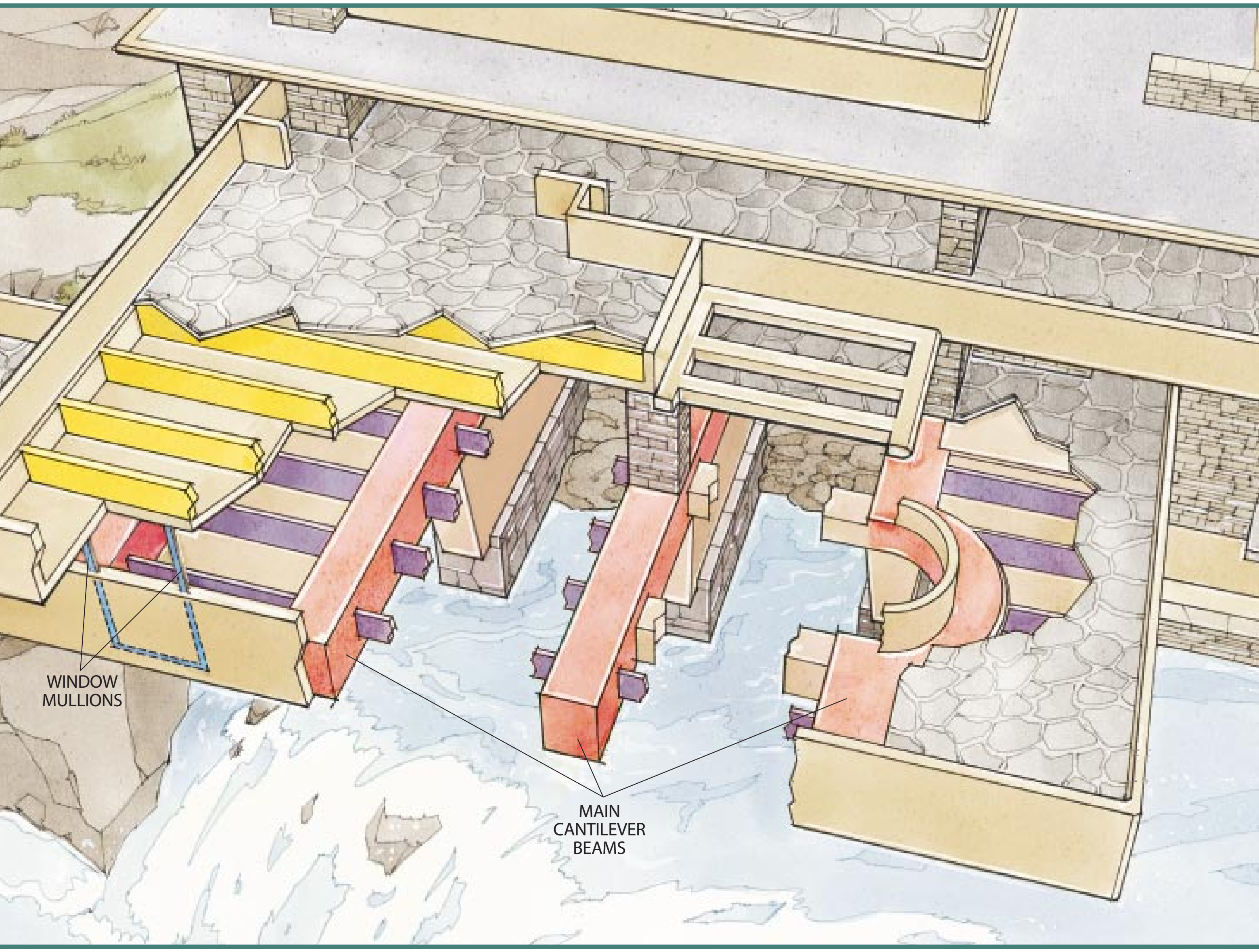
The conservancy initially asked our office to evaluate the structural adequacy of the master bedroom terrace, the part of the house that historically had the most severe visible cracks. Work was ongoing to repair Fallingwater's facade, including the terrace's cracks, and the conservancy wished to know whether it was wise to continue repairing these cracks cosmetically without first performing a structural review and, if necessary, repairs. We soon realized that we had to broaden our investigation to include the living room below, because the two floors are structurally interdependent.

