

Aesthetics in the education of civil and structural engineers

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ABSTRACT: Civil and structural engineers are responsible for the design of large scale public works, but they hardly receive any training in conceptual design or visual education. The paper raises the need to urge an aesthetic education for engineers, in order to develop their perceptive and creative abilities, and presents the experience of the course on Art and Aesthetics in Civil Engineering held at the Universitat Politècnica de València (Spain). The concept of engineering aesthetics used in the course arises from a holistic approach to the work of engineering and is focused on its form, trying to understand all the reasons behind it, be they heavily conditioned by technical constraints or not. Different course activities are described, intended to help the engineering student understand form not only through his brain, but also through his senses.

1 INTRODUCTION

Civil and structural engineers are responsible for the design of the biggest objects man is able to build on Earth, most of them belonging to the everyday environment of many people. On the other hand, there is an ever increasing awareness among engineers that the work of engineering belongs to the realm of creativity, even to the extent of considering it as a work of art, while at the same time society is demanding public works with ever richer content and meaning. Civil and structural engineering degree syllabus usually lay much emphasis on efficiency, economy, safety or strength, which are usually developed by subjects like advanced mathematics or physics, involving a much more abstract and quantitative approach to reality. Courses on engineering aesthetics, however, provide engineering students with the possibility to balance this with a more qualitative approach, awakening their form awareness, and training their design skills.

The paper raises the need to urge an aesthetic education for engineers, in order to develop their perceptive and creative abilities, and presents the experience of the course on Art and Aesthetics in Civil Engineering held at the Universitat Politècnica de València (Spain). This course rests on the assumption that civil and structural engineers belong to a broader family of form professionals or designers, such as architects, painters, sculptors or industrial designers, covering the whole scale range of artificial objects, from the smallest to the biggest, in which the engineer is responsible for the top end of the largest artefacts, the ones with maximum visual impact. While the other form professionals are trained in aesthetics and visual education, engineers only rarely include such courses in their syllabus, as they are usually considered irrelevant or secondary to their predominantly scientific approach. The reason behind this lies in the poor concept of aesthetics prevailing in most schools of engineering, as something alien or peripheral, far away from the core of the body of knowledge of engineering.

2 THE CONCEPT OF AESTHETICS IN ENGINEERING

The most widespread concept of aesthetics in engineering is that of the afterthought or optional extra you can easily dispense with. Aesthetics is often conceived as surface beauty, as a sort of last minute make-up that will make the work of engineering look pretty, once all technical and major decisions have already been taken, assuming there is a section in the budget to provide for aesthetics. If the budget is so tight so as not to include such section, no essential part of the work will be lost, and it will only be deprived of aesthetics. The assumption behind this concept is that there will only be aesthetics if there is enough money to cater for it.

All other form professionals or designers, however, are well aware that there is no physical object or work aesthetically neutral, no matter whether there has been a concern for aesthetics in its design or not. If there is a built work, there is always a physical object that has adopted a specific form. But form, on the other hand, is the main concern of aesthetics, even if it is strongly conditioned by technology. So, in the end, any built work does have an aesthetic consequence, as there is inevitably a form that is being perceived, and technology cannot be excluded from aesthetics, as technology generates form. There is therefore no point in splitting both areas.

This concept of aesthetics in engineering as an inessential added embellishment is typical of the 19th and early 20th century engineering, and can be found in many different examples, such as the lions at the entrance of the Britannia Tubular Bridge, or the pointed neo-Gothic arches of the stone piles of the Brooklyn Bridge or the arches at the base of the Eiffel Tower. But on the other hand, all these three works were pioneering examples of iron or steel engineering where technology had been pushed to its limits at that time. They gave rise to unprecedented forms made up by extremely slender and linear elements providing a new quality of lightness and abstraction.

A new aesthetics was actually emerging from this iron engineering, that was to be source of inspiration for many artists later in the 1920s. This impact on the world of art and architecture involved another concept of engineering aesthetics, where attention was no longer focused on ornament, but on the overall form of the work and its close link with material and technology. Thus technology was now becoming integrated and playing a leading role in engineering aesthetics. This is the concept of aesthetics in engineering characteristic of the 20th century, also exemplified with reinforced and prestressed concrete structures, as well as with thin shells and tensile membrane or cable structures.

