CONCEPTUAL DESIGN AND INNOVATIVE STRUCTURAL CONCEPTS TO PRODUCE SOUND CONCRETE STRUCTURES

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SUMMARY
Structural design is not the result of sudden inspiration as some people tend to believe. Talent is certainly necessary but insufficient. To design requires a constant effort to synthesize clear ideas of the problem to be solved and its limits, a profound structural knowledge and a rigorous search of the ideal solution to the problem.

INTRODUCTION
Is it possible to carry out good structural engineering?
Obviously, it is. The history of humanity is filled with excellent examples of great structural engineering, as seen in figure 1.

The Roman bridge of Alcantara (the word “alcantara” means “bridge” in Arabic) held the world record for the longest span for more than 1,300 years since its construction (Gaius Julius Lacer, 2nd century) until the Renaissance. Brunelleschi won the competition held to build the dome of the Santa Maria del Fiori in the 15th century because of the advantages of the novel execution system that he proposed. Roebling was, in 1883, the designer of one of the first great modern suspension bridges. Another example of excellent structural engineering and conceptual design is the work of Robert Maillart. Figure 1 shows the Magazzini Generali built by Maillart in Chiasso in 1924.

It is regrettable, however, the proliferation, in recent times, of bad examples of structures, typical of vulgar engineering and separated from any engineering tradition.

A kind of confusion has proliferated that has set forth a senseless and selfish current of structures almost worthy of demolition.

Although these observations are personal opinions, structural disorder and the vain abuse of sensationalist solutions should be left outside the code of ethics of structural engineering. Are ethics and aesthetics present in such examples? Definitively, not.
**Figura 2. Examples of bad and unacceptable structural engineering.**

**How to carry out good structural Engineering?**

It is really difficult to answer this transcendental question, but it is certain that it requires at least the following ingredients.

**Profound knowledge**

It is impossible to design without a thorough knowledge of the structural behavior, of the possibilities of the different materials, construction processes, etc. The calculation means available may create the false idea that profound knowledge can be replaced by powerful computing tools.

Profound knowledge, however, addresses the problems with elemental simplifications that lead to a clear interpretation of the flow of forces and the structural needs present in every proposed solution. Figure 3 shows some sketches from the book *Philosophy of Structures* by Eduardo Torroja (1958a), undoubtedly one of the most recommendable books for all engineers that should be read at different stages of the life of an engineer. This book explains in simple terms the basic structural concepts, the materials available at the time of its writing, the basic structural elements, their function and operation, and construction processes available and compatible.

**Figure 3. Basic structural knowledge (Torroja 1958a).**
Hard work and craft

It is wrong to think that the ideal design comes from the inspiration that the muses only bestow upon engineers with talent. In engineering and possibly in any other field, it is not so: a good design is, fundamentally, the result of hard work and the craft acquired over time.

Figure 4 shows the Pino Viaduct designed by the Spanish engineer Eugenio Ribera, built in 1914. It is an arch bridge that surprised Eiffel with its lightness; in fact, the viaduct was completed with 414 kg/m of steel in contrast with the 6,000 or 8,000 kg/m used in the bridges designed by the Frenchman. Figure 4 also shows part of the typological study carried out by Ribera that collects several different alternatives presented with an extraordinary level of development. In fact, this magnificent work was later published in a technical journal (Ribera 1897), with over 125 years that it is still published today, that presents in detail the typological study carried out and the calculation annex of the adopted solution. For each option there is a structural and economical evaluation, and a comparison with other solutions already built in Europe and the United States. A substantial and well done work. Ribera was 28 years old when he made this design.

Permeability

The third ingredient to make good structural engineering is permeability, especially at present. The structural engineer must show high permeability. Permeability to work in different structural domains: buildings, bridges, public works. Permeability to work with different materials: steel, concrete, composite structures, wood, fabric, etc. Permeability to work at any stage of the life of the structure: design, construction, maintenance, operation and demolition. These different fields of work create a flow of information and ideas that enrich the project, allow the transfer of experience from one field to another, from one material to another, from one stage in the life cycle of structures to another.
Humanism

Last but not least important, humanism is a constant reference to the work of engineers. Good structural engineering cannot ignore society, its history and its culture. Humanist engineering for living beings, as in the Renaissance, when the person was at the center and all other things revolved around it (anthropocentrism).