Our first question was, "Have the deflections stopped, or are they still growing?" Using an instrument called a water level, we took height readings at more than 30 locations and attempted to relate them to the survey readings done earlier. Our measurements showed that the edge of the west terrace had sagged by as much as 146 millimeters and the edge of the east terrace by as much as 184 millimeters. The deflection of the south end of the master bedroom terrace was about 114 millimeters. We then installed electronic monitors to measure very small movements of the terraces and changes in the width of the cracks in the terrace's parapets. The results over more than one and a half years, corrected for daily and seasonal temperature variations, confirmed that the cracks were still growing and the terraces sagging ever lower.

The next step was to examine the structure's as-built condition to see how closely it conformed to Wright's plans. In particular, we needed to verify the actual number, size and location of the reinforcing bars in the cantilever beams and other structural elements. We organized a program of nondestructive evaluation, employing instruments that used impulse radar, ultrasonic pulses and high-resolution magnetic detection to plumb the interiors of the beams, floors and parapets. The tests also provided data on the quality of the house's concrete. The work was performed by GB Geotechnics of Cambridge, England. To investigate the main cantilever beams, the technicians had to remove several paving stones from the living room floor so that they could gain access to the hollow space below.

Our engineers then conducted an independent structural analysis of the house. Metzger-Richardson had done such an analysis in 1936 and 1937, but we wanted to make our own determination of how the structure functioned.

FRANK LLOYD WRIGHT'S DESIGN for Fallingwater combined beams and parapets made of reinforced concrete with floors and walls made of sandstone (*opposite page*). A cutaway of the portion of the house overhanging Bear Run (*below*) shows the concrete bolsters that rise from the ground and support the horizontal cantilever beams (*red*). The beams are connected to one another by concrete joists (*purple*). The steel window mullions (*blue*) embedded in the first-floor parapet help support the concrete joists (*yellow*) of the second-floor terrace.



Using a computer model of Fallingwater, we tested three hypotheses: that the master bedroom terrace can support itself through cantilever action; that the living room is a self-supporting cantilever; and that the living room supports both itself and the master bedroom terrace. For each scenario we calculated the bending moments that would be caused by the dead load of the house. Then we calculated the resulting stresses in the steel and concrete of the supporting beams, as well as the amount of deflection that these loads would induce.

If our computer model predicted stresses that were significantly higher than the yield strength of the steel or concrete, we knew that some of our assumptions had to be incorrect, because such overstressing would have resulted in the immediate collapse of Fallingwater. Tests of the house's concrete indicated an in situ strength of about 34 megapascals (5,000 pounds per square inch). We also recovered a small piece of reinforcing steel from the building and sent it to a metallurgical laboratory; the results of the mechanical analysis showed a yield strength of slightly more than 283 megapascals (41,000 pounds per square inch).

First, we tested the hypothesis that the master bedroom terrace could support itself through cantilever action. If this were the case, our calculations revealed that the stress in the reinforcing bars in the terrace's parapet would be 1,195 megapascals, or more than four times the steel's yield strength. This scenario is therefore not possible. Next, we examined whether the living room is a self-supporting cantilever. Our analysis indicated that the weight of the living room alone would induce tolera-

TEMPORARY SHORING installed in 1997 ensures that Fallingwater will not collapse before permanent repairs can be made to the structure. A line of steel columns and girders rising from the streambed of Bear Run supports the concrete underside of the house's cantilevered first floor.

ble stresses: a maximum of 152 megapascals in the steel of the main cantilever beams and 16 megapascals in the concrete. We knew, however, from the failure of the first hypothesis, that the living room does not stand alone—it has to support the master bedroom terrace as well. If we assume that the living room is propping up the terrace by means of the T-shaped window mullions at its south end, the calculations predict stresses of 288 megapascals in the steel of the main cantilever beams and 30 megapascals in the concrete. These stresses are at critical levels—they are just about equal to the yield strengths of the materials.

Furthermore, the deflections that would be caused by these stresses closely match the observed tilting of Fallingwater's terraces. Our computer results yielded only the initial deflections and did not allow for the subsequent shrinkage and creep of the concrete in the main cantilever beams. Shrinkage occurs as concrete hardens; creep is the continuing contraction that takes place as concrete is subjected to a constant compression load over time. The amounts of shrinkage and creep depend on many factors, including the quantity of the reinforcing steel and the quality of the concrete. When we added these factors into our calculations, the expected deflections of the east and west terraces turned out to be surprisingly close to the actual conditions.

