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Form and structure in engineering and visual arts

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ABSTRACT: Structural and civil 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 addresses the question of the relevance of such training for engineering students, as it usually is the case for other form and design professionals, exploring the common ground between engineering and visual arts. Attention is focused on the experience of leading art and engineering schools, such as the Bauhaus and the MIT, as well as on the professional curriculum and aesthetic background of pioneering engineers, such as Maillart, Freyssinet, Torroja and Dieste.

1 INTRODUCTION

Structural and civil engineers are responsible for the design of the biggest objects man is able to build on Earth. Dams, harbours, bridges, high-rise towers, motorways, railway lines, are some examples of the type of work whose form they are responsible for. In spite of their relevance, not only because of their size but also because these artefacts belong to many people's everyday environment, engineers are not usually trained in conceptual design or analysis of form in a similar way as other form professionals, like architects, sculptors, painters or designers, usually are. This sort of training or visual education is normally considered to be irrelevant in the engineer's syllabus, as emphasis is laid on efficiency, economy, safety or strength, which are usually developed by subjects like advanced maths or physics, assuming a much more abstract and quantitative approach to reality.

Do engineering students need to develop a more qualitative approach to reality that would trigger their most creative and imaginative gifts to better tackle a design task? To which extent would visual education, design experience and some knowledge about aesthetics and form fundamentals be relevant in their training? Would courses on these subjects, usually taught in visual or fine arts education programmes, be valid also for engineers? Is there a common ground that engineers would share with other form and design professionals?

These are some questions we would like to analyse in this paper. We will first review the experience of two leading schools: the Bauhaus, one the most important art education institutions of the 20th century, and the MIT, a world-class prominent engineering school, and afterwards will relate it to the experience of some of the most innovative engineers that have pioneered new forms with new materials during the 20th century.

2 THE INTEGRATION OF FORM AND STRUCTURE IN VISUAL ARTS PROGRAMMES

2.1 *The Bauhaus experience*

The Bauhaus has generally been considered as the leading modern art school to implement new methods of teaching aimed at encouraging creativity and development of personal abilities, with much emphasis laid on practical work in workshops. One of the key courses which left and indelible memory in many of the Bauhaus students undoubtedly was the "preliminary course"

(*Vorkurs*) taught by Josef Albers. This course has been the source and starting point for many subsequent courses in basic design throughout the world. A key point, in the pedagogy of form developed in it, was the research of the relationship between form and material by experimenting with different workshop materials.

Albers applied in his course John Dewey's fundamental pedagogical principle "learning by doing". Convinced that personal experience is the most efficient teaching, he supported the idea that learning by discovering is a necessary element of teaching creativity. First of all intensive contact with specific materials was very strongly sought, in order to experience and understand its inner qualities. Albers was fascinated by the exploration of the properties of materials and their potential shapes. In order to be surer of avoiding the use of materials in their known application, because something that is known can no longer be invented, Albers preferred to work with unusual building materials, such as straw, corrugated cardboard, wire mesh, cellophane, stick-on labels, newspapers, wallpaper, rubber, match-boxes, confetti, phonograph needles and razor blades. Tools were also kept away from students at first, in order to further limit the known applicability of materials (Albers 1928).

Instead of confronting his students with an elaborate and abstract theory that very often goes beyond the horizon of their experiences, he exposed them to one of these unusual building materials and asked them to investigate what could be done with it, trying to take full advantage of its inherent characteristics. These open-ended exercises were intended to experimenting without aiming at making a finished product. Prior knowledge was not important and work without preconception through direct experience was the way, in this inductive approach, not only to encourage inventiveness and acquire some basic technological knowledge, but also to infer some general principles of form, such as harmony, rhythm, measure, proportion, symmetry, etc. (Wick 2000).

The projects were evaluated according to the proportion of "effort" to "effect". Economy was therefore much stressed. It was understood in the sense of "thrift in labor and materials and in the best possible use of these to achieve the desired effect" (Albers 1928). Albers stressed optimal use with as little waste as possible. Economy in the use of materials would lead to lightness and would be sought by testing the maximum strength to compression, tensile and bending stresses. Here we find a common target with engineers, in their search for efficient form to optimize structural response.