The contribution of engineers to the evolution of mankind has been extraordinary and anonymous. The evolution of life expectancy in Spain in the 20th century has practically doubled. An analysis of the causes of such positive evolution would find that sanitation and water purification have had more influence than the evolution of healthcare. Unfortunately, I do not know if we are aware that we, engineers, are protagonists of this role, that we play a
great role in society and that our contribution goes beyond the isolated facts of a simple design.

WHAT IS CONCEPTUAL DESIGN?

During the last decades, this term has been used to refer to many concepts, which have not yet been clearly defined.

The symposium on Conceptual Design, organized at the University of Stuttgart by Prof. Jörg Schlaich (Heinle and Schlaich 1996), was possibly the first event organized by engineers to analyze this problem. It was the result of a long felt concern of a few professionals.

The preface to the symposium papers, literally states: The overall quality of many structures today leaves much to be desired. The rapid technological progress does not reflect adequately in their variety, beauty and sensitivity. Too often structural engineers neglect the creative conceptual design phase by repeating standard designs and not sufficiently contributing with own ideas to the fruitful collaboration with architects. Engineers thus often waste the chance to create building culture.

The announcement of the symposium invited participants, supposedly expert designers, to describe the process of design, the process of the creation of a solution to a problem. The symposium had a high attendance and was very interesting, but was not definitive as to the definition of conceptual design, nor as to the definition of the process leading to the final solution.

Conceptual design (Balázs et al 2009; Corres 2013) is a process or design method, which using the available resources – structural, technological, cultural, creative, etc. – eases the search for the solutions to a design, to a structural problem, etc.

The objective of the process is to find the optimal solution to a multi-variable problem, in which all of the variables are important.

It must be made clear that this process does not guarantee the quality of the idea. An interesting idea, even a brilliant one, does not come from sudden inspiration. It is the result of a persistent search and of detailed and hard work. We have all sometimes seen how hard work, the intelligent and tireless search, the tenacious persistence in finding by discarding, ultimately yields results. The best results.

HOW IS CONCEPTUAL DESIGN CARRIED OUT?

It is not easy to define the process of Conceptual Design. Figure 7 shows a flow diagram, which was presented by Jean François Klein (2004) at the fib SAG 5 New Model Code meeting held at Lausanne, meant to serve as a basis for the introduction of these concepts into the new Model Code (2010).
Figure 7. Flow chart and tables describing the process of Conceptual Design (Klein 2009 and Model Code 2010).
For the first time, Model Code (2010) introduces this procedure in a design code. Conceptual Design forms part of the first tasks in a design project and covers its entire process. The Textbook (Balázs et al 2009; Corres 2013), published by fib, has a chapter dedicated to this problem.

HISTORICAL APPROACH

Engineers of the past have left us a fabulous legacy, filled with examples, which show great ideas, despite the very limited technological resources they could count upon when compared to those available today.

There have been many examples of creativity, innovation and craft in many of the works of the different masters of structural engineering, in general and of concrete, in particular. Practically every country has had a master of structural engineering. There is no documented evidence of the process of Conceptual Design carried out in all of these masterpieces of structural concrete. Considering that this is a very personal process, it is not easy to explain the work of other authors. It is only possible to make an interpretation, which will not always be correct.

The Pantheon of Rome (figure 8) is one of the most outstanding examples of building engineering. The inside of the building is inscribed in a perfect sphere of 150 feet of diameter (43.44 m), a record span in concrete construction, only broken at the beginning of the 20th century by Max Berg with the Centennial Room in Breslau. Rebuilt in the 2nd Century by Apollodorus of Damascus, then at the service of Hadrian, its architectonic configuration is adapted to the philosophical concept that related human beings with the vault of heaven, whose center, the oculus, is the sun. This is the theme of the architectural configuration from which was built the most outstanding example of roman antiquity, filled with excellent engineers. The counterbalance of the dome is formed by a drum of opera latericia (brick) 7 m deep, wisely configured with a grid of arches built into the drum walls, which allow it to resist both the meridian compressions of the dome as well as the circumferential tension stresses at the spring of the dome. The dome itself has a variable depth, ranging from 5,90 m at the dome springs to 1,5 m at the oculus, masterly distributed with recourse to partial waffle-slab-like voids on the inside and a discrete set of rings on the exterior of the building.