The logical conclusion is that the T-shaped window mullions do, indeed, support the weight of the master bedroom terrace. Our engineers confirmed that the mullions could handle the load: the maximum stress induced in them would be 64 megapascals, which is well below their allowable strength of 112 megapascals (assuming that they are braced by the concrete of the living room parapet). What is more, it is this extra weight supported by the mullions that has raised the stresses on the main cantilever beams to critical levels. Although we cannot know for certain what led to this design flaw, the structural evidence suggests a possible chain of events. According to this scenario, when Wright's engineers realized that the master bedroom terrace could not support itself, they redesigned the window mullions to carry some of the load. The engineers failed, however, to redesign the main cantilever beams to support the extra weight.

Fixing Fallingwater

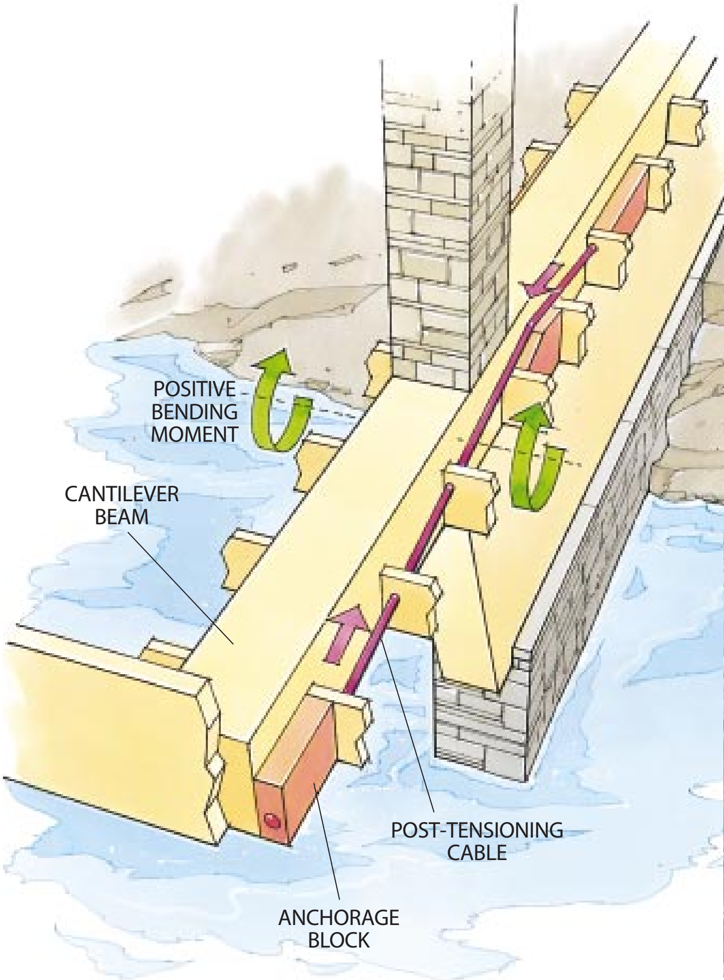
When the conservancy's trustees received the results of our analysis in May 1996, they were naturally concerned. Our study indicated that the stresses in Fallingwater's main cantilever beams were great enough to raise questions about the house's safety. The trustees decided to commence the design of permanent repairs. We advised them that during the construction phase it would be necessary to shore the ends of the main beams while repairs were under way. Because the house would ultimately have to be shored, the trustees wisely chose to do it immediately and thereby eliminate the fear that the building might collapse or that some structural element might fail before repairs could be made.

Thus, in 1997 workers installed a relatively unobtrusive line of steel columns and girders rising from the streambed of Bear Run to the underside of the first floor [*see illustration at left*]. In addition, they also shored a portion of the streambed itself, the jutting sandstone ledge over which Bear Run cascades. The ledge was braced with pipe struts in a cave behind the waterfall. The temporary shoring, which ensures the safety of the tourists who continue to visit the house, will remain in place until the permanent repairs are completed.