If we take as an example the exercises carried out with newspapers or corrugated cardboard (Figure 1) we find different form structuring processes, such as folding or curving, as a natural means to stiffen a pliable material. In this way, Albers pointed out, newspapers, usually used lying on a table and therefore having one side without any expressiveness, could now stand up, becoming both sides visually active. While lying, edges were hardly ever used, whereas in an upright position emphasis was laid on them. Folding and curving are principles of form that, curiously enough, will reappear further ahead, when analysing some of the works of the most innovative engineers pioneering new materials in the 20th century.

Figure 1. Josef Albers' preliminary course at the Bauhaus.

Two important points can be highlighted in Albers' Bauhaus course, which are common ground with these pioneering engineers. On one hand form was considered as a result of a search process; it was not a precondition to be imposed on material, but something to be discovered after a careful research and understanding of the properties and essence of each material. On the other hand the sensory experience of working with hands to build physical models and to develop a feeling for materials and strength, helped cultivate the ability to invent through construction and to discover through observation, resulting in a close integration of form and structure.

2.2 *Visual education for engineering students at the Massachusetts Institute of Technology*

We can also trace, among engineering educational institutions, some examples reflecting a clear awareness about the importance of the visual, physical and tactile dimension to develop a sense of form in engineering students. These examples are closely linked to the above mentioned Bauhaus experience and show a common ground between art and engineering education programmes.

The Massachusetts Institute of Technology, being one of the most renowned educational institutions in the world of engineering, and having acknowledged the importance of visual education for engineering students, launched a course in visual design in 1946, which was set up by 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.

A key target in this course was to train science and engineering students in "the discipline of visual invention, organization and expression, focused upon subjective-qualitative values, as a counterbalance to inductive-quantitative learning on which scientific education is based" (Preusser 1965). This involves the underlying conviction that both the scientist and the artist are motivated by seen and unseen structural orders, seeking the same principles of unity and organization, though in different ways and for different purposes. It is assumed that there is a parallel need to perceive rhythm, pattern, proportion and form in the functions both perform.

Studio work was a key feature in the methodology used in this course. Students were kept away from the traditional artist tools, such as charcoal, brush or chisel, and were encouraged to take full advantage of the possibilities offered by industrial materials, tools and techniques more akin to engineers. They were invited to observe and discover forms generated by different physical processes applied to various materials, as well as to explore variations arising from the introduction of specific organizational principles, such as grouping, contrast, similarity, pattern, rhythm and continuity, or visual elements such as shape, size, position, direction and colour. The main aim was to help them open their eyes to the aesthetic potentialities of forms coming from industrial materials and technical processes, and, in this way, to let them develop their creativity and intuition without resorting to conventional artistic means of drawing, painting or sculpture.

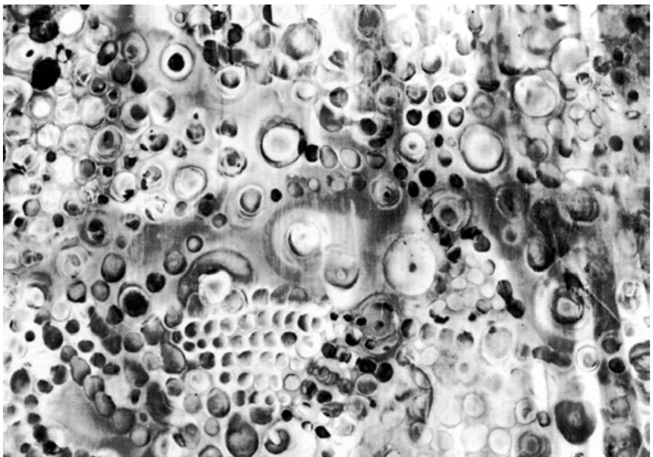

Figure 2. Visual design exercise at the MIT.

One type of exercises was intended to observe and develop chance formations in nature, or to create situations in which visual discoveries could be made, like floating colour on glass and imprinting it on paper with frictional pressure, or mounting a randomly charred and burned sheet of paper on contrasting rhythms of a plywood panel. In another type of exercises students were asked to use lines to enhance or transform surface by conventional or unconventional methods, such as string instead of pencil, or by creating an illusion of undulation with line. In a different exercise students of metallurgy observed the motif and rich colour arrangements a blowtorch flame can suggest when applied to a sheet of copper, exploring variations in colour and size by controlling temperature and distance between blowtorch flame and copper surface (Figure 2), whereas others investigated textural possibilities for enriching the surface of a sheet of tin with linear patterns of molten lead solder.