Figure 8. Constructive sketch of the Pantheon in Rome (Heinle and Schlaich 1996), Cross-section and axonometric view of the same work (Escrig 1994).

The following lines describe some of work of, the already mentioned, Eduardo Torroja, professor, researcher and design engineer, rara avis, whose creative process perfectly fits with the modus operandi defended in this paper.
When he was 26 years old, Torroja faced the need to solve the problem of the design and construction of the Tempul aqueduct (1925). Figure 9 shows on the top the original project, an aqueduct with simply supported spans and two piers placed within the river bed, and at the bottom, the solution, which was built in which these piers have been replaced by cable stays (Torroja 1958b).

![Figure 9. Tempul Aqueduct, 1925 (Torroja 1958b)](image)

At the time of construction, there was no commercial technology for the stays designed by Torroja. He proposed to use closed cables, commonly used in harbors, and in order to stress the stays he proposed to use jacks acting in the vertical direction on the tops of the pier, as shown in figure 10. Moreover, in order to improve the conditions of the stays, the stressing operation was done with the stays already in tension, supporting the stretch of the U shaped beams going from the pier to the expansion joints. In this way the stays were enveloped in concrete thus achieving greater stiffness, greater protection and better durability conditions.
This example clearly shows how the conceptual solution to the problem, that is the use of stays in order to suppress the piers in the riverbed, is combined with many other ideas aimed at solving the practical problem of stressing and materializing the ties. To this, add that, although many Torroja worshipers saw in this solution a predecessor of prestressing, by the compression produced in the deck due to the horizontal component of the tie forces, the great engineer politely declined the honor, and acknowledged his contemporary colleague Freyssinet (Torroja 1958b), by saying that he had not deliberately sought to produce a previous and favorable tensional state, as a prestressing concept, but had only solved a construction problem. Great figures often are and should be humble like him.

In the brief and dense preface of Philosophy of Structures, Torroja (1958a) wrote: Each material has a specific and distinguishing personality, and each form imposes a different stress phenomenon. The natural solution to a problem – art without artifice – optimum in the face of the previous impositions which originated it, is impressive by its message, satisfying at the same time, the demands of the technician and of the artist. The birth of a structural ensemble, the result of a creative process, escapes the sole domain of logic and penetrates the secret frontiers of inspiration. Before, and above all calculation there is the idea, which shapes the material in a resisting form, in order to comply with its mission.

It has been believed that it is not possible to better describe what is and how to synthesize the Conceptual Design process.

**PERSONAL APPROACH**

The following sections show a series of designs developed by a group of structural engineers at Fhecor Consulting Engineers (Fhecor 2014), which embody the indicated design concepts.

The presented works are grouped according to the moment of the life cycle of the structures in which we participated: conception (design)-construction (construction assistance)-exploitation-rehabilitation-demolition.
Conception, design and construction assistance

In field of bridges, this section shows a series of examples or arch bridges of different typologies, materials and construction systems.

In first place, the concept developed for the competition of the bridge over the Lerez River, in Pontevedra is presented. In 1990 the regional government of Galicia called for a competition of ideas for a new bridge over the Lerez river, in Pontevedra.

FHECOR Consulting Engineers were awarded the second prize of the competition with a bridge with two spans, each one formed by an arch with lower deck. The arches were conceived as made of concrete with a structurally optimum geometry, to control lateral buckling and to minimize the occupation of the deck. The cross-section of the arch is practically constant but with large height and small width at the arch springs and with small height and large width at the crown. At the zone of the intermediate pier the arch transforms into a shell.

After some time, this same idea was used for the design of the bridge over the Jucar River (Romo and Corres 1999) solved with a double arch with intermediate composite deck, strongly skewed. The arches on the deck are made of steel with a constant area, although conceived with the different widths throughout the length of the arch. Small width and large height at the springs and large width (in order to achieve more stability) and small height at the crown. The length of the arch at the intersection with the deck is of 87.00 m.

This bridge presents an additional singularity, which is the structural disposition used to prevent important horizontal loads on the foundation piles. The arch is continuous because of a concrete box that is connected to the abutment, which is used to “verticalize” the loads on the foundation piles.

