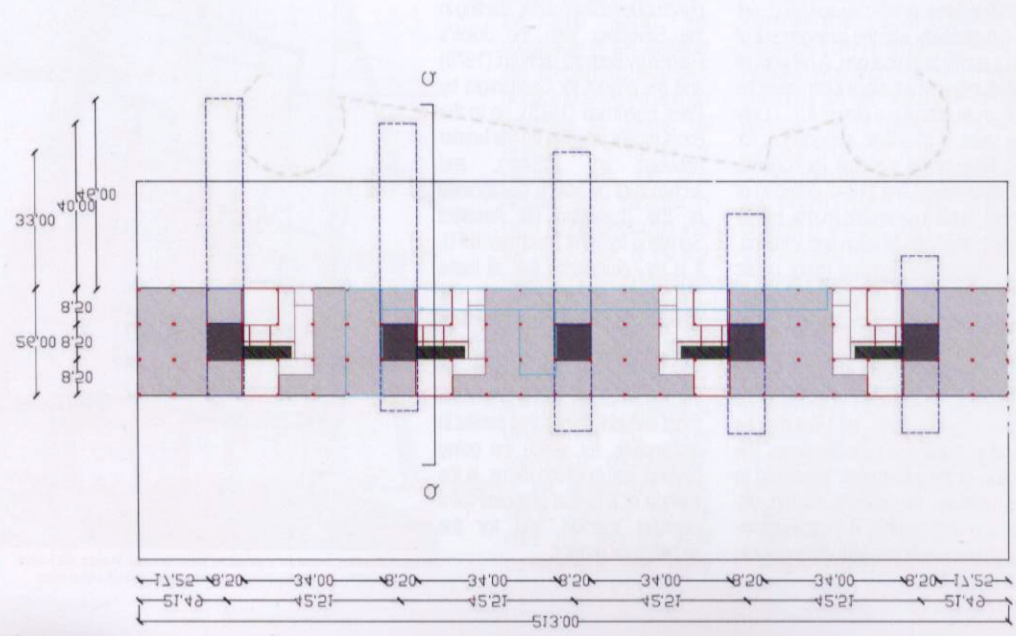
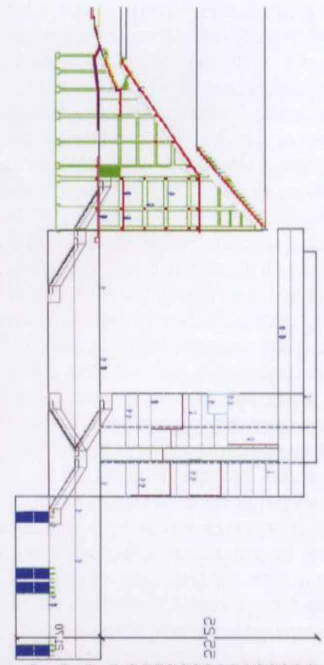
THE PHYSICAL FORM OF STRUCTURES FOR ARCHITECTURAL DESIGN

Claudio Chesi

The teaching of Structural Mechanics, as it is offered in Architecture Schools, suffered and is still suffering of an excess of formalization of knowledge. As a result, the deductive reasoning is privileged, in order to introduce these concepts not only in a correct way, but also as formally refined as possible. This approach – starting from purely theoretical premises – lacks of any specific relation with real construction case studies. On the basis of such premises, given the clarity of the logic rigour and the refinement of the deductive principle, the inductive process is completely disregarded - despite its historical relevance. An inductive approach - based on experimental evidence - drove, with time and effort, to the formulation of the theories explaining the physical behaviour of constructions: more precisely, the structural response to environmental actions. The comprehension of these concepts, presented according to a deductive criterion, implies an attitude to abstraction that fits the mind of who is devoted to studies in physics and mathematics, but it's scarcely compatible with the mental set of an Architecture student. The latter is used to reflect on tangible aspects of a visible reality, directly perceivable with senses.