The approach of this MIT course lets the engineering student discover that "ways and means, originally developed for functional purposes and as solutions to practical problems, often have aesthetic potentialities unfamiliar to the artist, [dispelling] the notion that science is incompatible with art, and [making] evident that the developments in both affect the substance of each" (Preuser 1965).

Here again we find the experimental methodology of the Bauhaus workshops, which involves a similar conception of form as a result of a search process, as well as the sensory experience of direct contact with materials, and visual perception of form generation processes coming from physical phenomena. This emphasis on exploring the relationship between form and material will also be shared by many pioneering engineers.

3 THE ENGINEER'S SEARCH FOR STRUCTURAL FORM AND HIS AESTHETIC BACKGROUND

The contribution of some pioneers of 20th century engineering will now be surveyed, both in their professional curriculum and educational background, in order to trace the form structuring principles they used to achieve and improve strength, and the specific aspects they found in their background that helped them develop an aesthetic sensitivity and a sense of form.

The analysis of these engineers' contributions will be focused on surface structures, as this type of structures has been a major stimulus for formal, structural and constructive reflection in 20th century engineering. They are easily malleable, offer much freedom for formalization and show more clearly the relationship between form and forces, and consequently also the integration between form and structure.

3.1 *Robert Maillart*

We find in Maillart's educational background that he showed talent in mathematics and drawing, excelling in both freehand sketching and technical drawing (Billington 1997). A key figure that helped him build up his vision of form during his engineering studies at the Federal Polytechnical Institute (ETH) in Zurich was Professor Wilhelm Ritter, one of the fathers – together with Carl Culmann – of Graphic Statics, a new discipline which aimed at showing structural behaviour through geometric diagrams, rather than through algebraic formulas. This visual method of structural analysis set up a direct link between forces and forms, and was indicative of the design approach at ETH, with an engineering curriculum more visually oriented than that of its contemporary schools, and a strong emphasis on physical experience on actual structures, in contrast with the applied science approach of other schools, which relied more on general and abstract mathematical theories for understanding engineering works (Billington 1997).

Maillart's professional curriculum starting point coincides with the introduction of concrete as a new building material in Switzerland. In one of his first designs, the Stauffacher Bridge in Zurich (1899), he uses unreinforced concrete to build a single-span three-hinged segmental arch, which is basically a thick solid curved slab, on which vertical cross walls connecting the deck with the arch are resting. Concrete was then considered as artificial stone, and consequently thickness and massiveness were key features of the structural elements designed with this new material. The overall structural concept does not differ much from a masonry structure, where we find the traditional load descending scheme, from upper supported inert elements – the deck

– to lower supporting elements: the thick massive unreinforced concrete arch carrying all loads at the bottom.

Two longitudinal stone masonry walls were added on both sides of the Stauffacher Bridge in order to hide the concrete elements, still considered unworthy of an urban setting, and give the bridge a more dignified appearance. In the Zuoz Bridge, a subsequent work completed in 1901, Maillart started his design from the form the Stauffacher Bridge visually suggested, but trying to use its elements more efficiently and to make all of them structurally relevant, and so he replaced the longitudinal added-on stone façades with longitudinal reinforced concrete walls which, together with the reinforced concrete arch and deck, formed a hollow box girder. In this way, he managed to integrate form and structure closely, as all the elements simultaneously became active in the load transmission, from top to bottom, overriding the distinction between supported and supporting elements. This hollow box scheme makes possible a significant mass reduction, as all the elements of the structure, built in reinforced concrete, now become thin shells, or surface elements. Concrete is therefore no longer considered as artificial stone, and consequently any more associated with big masses. Loads are now supported by form rather than by mass.

We can detect here a similar drive as in Albers' Bauhaus course to explore the properties of unusual building materials and their potential shapes so as to achieve optimal use with minimum waste. Economy in the use of materials would again lead to lightness, emphasizing the visually expressive potential of thinness. New forms, which cannot be associated to any traditional building material, suggesting abstract, elementary and practically immaterial geometries, perceived as 20th century art forms.

Clear examples of this are the Schwandbach Bridge (1933) and the Cement Hall for the Swiss National Exhibition of 1939 in Zurich, two surface structures whose thin edges were fully exposed to view. In the continuous parabolic profile of the latter, which folds horizontally at both ends, we can easily recognize two form structuring principles we already identified in the exercises carried out with newspapers or corrugated cardboard in Albers' preliminary course at the Bauhaus (Figure 1): curving and folding.