Since the 1980s, postmodernist times have produced yet another concept of engineering aesthetics, whenever political authorities have demanded an approach to the work of engineering as an outstanding landmark or emblematic icon, and the spectacular or "aesthetic" effect has become first priority. Form in these cases is an imposed precondition, not the result of a process of integrating the highest amount of conditioning factors. Prevalence of form means that other requirements, be they functional, constructive, structural or environmental, will most likely not be adequately met, and consequently the meaning conveyed by the form of the work loses part of its richness, as it is to a great extent explained by the intention to make an impression or to create a spectacular effect.

An aesthetically valuable work arises from a balanced and inspired synthesis of conditioning aspects, very often also in conflict with each other, that explain and enrich the form of the work, which becomes the outcome of a process where aesthetics and technology have run parallel from the very beginning, without one being relegated to the other, both being appreciated in their true value. As Frederick Law Olmsted puts it: "The demands of beauty are in a large measure identical with efficiency and economy, and regard for beauty neither follows after regard for the practical ends to be obtained nor precedes it, but must inseparably accompany it."

3 ART AND AESTHETICS IN CIVIL ENGINEERING AT THE UNIVERSITAT POLITÈCNICA DE VALÈNCIA

The concept of engineering aesthetics put forward in the course on Art and Aesthetics in Civil Engineering held at the Universitat Politècnica de València is focused on the form of the work of engineering, and therefore includes all aspects affecting form, be they technical or visual, be

they heavily conditioned by technical constraints or not. It is a concept that arises from a holistic approach to the engineering work, considering its form as a integrated synthesis of very different determining factors affecting it, and providing a greater wealth of meaning to the work: functional, environmental, structural, constructive, economic, geometric, visual, etc. Engineering aesthetics, in short, is presented as an urge to understand all the reasons behind the built form, as form is considered to be the main object of aesthetics.

When we are studying a work of structural engineering, aesthetics helps us explain and analyse its form as an effective response to achieve strength, stability and durability, but at the same time also as a response to other non structural requirements which may come into conflict with structure, such as function or environment. Furthermore, aesthetics helps us become aware of the visual and geometric order underlying the form of the work of engineering, that stems from the design process.

3.1 *Purpose and targets of the course*

The main target of the course is to develop the perceptive abilities and the creative and design skills of civil and structural engineering students. In order to achieve this, we make use of didactic resources for developing perception and creativity already experienced in other disciplines linked to the world of creativeness and design, such as Fine Arts, Industrial Design or Architecture, through subjects or courses on basic design, visual education or analysis of form. On the other hand our course relies also on the experience of other similar courses for engineering students, like the visual design course for students of science and engineering at the Massachusetts Institute of Technology (Preusser 1965), promoted by Professor Gyorgy Kepes, an outstanding Hungarian artist and pioneer in the marriage of art and technology, who had collaborated with Laszlo Moholy-Nagy, one of the leading teachers at the Bauhaus.

This main target can be split more specifically in the following basic targets:

- To train engineering students in design processes, developing their creative abilities and their skills to make up a meaningful whole out of many particularities.
- To develop the students' perceptive abilities to grasp the possibilities and suggestions offered by those aspects interacting with the engineering work and incorporate them to the design process.
- To develop skills for critical, qualitative and conceptual analysis of the engineering work.
- To train aesthetic sensitivity, form awareness and its control during the design process.
- To know, develop and apply different form and visual perception structuring and ordering principles.
- To know and appreciate historic and contemporary heritage of public works, and develop skills to carry out a critical analysis of their forms.

3.2 *Course programme*

The headlines of the course programme reflect the concept of engineering aesthetics adopted, and intend to deal with some key aspects affecting form in civil and structural engineering. A summary of contents is included under each headline.

- Aesthetics, design and criticism of form in engineering. A qualitative and conceptual approach to engineering. The engineering work as a work of art. Form under the particular conditions of the engineering work. Form in large and middle scale engineering. Creative processes and iterative approaches to design. From the whole to the parts and from the parts to the whole. Aesthetic quality of an engineering work as an assessment of the integrating synthesis of all aspects affecting its form.
- Form and place. The topological dimension of engineering. Concept and categories for the analysis of the place. Perception of the morphology of the environment. Visual and formal elements of the landscape. Fitness and links of the engineering work with its environment. Scale and visual measurement of the engineering work and its environment.
- Form and utility. The functional dimension of engineering. Qualitative analysis of uses and functions made possible by public works. The relationship between form and function. The functionalist tradition. Conventional and hybrid functional typologies. The integration of uses as an enrichment of the engineering work's meaning.