Unfortunately, this ineffective planning of teaching methods is typically applied to one of the main issues in Structural Mechanics: strength verification. The scientific approach to this problem, indeed, is based on the concept of stress - i.e., the physical quantity which represents the stresses exchange between the particles constituting the construction material. A theoretical premise is essential while discussing about this topic, since the debate on physical implications refers to phenomena which - taking place inside the solid matter - are excluded from the possibility of any direct perception. The starting point of the rigorous studies on this subject was set by Galileo, in parallel to the formulation of the scientific method. This consisted in the analysis of a simple physical model: a cantilever beam supporting a weight at the free end. The popular "Galileo's formula" for the evaluation of the cantilever capacity was partially incorrect, due to a wrong assumption on stress' distribution. The progresses of the scientific research led – in the span of two centuries – to the precise statement of the issue and to the development of a general theory regarding the state of stress inside structural elements. As already mentioned, teaching this discipline will probably be unsuccessful if the starting point for the discussion is set inside the inaccessible world of the solid matter and based on a purely mathematical formulation of the stress issue. An easier understanding of the problem would rather be achieved by looking at the stress effects as they can be directly perceived, in terms of deformations of solid elements. Deformation, indeed, through the description of the changes occurring in the materials' shape and volume, provides a tangible evidence of the effects of these stresses. This could therefore be adopted as a useful reference to develop a theory on the issues caused by propagation of forces inside materials. Inferring the concept of stress from deformation - based on the pure observation of experimental evidences - might therefore be a more effective way of understanding the physical issues. Experimental evidences, indeed, directly lead to the formulation of the stress-strain relationship - i.e., the material constitutive law, that characterise the material response at all the stress levels, up to failure. Given the concept of stress and the capability of computing its values as well, the issue of the strength of materials can be faced, in order to assess both deformation and load transfer capacity. Again, the design implications of the issue are effectively outlined by Galileo when he acknowledges that a suitable structural configuration must be directly associated to the correct sizing of structural members. Well defined minimum dimensions have to be assigned to every structural element, as a requirement imposed by strength limits. The inner duality of the design process becomes clear: conceiving a correct structural scheme has to go with the precise evaluation of the cross sections prescribed for all the structural components. Going back to the main issue – understanding the stress states which generate inside the material and their characteristic limit conditions – it is interesting to recall the Principle of Virtual Works as a charming an effective way of providing a further insight into the concept of stress. The equivalence between the calculation of external and internal work, indeed, sets a relation between the external view of the problem - which is clearly perceivable in terms of forces producing displacements - and the internal world of the solid matter. Here, under the effect of external loads, local stresses, which generate deformation of solid particles, are displayed, since they perform work in the same way as in the external world. The mathematical statement of the Principle of Virtual Works, therefore, reflects the correspondence between two parallel visions of the same problem: the first regarding the view of the structure from outside, and the second that unfolds the relations between the internal parcels of solid matter. Here the interaction among solid particles is defined in terms of stresses and strains. As a conclusion we can state that - with reference to the Mechanics of Solids, a key topic for both Civil Engineering and Architecture Schools - wide possibilities still exist for the development of more effective teaching criteria, suitable for both faculties. These should allow an in-depth understanding of the physical phenomena which characterize the behaviour of structures, in order to build a fruitful dialogue between the architectural and engineering expertise, at the base of any design process.





THE CHOICE OF A STRUCTURAL SCHEME.

Claudio Chesi

A suitable structural scheme has necessarily to be identified with reference to the main peculiarity characterizing the design proposal. This has to do with the long span values which are required for the cantilever portion of the building (46 m). Also in the design variant by which supports are present at both the beam ends, the span values are still very long; the design problem, therefore, is more typical of bridges than of buildings. Based on such a consideration, a logical sequence of concepts leads to the definition of all the structural details, starting from the construction material and the structural typology.

The building material

As to the material choice, reinforced concrete will necessarily be used for cores hosting stairs and elevators and acting as the main bracing system for the building; for long span beams, the two basic options which are normally considered in the design of bridges refer to steel or pre-stressed reinforced concrete. In the case of a building structure, however, due to weight considerations, the recourse to the use of steel is highly preferable.

Global equilibrium and structural implications

The presence of a long span cantilevering portion of the building results into a lack of regularity in the spatial distribution of weights corresponding to the building single portions. In this situation stability has to be verified with respect to global overturning. This can be easily done with reference to a simple global scheme (see fig. 1) reproducing the correct distribution of volumes and relative weights. The analysis of global equilibrium gives evidence to the stabilizing effect produced by the main building block and the possible need for a foundation system of suitable shape and mass. Last but not least, through this simple analysis the propagation of loads through the structure can be highlighted, showing the increase in the compression levels in some regions and the possible presence of tension forces in some other parts. Within the examined cases, when the maximum length is considered for the cantilever portion (46 m), the weight of the main building block is not enough to counterbalance the overturning effect due to the cantilever; consequently, an anchoring foundation block is required on the building opposite side. In terms of load propagation, this implies extra-compression on the façade close to the cantilever portion and tension on the opposite one (see image 1).