Once the concrete infrastructure was built, the steel deck was installed. The steel arch was installed on the deck, ties were later installed and finally, the concrete of the deck slab was placed.
In recent years it has been possible to build a series of arch bridges with lower composite deck with these principles.

Balanced cantilever bridges are already traditional in the construction of bridges for spans greater than 100 m. In Spain the bridge with the longest span is the Manzanal bridge (Corres and Prieto 2008), in Zamora, designed by Fhecor Consulting Engineers that has a span of 190 m.

Nevertheless, this typology still has possibilities in other situations with greater spans and lengths. The bridge over Tajuña (Corres, Torrico and Milian 2008) is a bridge with a total length of 2,000 m and with 250 m high piers.

After a profound and detailed typological study, the bridge was designed with multiple 250 m long spans. The deck is fixed at the piers that are shaped like tuning forks at their tops in order to increase flexibility and reduce the effects of the movements caused by imposed strains in the deck. The deck has a longitudinal buffer stop, using a block for instantaneous loads that allows the control of the longitudinal buckling strain, which is the most critical one for these cases. This is a bridge that collects many of the ideas that have been successfully explored in other projects.
Another very interesting field is the field of railway bridges (Corres, Pérez and Romo 2004) and, in particular, High-Speed Railway Bridges. In Spain, over 20 years ago the construction of High-Speed Railway bridges considered a design speed of 250 Km/h and the lines that were designed and built in the last 10 years consider a much superior design speed of 350 Km/h.

These bridges have many particular features they are normally long viaducts in which it must be decided whether they will be designed as continuous bridges or with joints between spans. While the first generation of High-Speed Railway Bridges was of statically determinate bridges, the second generation is usually composed of bridges with continuous decks.

The braking forces are very important and it is necessary to resist them with an adequate and efficient structural system. Figure 15 shows different strategies to longitudinally contain the deck.

In general, the construction of this kind of viaducts is very important. Three methods have normally been used: incrementally launched, span-by-span construction and prefabrication.
a) Statically determinate deck

b) continuous deck

Figure 15. Different solutions for the control of longitudinal braking forces.

a) Arenteiro Viaduct, incrementally launched
The world of buildings presents many possibilities for structural engineering. Frequently, the structural proposals lie hidden under the skin of architecture, but we must not forget of what they are capable of doing.

Some examples show the importance of the concept of the structure in architecture. In this framework it is also of great importance to conceptually solve the structural proposal optimizing the use of materials, the typologies and the construction systems.

The Hospital of Fuenlabrada (Corres and Ruiz 2002) by the architect Andres Perea is a 250.000 m2 building with floor plan dimensions of 159,5x123 m. Since the design stage of the project, a prefabricated solution was proposed with rigid unions without dilation joints.
The proposed solution is a good example of how to solve, with non-standard prefabrication, a modulated building, obtaining an optimization of construction time and taking advantage of the higher quality that industrialized construction can offer.

![Image 1](image1.png)

**Figure 18. Hospital of Fuenlabrada, Madrid.**

The new airport of Barajas in Madrid, work of Antonio Lamela and Richard Rogers, has unusual dimensions for which, its greater challenge has been to determine an adequate structural solution, fast and adapted to the requirements imposed by its construction.

The project has a parking building with floor dimensions of 656,4x80 m and six levels. It is divided in six jointless modules of 112x80 m. Structurally, it is a reinforced concrete hollow core slab with a thickness of 0,38 m supported by a 8x8 m mesh of columns. The columns are circular with a diameter of 0.5 m, very flexible, which improves the behavior of this large structure. In order to avoid the duplication of columns between modules, the dilation joint is set in such a way to guarantee the vertical continuity with shear keys.

The Terminal building has a Surface of 125.00 m² and it is distributed in a central zone with plan dimensions of 360x216 m and lateral walls with 396 x54m. Depending on the zone, there are up to three underground levels and two above the ground levels.

The Satellite building has 70.000 m² distributed in a central zone with plan dimensions of 144x180 m and lateral walls with 396 x54m. Depending on the zone, there are up to three underground levels and two above the ground levels. One of the lateral walls is supported by a tunnel that belongs to the M-111 highway.