- Form, structure and construction. The tectonic dimension of engineering. The relationship between form and strength. The dialectic between the geometric logic of form and the mechanical logic of forces. Form as a precondition or as a consequence: arbitrariness vs. causality. Forces as form generators. The expressive quality of materials, structure and construction. The perceptive experience of stresses. Static and aesthetic sensitivities in the experience of pioneering engineers of new materials in 19th and 20th centuries engineering.
- Form and the geometric and visual order of engineering. Elements of visual perception of form: light and shadow, figure and ground, texture and colour. Elements of form governing the relationship between the whole and the parts. Dimensional relationships: Proportion and scale. Geometric relationships and ordering principles: axuality, rhythm, modulation, hierarchy, patterns. Form coherence between large and small scales. The spatial quality of the engineering work.

3.3 Course practical activities

Apart from ordinary lectures giving a theoretical background to the concepts of the different programme headlines, illustrated with many examples taken from real works of engineering both historical and contemporary, the approach of the course attaches also great importance to their practical application and experimentation. A number of different types of practical activities have been designed to help the engineering student develop his aesthetic sensitivity to understand form not only through his brain, but also through his senses. The idea is to help the student open his eyes to appreciate form and visual perception, and to encourage him to work with his "thinking hands" (Pallasmaa 2009) to experience physical processes of form generation and the relationship between form and material.

3.3.1 Exercises

3.3.1.1 Design of a cardboard chair

Students are asked to design a chair to be built only with doubly layered corrugated cardboard and glue. The chair must include a back, and should support a heavy person (about 100 kg) sitting on it and leaning on its back. The purpose of the exercise is to grasp the link between form and strength. Students must find the most suitable forms to build the chair with the least amount of material and maximum strength. As cardboard is an unusual material to build a chair, there are no known forms available, and this compels students to explore the behaviour of cardboard to get maximum strength from it. They usually find that folding cardboard to produce sharp edges as in a triangular prism is an effective way to obtain strong forms. So, most designs show a tendency to adapt these prismatic forms to the well known traditional four legged chair, keeping that overall pattern, and designing cardboard legs with triangular prisms.



Figure 1. Left: typical student design for a cardboard chair. Right: real built cardboard chair.

At the end of the design exercise, a real cardboard chair, designed and built by the teacher, is displayed in front of the students and tested to prove its strength. To the astonishment of most students, the chair includes no legs, showing entirely unexpected forms, which are then explained in their different parts, in the way they are assembled, and in the way they behave as a light and efficient whole, able to withstand all required actions. Instead of typically linear legs, usually built with metal, the chair is made up of large folded surface elements, more appropriate for cardboard. The exercise is also relevant to illustrate an important point concerning the historical evolution of structures. Whenever a new material has been used to build a structure, engineers have tended to apply the known forms of the traditional materials to the mostly not yet fully experienced material. This is the case of the Iron Bridge in Coalbrookdale, whose cast iron bars were laid out following the typical radiating pattern of stone voussoir joints, and whose cast iron joints mostly resembled typical timber joints. Or the case of the Hennebique patented system for multi-storey reinforced concrete buildings, whose forms remind us of the typical timber girders, beams and pillars.

3.3.1.2 Building funicular vaults

A workshop is organized to build vault models with hanging cloths soaked in plaster, dried and inverted, to produce different funicular forms. The purpose of the exercise is to understand the principle of inversion to generate funicular forms, and the self forming processes involved in it. The experience of seeing how form is physically driven by the forces of gravity to shape a specific material is considered to be of high didactic value to develop the aesthetic sensitivity to form. The exercise starts with an introduction to the philosophy of funicular forms, illustrated with examples taken from the work of Gaudí, Frei Otto or Heinz Isler. Students working in teams are then asked to design the form of the vault they are going to build. Apart from the mentioned examples, other sources of inspiration are also suggested to help the students imagine forms for their vaults. These sources include historical barrel, groined, ribbed or domical vaults, as well as thin shells designed by pioneering engineers, like Félix Candela or Eladio Dieste.