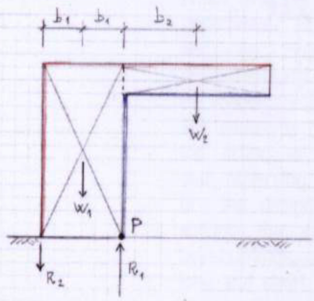


Image 1 – Static scheme for the analysis of global equilibrium.
Blue indicates compressed elements, red indicates the ones subject to tension.

The adoption of a structural typology

The need of covering long spans necessarily leads, in terms of the structural scheme, to the use of truss systems. This kind of solution, indeed, is normally employed in buildings whenever special problems arise producing irregularities in the normal mesh of beam and column elements or requiring longer spans. As in the case of bridges, a considerable height is required to the truss beam if spanning over a long distance; namely, one or more inter-storeys are included in the beam thickness. In the examined case, the beam height is 10 m and includes three storeys. The structural scheme, in this situation, acquires a dominant role in the design, with a marked influence on the building final appearance and usability.

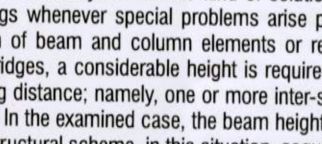


Image 2 – The truss scheme adopted for the cantilever beam. Minimum thickness is 10 m.
Blue indicates compressed elements, red indicates the ones subject to tension.

Advantages and peculiarities in the truss scheme

A truss scheme, as it is known, necessarily implies a considerable transversal size; at the same time, it provides a very light structural solution, being derived from the reduction of the traditional beam to the main load propagation lines. This implies, in addition to top and bottom longitudinal chords, the presence also of connecting elements arranged along both vertical and inclined directions (i.e., diagonal elements). The adoption of a truss scheme results, in any case, in a very flexible solution, also in consideration of the possibility of varying the transversal size, following the bending moment variations.

Primary and secondary structures

Typical proportions in the design general layout are such that relevant values are present for the distance between primary structures as well; for instance, between parallel cantilever beams (34 m). As a consequence, the adoption of the truss scheme is extended form primary to secondary structures, corresponding to transversal beams. Also in this case, the beam thickness corresponds to the inter-storey height; diagonal elements, therefore, go across the inter-storey space. In the building main portion one of the examined design variants is based on this structural solution. Each truss beam, indeed, provides support to a couple of storeys; in this way, diagonal elements are present at every other inter-storey. In this way, usability conditions at the different floor levels are determined by the adopted structural scheme.

From structural typologies to sizing of resisting elements

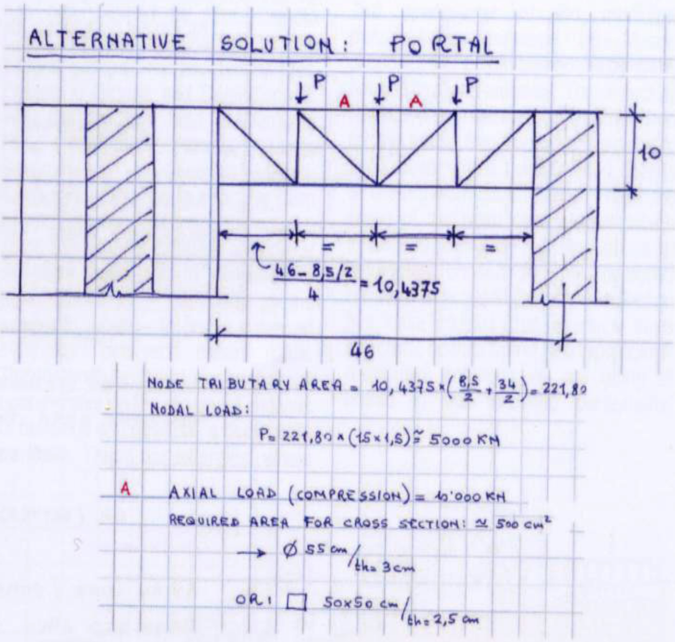
Once the load propagation path has been defined throughout the structure, single structural elements along this path can be considered for the cross section sizing, in line with the material resistance properties. In the case of primary structural elements, sizing criteria depend on simple rules: in the design of truss beams, where bending dominates, a good balance has to be achieved between the beam total height and the top and bottom chord cross section. In the case of long span beams, it may be of interest varying the beam height according to the bending moment value, keeping the chord section constant. In façade columns, where high compression values are present, capacity may be strongly reduced by instability; design aims, in this case, at a proper choice of both shape and size for the column cross section.