In general, a 9x18 m column mesh was conceived, which forms frames with a general span of 18 m and a length of 72 m. The frames are formed by columns, which are circular with diameters of 1.2 and 0.8 m and prestressed girders with post-stressed reinforcement with a height of 1,8 m and width of 0,8 or 0,9 m. In order to ensure the continuity of the 72 m long frames, some in the lateral walls zones reaching a length of almost 1.000 m, joints and shear keys have been placed. The joints were placed at one-fifth of the spans and the shear keys have great load and opening capacities that have been specifically tested.
The construction system followed to build over 80 Km of prestressed girders with post-stressed reinforcement has been the following: placing the concrete of the girder over a moveable framework; removing the framework and moving the girders, which at that stage act as reinforced concrete elements; aligning the strands and stressing them; installing the hollow core plates; placing the concrete of the top slab on the hollow core plates.

**Exploitation, Rehabilitation y Reconstruction**

Over its lifetime, a structure requires a correct control, a routine of inspections and diagnostic of its behavior and pathologies (León, Corres and Prieto 2008). These increasingly important activities play a significant role, not only for the structures currently subject of these activities but also as feedback for the design of new projects.

This activity requires great experience, knowledge and humility. To understand the behavior of existing structures represents a greater responsibility and dedication than the design of a new structure.

Rehabilitation is another field that becomes more important in structural engineering. It is an activity that also requires great skill and new developments. Reparations represent relatively uncostly processes that require great specialization and in which there has been much development on the study of the raw materials used but few advances in the applications processes. For example, there are but a few means to measure the efficiency of the executed repairs.

A very interesting example is the widening of the Santos viaduct (Corres et al 2008). This bridge with large dimensions and spans of 150 m was built in the 1980's with original width of 12 m and due to the new traffic needs it was proposed to widen it to 24 m. Due to environmental reasons it was impossible to build another bridge parallel to the original one, or other solutions of that sort. It was necessary to study the widening of the existing bridge. Furthermore, due to the characteristics of the area it was necessary to consider that the widening will occur with traffic flowing on the bridge during construction. In first place, a

![Figure 19. Barajas Airport, Madrid.](image-url)
detailed inspection was conducted as well as an evaluation of the resisting strength to confirm the capacity of the existing bridge, with reinforcements, to resist the new loads product of almost doubling the width of the deck.

Then, as it is usually done, an analysis of the possible options was carried out until it was feasible to decide the final solution. The concept of the adopted solution is shown in figure 20. A new web was installed inside the existing box girder and a widening was proposed by using slabs made of lightweight concrete, which carries the loads to the new web with a steel structure composed of struts and a hinge. The intervention, at the level of the deck is completed with the introduction of an external prestressing inside the already existing box girder. Figure 20 also shows the concept of the strengthening of the foundation.

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a) Cross-section of the adopted solution
b) External prestressing

c) Concept of the strengthening of the foundation.

Figure 20. a) Cross-section of the adopted solution. B) External prestressing c) Concept of the strengthening of the foundation.

At a very conceptual level, the bending increments are resisted with the reinforced lightweight concrete slabs at the top flange and the composite web, and steel box filled with high strength concrete at the bottom flange. The shear increments activate the new web. The torsion increments are solved with the compression produced by the external prestressing inside the box girder.

The construction procedure, due to the characteristics of the intervention and to the necessity of maintaining the traffic was a very important problem and required solutions particularly developed for this project as shown in figure 21.

a) Execution of the slabs in the widening zone
b) Finished Bridge.

Figure 21. a) Execution of the slabs in the widening zone b) Finished Bridge.

In some cases, the structure reaches the end of its service life and it is necessary to accept this vital moment and proceed with the demolition and, in some cases, the later reconstruction. It is a moment in which it is possible to perform an autopsy that allows designers to know more about the demolished structure and about many other structures built at that historic period, since the materials, the design criteria, the construction means, etc., were the standards of that time.

**STRENGTHS AND WEAKNESSES OF STRUCTURAL ENGINEERING AND ITS RELATION WITH CONCEPTUAL DESIGN**

Nowadays we are filled with so many paradoxes that, at times, it seems chaotic. We have at our disposal modern design codes, which are meant to be the synthesis of the most updated knowledge; powerful and versatile means of calculation; new materials, which are a product of a not so well known technological progress (probably because the capacity of amazement of the post-modern man has decreased); very powerful means of construction, never before seen, and, in spite of it all, the production of structural engineering is not always up to the level of these favorable circumstances. It is possible that the following factors may justify this situation.