From the analysis of existing stresses, we determined that three of the four cantilever beams below the living room need reinforcing. (The fourth beam, the easternmost one, does not require intervention because it is already propped up by a steel strut that is part of the railing for the stairway that goes down to the stream.) Practically, there is only one method that can provide sufficient reinforcement without altering Fallingwater's outward appearance. This method involves post-tensioning the main beams—that is, connecting them to steel cables and using the tension in the cables to relieve the stress in the beams.

The repair scheme calls for the stone floor of the living room to be removed temporarily. This will allow access to the three main cantilever beams from above. At the south end of each beam—the end jutting over Bear Run—we will attach concrete blocks to both sides of the beam [*see left illustration on opposite page*]. Into each block we will insert a hollow duct with an inside diameter of 6.35 millimeters. The ducts will run alongside the beams, angling upward and extending through holes drilled in the concrete joists. We will also drill holes in the exterior of the south parapet so that high-strength post-tensioning cable can be threaded through the ducts.

The cables will be anchored at the north end of each beam. At the south end, we will tighten the cables from the outside using a hydraulic jack. The tightened cables will be rigged in such a way that they exert a positive bending moment on each cantilever beam. This positive moment will essentially coun-



PLANNED REPAIRS involve relieving the stresses in the cantilever beams through the creative use of post-tensioning. Steel cables will be rigged on both sides of each beam, anchored in concrete blocks attached to the beam's ends (*left*). The cables will then be tightened from the outside using a hydraulic jack. The tension in the cables will exert a positive bending moment on the beam, counteracting the negative moment caused by cantilever action. A section of one cantilever beam beneath the living room floor (*below*) has already been exposed to allow engineers to inspect it.

ROBERT P. RUSCHAK/COURTESY OF WESTERN PENNSYLVANIA CONSERVANCY (*photographs*); BARRY ROSS (*illustration*)

teract the negative moment caused by cantilever action, lowering the tension in the upper part of the beam and the compression in the lower part. We will also connect post-tensioning cables to the parapet edge beams in the east and west terraces to relieve the stresses in those beams. On the second floor, we plan to reinforce the overstressed concrete joist just above the steel window mullions, either by bolting steel channels to each side of the joist or by bonding carbon-fiber plates to it. At the conclusion of the project, we will patch and paint the holes in the parapet, replace the stone floor and remove the temporary shoring.

We anticipate that the structure will lift slightly off the temporary shoring when the post-tensioning forces are applied, but we do not intend to restore the cantilever beams to their original horizontal level. We will fill the cracks in the tops of the beams prior to jacking to limit the amount of upward movement. When the repairs are completed, the terraces will still be tilted, but they will not sag any further. The deflected structure will illustrate the history of the building and the problems that it has encountered over its lifetime.

The repairs are scheduled to take place during the winter of 2001–02 as part of a larger restoration project that also includes the waterproofing of the entire house. This work will be supervised by Wank Adams Slavin Architects of New York City. The conservancy is also upgrading the water supply and sanitary facilities at the property.

The strengthening of Fallingwater's cantilever beams will guarantee the structural stability of the house for years to come. Moreover, the plan stabilizes the house without the need for permanent props rising from Bear Run. Thanks to state-of-the-art technology, we can preserve the most striking architectural element of Fallingwater, its cantilevered terraces stretching gracefully over the rushing stream. SA

The Author

ROBERT SILMAN is president of Robert Silman Associates, P.C., Consulting Engineers, a structural engineering firm with offices in New York City and Washington, D.C. Since its founding in 1966, the firm has worked on more than 7,300 projects, including the renovation of 300 designated landmark buildings. Among these are the U.S. Supreme Court Building, Carnegie Hall, George Washington's mansion at Mount Vernon and six other Frank Lloyd Wright buildings. Silman received a bachelor's degree in government from Cornell University and bachelor's and master's degrees in civil engineering from New York University. He is a fellow of the American Society of Civil Engineers.

Further Information

FALLINGWATER: A FRANK LLOYD WRIGHT COUNTRY HOUSE. Edgar Kaufmann, jr. Abbeville Press, 1986.

FRANK LLOYD WRIGHT'S FALLINGWATER: THE HOUSE AND ITS HISTORY. Second edition. Donald Hoffmann. Dover Publications, 1993.

Models of Fallingwater are available at www.greatbuildings.com/buildings/Fallingwater.html on the World Wide Web.

Information on visiting Fallingwater is available at www.paconserve.org on the World Wide Web.