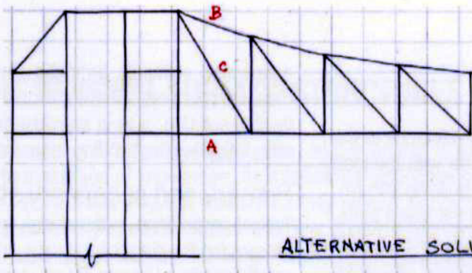
Characterization of construction loads

The design of single resisting elements necessarily follows the characterization of the design loads which, in the presence of long spans, must be reduced to minimum values. This applies to both permanent and variable actions; as to the first, use conditions of different areas have to be carefully examined and suitable values assumed for the corresponding loads; as to the permanent loads, technological solutions allowing for maximum lightness should be adopted both for slab and façade elements.

Structural deformability

The design of structures is normally based on both resistance and deformability requirements. In case of reduced span structural elements, design is conditioned by resistance, whereas the opposite applies to the case of long span elements. Truss systems typically exhibit high stiffness properties, not exempting, however, from the numerical characterization of displacements. Due to inherent computational difficulties, this check is often skipped in preliminary design, and postponed to the working plan phase of design.





ALTERNATIVE SOLUTION

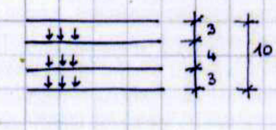
A AXIAL LOAD (COMPRESSION) = 25'300 KN

B AXIAL LOAD (TENSION) = 18'834 KN

C AXIAL LOAD (TENSION) = 15'068 KN

CANTILEVER BEAM:

LOADS ON THE BEAM, COMING FROM 3 FLOORS:



FLOOR	SLAB	PERMANENT	LIVE
ROOF	1	0,5	3
MAIN	1	1	5
SERVICE	1	0,5	2
TOTAL	3	2	10

TOTAL LOAD FROM 3 FLOORS: $15\ KN/m^2$

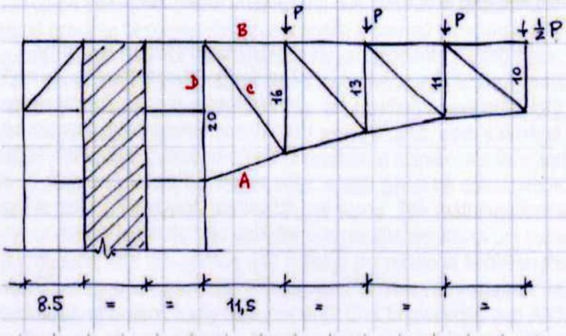
LOADS TRANSFERRED TO BEAM NODES:

NODE TRIBUTARY AREA = $\frac{46}{4} \times \left(\frac{8.5}{2} + \frac{34}{2}\right) = 244{,}38\ m^2$

NODAL LOAD:

$P = 244{,}38 \times (15 \times 1{,}5) = 5'500\ KN$

↑ γ FACTOR, FOR U.L.S. DESIGN



A AXIAL LOAD (COMPRESSION) = 26'787 KN

REQUIRED AREA FOR CROSS SECTION: ≃ 1200 cm^2

→ 1 ⌀ 100 cm / th = 4 cm

OR (BETTER): 2 □ 60×60 cm / th = 2,5 cm

B AXIAL LOAD (TENSION) = 17'789 KN

REQUIRED AREA FOR CROSS SECTION: ≃ 600 cm^2

→ 1 ⌀ 50 cm / th = 4 cm

OR (BETTER): 1 □ 60×60 / th = 2,5 cm

C AXIAL LOAD (TENSION) = 12'869 KN

REQUIRED AREA FOR CROSS SECTION: ≃ 420 cm^2

→ 1 ⌀ 45 cm / th = 3 cm

OR (BETTER): 1 □ 45×45 cm / th = 2,5 cm

D AXIAL LOAD (COMPRESSION) = 10'450 KN

REQUIRED AREA FOR CROSS SECTION: ≃ 600 cm^2

→ 1 ⌀ 50 cm / th = 4 cm

OR (BETTER): 1 □ 60×60 cm / th = 2,5 cm