The education of engineers, no doubt, an essential factor, has suffered great changes in recent times. It is clear, on the one hand, that the University must provide solid and profound theoretical knowledge, but it should also provide a broad vision of engineering and culture. It is well known, and with very few exceptions, that the contribution of the University to the humanist education of engineers has become almost non-existent. Finally, practically there is no teaching whatsoever on conception, a process that must be present in the education and should serve as the initiator of the design process. Students are attracted to this type of subjects that should not only show other projects but spark a creating experience. When one creates one time, even something as simple or as complex as a poem, one knows the process and generally, if one is aware of it one tends not to stop.

On the other hand, it is necessary to learn the craft of the structural engineer, which is not acquired at the University, but rather by professional experience. This requires having wise senior colleagues, which serve as masters for the younger engineers. The masters should be well taken care of and the younger engineers should learn from them, and
eventually succeed them. Unfortunately, this process is not currently well controlled and this is a sad waste.

**Knowledge has advanced and has become atomized.** Frequently we find that there is no connection, no bridge between the generated knowledge and professional practice. It is evident that the world of research is disconnected from the world of design, the languages are different and they serve interests which are not common, or sometimes clearly divergent, without points of contact.

**Design Codes, which have evolved remarkably, can be, in many occasions, an obstacle to invention.** They should be written to provide liberty, not to establish restrictions. In this sense, the increasingly important performance and client oriented character of modern codes contributes to encourage progress that can be brought by the better prepared engineers, those who better apply the art of Conceptual Design.

**The computer resources, which at first glance are a significant step forward, can in fact become traps which imprison the minds of engineers,** which can only see though the limited and distorted windows offered by mere models, which restrict the act of thinking, which confuse designers, now young, which take as sources of inspiration what are mere working tools conceived to free them form a routine of calculations.

Reality is rich and complex. Engineering has always distinguished itself by the capacity to manage uncertainty, in words of our dear colleague Javier Rui-Wamba, and naturally, computer programs cannot solve the uncertainties we face. However, to be aware of this, it is necessary to be aware of what are these uncertainties. Today it is frequent to see an engineering of ‘Technicolor’, supported by the post-processors of computer programs, in which complex models offer the false hope of solving that which is not known which is not possible. Only knowledge can identify the limits of ideas, and therefore the limits of computer programs. It is essential to know what can be expected from models, it is essential that, at all times, the intellectual fruit, the idea which comes from a good process of Conceptual Design prevails, and that computational models should serve this process, to more coherently quantify those previous ideas.

**New technologies must be controlled by designers,** at least to a sufficient level as to guarantee enough control over them. New materials, new gadgets, new technological inventions must be assimilated by designers in order to guarantee their optimal use. Many times, the products offered in the world of civil engineering have been developed for other applications and only a sufficient knowledge can allow engineers to use them efficiently.

Finally, knowledge, today, requires teams, because it has become so vast that it cannot fit into the minds of individual figures who were ever powerful in a past not so far away, but who could not today seize it all with the required degree of detail. This requires a new culture of working towards a common goal: engineering.

**FINAL CONSIDERATIONS**

Design is an art which must be cultivated, it is an act of creation, for which Conceptual Design is an indispensable instrument. Design is the magical passage from a problem in a white sheet of paper, to a reality.

Design is an art which is learned with time, each project is an opportunity which cannot be wasted. Brilliant ideas are not always obtained, but ideas are essential, if they are good it is magnificent and if they are brilliant it is an exception.
The development of technology, materials, construction means, etc., is an offer of good possibilities for potential creators.

It is paramount to educate our students to be motivated for this creative process and have the tools, a profound knowledge of the structural concepts and of our history and the motivation to carry out our profession creatively, efficiently and proud to contribute anonymously and transcendentally to the betterment of the human existence.

It is very important to have the capacity to work in teams. It is true that the creative process is individual but teams are essential, our own teams, external teams, interdisciplinary teams, all teams.

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