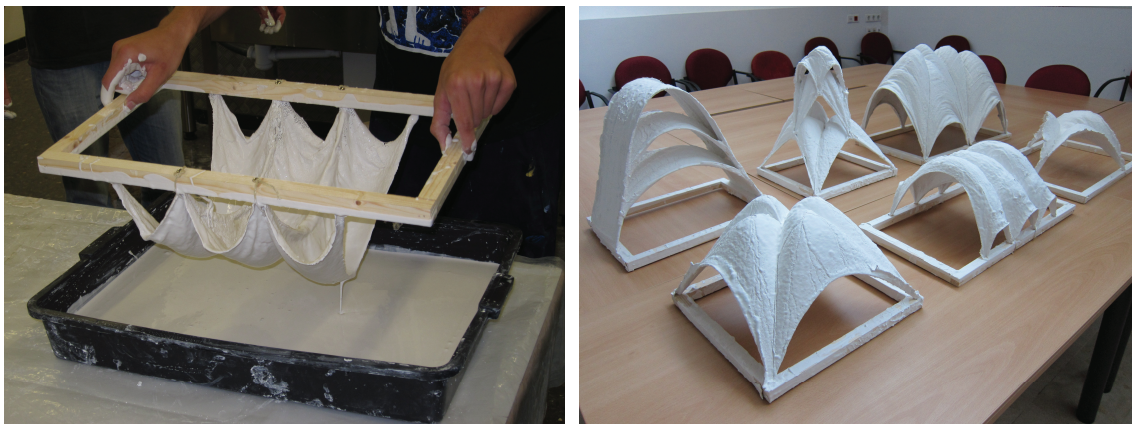


Figure 2. Funicular vaults workshop

During the building process of the models, special attention is attached to patterning in order to ensure that no wrinkles will come up, and a smooth and continuous surface will be generated, once the flat cloth pattern has been cut and hung. A critical review session is held with the finished plaster models in order to analyse the built forms and understand their geometry in relation to the loads applied. A remark is then made to highlight the difference between the geometry of the funicular vaults obtained, and the geometry of the above mentioned examples of inspiring vaults, which show a wide variety of shapes, ranging from cylindrical or spherical surfaces to hyperbolic paraboloids or doubly curved "gaussian" vaults. The opportunity is then taken to deliver a lecture on different works and engineers concerned with thin shells from the early twentieth century onwards, such as Maillart, Freyssinet, Torroja, Candela or Dieste.

3.3.2 Field trips

3.3.2.1 Bridges of the old Turia riverbed in Valencia

The old Turia riverbed runs through the city of Valencia, but stopped carrying water since three decades ago, when a new riverbed was built around Valencia, and the old one was converted into a public park. The reason to divert the Turia river outside the city of Valencia lies on a very severe flood that took place in 1957 causing much damage on people and property in many areas of the city. The present situation of the old Turia, as a dry riverbed converted into a sunken green strip of parkland about 160 m. wide, 4 m. deep and 9 km. long, running all the way from west to east through the city of Valencia, is therefore quite a remarkable urban landscape for a European town. A number of different bridges have been built over the years along the riverbed to link both banks. Four of these bridges have been selected to be visited on this field trip.

The purpose of this field trip is to analyse and compare the forms of the four selected bridges, as four different responses given at different points of time to a common environment, each one with its specific functional, constructive and structural conditions and requirements. One important point is to show real examples of built works, which can be seen, touched and walked around, whose form can be understood as a synthesis of different conditioning aspects. Students are therefore encouraged to observe the works and wonder about the different influencing factors that explain their built form.



Figure 3. Left: Puente del Real. Right: Puente 9 de Octubre

The four selected bridges include two historical stone bridges, "Puente del Real" and "Puente de San José", both enlarged in the 20th century, and two modern steel and concrete bridges, "Puente 9 de Octubre" and "Puente de la Exposición", both designed by Santiago Calatrava when the Turia riverbed had already been converted into a park. A point is raised with the two historical bridges concerning bridge enlargements, a frequent issue nowadays, as the enlargements carried out in these bridges show two completely different criteria and approaches to the historical heritage of public works. In "Puente del Real" the longitudinal section of the bridge was "extruded", and the stone vaults became two and a half times longer, drastically altering the bridge proportions, which gave it a weird appearance as a sort of "medieval motorway". In contrast, "Puente de San José" was enlarged by building additional shallower vaults on each side, taking advantage of the extra width provided by cutwaters. The criteria applied in this case involved the limits of the intervention.

The two bridges designed by Calatrava, on the other hand, have a unitary, bright and attractive space under their decks, as they break the typical pattern of separate dark tunnels between continuous piles of traditional bridges built before the riverbed was converted into a park. "Puente 9 de Octubre" shows in its scale, its horizontality and its rhythms, a form with closer links to the typical bridges of old Turia riverbed. In contrast, "Puente de la Exposición" displays a more ambitious, effect-seeking form, with a complex design integrating a tube station with natural light underneath.