3.2 *Eugène Freyssinet*

If we track in Freyssinet's educational background the origins of his sense of built form, we find in one of his writings (Freyssinet 1954) that he attached great importance to his experience as an artisan in his home country village. He refers to his fellow countrymen as "universal artisans" who had "built up a civilization characterized by an extreme concern for simplification of forms and economy of means". He held them as his "first and most efficient educators", who made him a "thorough artisan", and he regarded that experience as "the soundest basis of his technical training". This led him to rely strongly on first hand physical perception of reality and on sound intuition, developed and controlled by experience, to the extent of questioning the results of calculations if intuition was in contradiction with them. It is therefore not difficult to link Freyssinet's background with the experimental methodology of the Bauhaus and MIT workshops, which also involved the sensory experience of working with hands to develop a feeling for materials, physical phenomena and strength. Certainly, of paramount importance in Freyssinet's career was the knowledge of materials he gained through close on site observation of his built works.

The Orly Dirigible Hangars (Figure 3), built between 1921 and 1923, are a good example of the way he managed to integrate form and strength in his designs. The point of these hangars was to cover a space with extremely unusual requirements of clearance (50 m) and span. Two major actions had to be tackled: dead load and wind. A reinforced concrete thin shell barrel vault with parabolic cross section was adopted as the most suitable form to withstand dead load, making sure in this way that the intended reinforce concrete thin shell would work mainly in compression. But the required dimensions involved a great slenderness, and therefore buckling had to be tackled as well. A stiffening form providing maximum inertia with minimum material was therefore needed for this thin shell barrel vault in order to avoid buckling and withstand wind load.

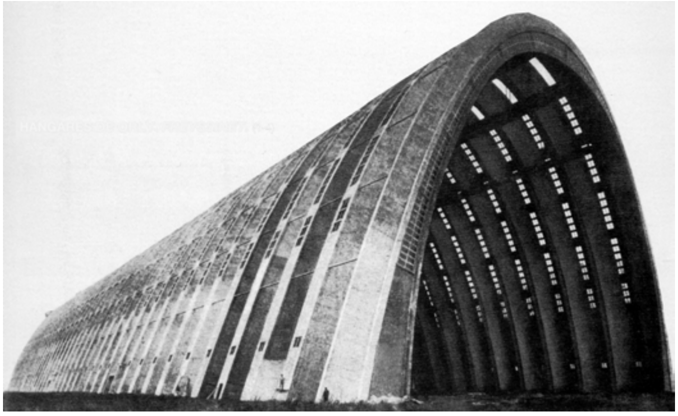

Figure 3. Orly Dirigible Hangars. Eugène Freyssinet. 1921-1923.

Folding was again the form structuring principle chosen to stiffen the reinforced concrete shell, its longitudinal section now following a polygonal undulating pattern designed to make easier the formwork withdrawal process. A form which easily reminds us again of the forms obtained with the paper and cardboard exercises in Albers' preliminary course at the Bauhaus.

We find in the Orly hangars another excellent exercise of integration between structure and form, of strength obtained through form rather than through mass. Roof, space and structure make up an integrating synthesis, showing an apparently simple solution to an extremely complex problem.

3.3 *Eduardo Torroja*

Torroja's educational background also shows aspects that helped him build up a sense of form and a visual culture. First and foremost, his father, both an architect and professor of geometry, who introduced and developed in Spain the geometry of ruled surfaces (Tarragó 1979), a type of forms we often find in Eduardo Torroja's designs. On the other hand thin brick vaulting was a vernacular building method frequently used in eastern Spain, where his father came from, and it can be considered as a precedent of shells and as a starting point to develop sensitivity for continuous, light and elegant surfaces.

One of Torroja's major works was the Fronton Recoletos (Figure 4), built in Madrid in 1935, a space covered by a thin reinforced concrete shell made up of two unequal cylindrical sectors intersecting orthogonally along a common line parallel to their axes. This asymmetrical cross section scheme was required to provide two skylights facing north: one for the playing pitch and the other for the stands.

Figure 4. Fronton Recoletos. Eduardo Torroja. 1935.

One intuitively associates this cylindrical vault comprised of two unequal lobes with a barrel vault, but this type of vault requires continuous support along its longitudinal edges, in order not to break the continuity of the descending load flow of the series of parallel arches which conceptually make up a barrel vault. Such continuous longitudinal support is missing in one of the edges of each cylindrical lobe, so the shell is actually not working as a barrel vault, but as a longitudinal beam along the generatrix lines of the cylinders, and therefore resting not on the longitudinal edges but on the two gable sidewalls (Torroja 1958).

Quite a novel approach to the relationship between form and structure: a new vision of a traditional form (the barrel vault) made possible through a new material (reinforced concrete) and a new structural form: the longitudinal beam, far from the classical linear prismatic form (usually linked to a traditional material like timber), now adopting the form of a thin singly curved shell.

Single curvature is now the form structuring principle, which, curiously enough, can also be detected in the paper and cardboard exercises of Albers' Bauhaus course. Here again form and structure are so closely integrated that roof, space and structure coincide in their form to produce through these smooth surfaces, devoid of any stiffening ribs or any transverse arches or any ties, a spatial continuity and an abstract geometry of primary forms which straightaway connects with cutting-edge forms of 20th century art.

3.4 *Eladio Dieste*

Eladio Dieste's work is particularly interesting in this analysis of the relationship between form and structure, with an outstanding contribution of visual and architectural quality, reflecting a background of sound visual education and aesthetic sensitivity, built up, among other things, by frequent contact with artists such as Joaquín Torres García or the sculptor Eduardo Yepes.

Being a Uruguayan engineer, he developed reinforced brick masonry as a new building material based on brick, a traditional material deeply rooted in the local culture, providing new possibilities for expression and making it structurally active to produce new shell forms by adding steel reinforcing bars and mortar (Dieste 1996). On the other hand, colour and texture of brick masonry lend a quality of warmth to the space that reinforced concrete shells cannot offer.

One of these new shell forms are the so called Gaussian vaults (Figure 5), whose cross sections are defined by a series of catenary arches of varying height, springing from two straight parallel lateral edges supporting the vault. Longitudinal sections are undulating lines of varying amplitude from maximum at mid-span to zero at the supporting lateral edges. The resulting geometry is a doubly curved surface, a most appropriate form to stiffen the thin shell and prevent buckling. Double curvature with both synclastic and anticlastic areas in the same surface is therefore the form structuring principle adopted by Dieste for this new material (reinforced brick masonry) to achieve not only strength, but also most suitable rainwater drainage in the lower anticlastic areas. This principle also allows the possibility to design a discontinuous roof with separate slices so as to provide skylights between them.

Figure 5. Gaussian vault. Eladio Dieste.

The Church of Jesus Christ the Worker in Atlántida, Uruguay, of 1960, is one of his best known works, where a continuous Gaussian vault without skylights is supported by brick walls following the form of sinusoidal conoids. The cross section conceptually reminds us of a series of post-and-beam portals, but in this case formed by reinforced brick shells, whose geometry (ruled surfaces and doubly curved surfaces) makes their connection rigid. Form, structure, function, material, space and visual perception make up an integrating synthesis from which the aesthetic value and architectural quality of Dieste's work arise.

4 CONCLUSION

In this itinerary we have been following to explore the common ground between engineering and visual arts, several common principles have emerged. Economy has proved to be a key one, showing a common drive to achieve maximum performance with minimum means. Form, instead of mass, as a means to obtain strength, has also been a shared ideal resulting in similar form structuring principles, such as folding, simple or double curving. Lightness, as a consequence of the previously mentioned principles, can also be regarded as a common target, often materializing in form-active or surface-active thin structures, where the relationship between forms and forces can best be traced. Form as a consequence of a search process, in which experimenting with physical models plays a key role, is another joint feature involving close observation of natural phenomena and attentive exploration of physical self-forming processes. In this respect, the sensory experience of working with hands, of touching and feeling, has proved to be of paramount importance for both artists and engineers to understand the relationship between form and strength, not only through our brains but also through our senses.

Frei Otto's work and experimental methodology would suitably summarize this common ground, with a strong personal commitment to investigate the processes of form generation in nature, technology, and architecture, searching for common principles and exploring all types of materials and physical processes. It is no coincidence that Walter Gropius, the founder of the Bauhaus, regarded Otto as an authentic successor of the philosophy and methodology that inspired the founding of Gropius' pioneering modern art school (Otto 2010). After the achievements reached with thin shells, Otto's cable net and membrane structures actually mean a step forward in that process towards lightness, involving now tension instead of compression and consequently avoiding buckling. His experiments with soap film generating minimum surfaces cannot be disconnected from the geometry of his innovative tensile structures.

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