3.3.2.2 Dam, roads and bridges over the Cabriel gorges in Contreras

The deep gorges of the river Cabriel in the Contreras area are an important natural obstacle on the shortest route between Madrid and Valencia. Different passage ways have followed one another over the centuries on this area, and a dam was built in one of the narrowest gorges to produce a reservoir for water supply, irrigation and hydroelectric purposes. The result is a high concentration of different types of public works belonging to different periods of history on the area: the stone bridge and winding road built in 1851, the N-III road running along the top of the dam (1974), the viaducts for the A3 motorway (1999) and the viaducts for the high-speed train (2011). The area is therefore considered of high didactic interest to analyse and compare the forms of all these works, built with different materials and structural types, in a remarkable rural setting, where nature and engineering come together to create a landscape of great value as natural, cultural and built heritage.



Figure 4. Contreras area. 19th century road and arch bridge, dam, motorway and high-speed train viaducts

3.3.3 Visits to exhibitions

Every year we try to take full advantage of possibilities offered by occasional exhibitions, which often become unique opportunities for a stimulating first-hand knowledge of outstanding works or engineers. Different important exhibitions have been visited over the years, among which three examples are mentioned: one on the work of Eladio Dieste, another one displaying working models of different structures designed by Mamoru Kawaguchi, who very kindly explained them to our students, as he happened to be in Valencia for the 50th Anniversary IASS Symposium organized by our university, as well as another one with the selected models of an experimental workshop on white concrete carried out in different Spanish schools of architecture.

3.3.4 Projects

These are the most important practical activities of the course, as they require the most active and insightful involvement of students, now being confronted with one specific built work or design task. Projects are meant to be a personal experience where the student's perceptive and creative skills are tested and developed. In accordance with these two types of skills there are two types of projects: analysis project and design project.

3.3.4.1 Analysis and aesthetic assessment of an engineering work

In this type of project students are asked to assess and analyse the aesthetic value of a specific work of engineering. They can choose it from a list of suggested works without excluding other possible personal choice, bearing in mind that the final decision must be taken with the teacher's supervision. The point is that the chosen work should preferably be a nearby and easily accessible one, which has aroused in the student an interest to gain a deeper insight into it. The project is based on the conviction that analytical and critical observation of works belonging to our close environment can be a rich source of knowledge as valid and useful as academic education, as well as a stimulating self-learning experience.

An index or item list is offered to the students as a guidance to help them raise questions to the work they are analysing, in order to discover the reasons lying behind its form. In accor-

dance with the course approach, the main aim of the project is to see form as the outcome or final synthesis of a number of influencing aspects. Students must find out which ones, to which extent and in which way. The project is intended to help them discover how the aesthetic value and wealth of meaning of the built work largely relies on the ability to integrate in its form the highest amount of these conditioning factors.

The index or item list follows the same headlines as the course programme, and specifies them for the analysis of a particular work:

- The place. Plans showing contour lines and urban fabric, and cross-sections showing landscape and built profiles. Views of the work from different approaches as a figure outlining against its environment. Way and extent to which the environment has influenced the design of the work, and the work affects its environment. Visual scales and measurements of the work and its environment.
- The use. List of uses and functions made possible by the work. Way and extent to which uses and functions have affected the form of the work. Degree of integration of different uses in the design of the work. Actual uses versus conventional functional typologies.
- The structure. Analysis of the behaviour of the structure as a whole. Overall structural form of the work and relationship with the materials used. List of structural elements which make up the structure, analysis of each element's form in connection with its material, and recognition of its function in the structure as a system. Identification and analysis of the links or joints between elements and their role to make the structure work as a unified whole.
- The visual and geometric order. Elements of visual perception of the work: light and shadow, figure and ground, texture and colour, outline and frame, and visual sequentiality. Point, linear, surface, and massive elements of the work. Proportions and scales. Axes, rhythms, modules, hierarchies, patterns. Form coherence between large and small scales of the work. Spaces generated by the work.

3.3.4.2 Design project

In this type of project students are asked to make a preliminary design of a small work of engineering, such as a water tank, a pedestrian footbridge or an electric pylon, with a number of specific conditions of site, functionality or material availability. It is intended that the type of work to be designed does not require a thorough calculation process for this preliminary stage of design, as emphasis is laid on the ability to generate a form that gives a suitable response to the maximum number of requirements. The project is meant to give engineering students an opportunity to experience a design process as an open-ended iterative search for an overall best balance of often conflicting needs. It should help students develop their perceptive abilities to detect the possibilities and suggestions offered by those aspects interacting with the engineering work and integrate them into the design process. It should encourage them to look at problems in a broad-minded way, taking nothing for granted, challenging even the initial brief.

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