

SPATIAL RECIPROCAL FRAMES AND TENSEGRITY PRELUDE TO FORM-FINDING

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ABSTRACT

If the dualism between form and structure, which appeared with the scientific and technological progress, has allowed to explore new frontiers in the construction field, the consequent disciplinary specializations have increased the separation of the knowledge related to the project. The architect and the engineer, who were the same figure in the past, have progressively begun to separate, increasingly distancing themselves from one another. This essay investigates the potential of building systems based on the structural conceptualization and stability, referring to reciprocal frame structures and tensegrity systems. From a didactic point of view, they can help understand the importance of the control of form and structure, starting an absolute unitarity of process.

KEYWORDS

design, process, spatial reciprocal frames, tensegrity, form-finding

The establishment, in 1671, of the Académie Royale d'Architecture – promoted by Louis XIV and inspired by Jean-Baptiste Colbert – confirms on a symbolic level the reciprocal self-determination of architecture and engineering and the formalization of two autonomous and independent scientific sectors among the transformative processes of the built environment¹. From that moment, specific contents and expertise of architects became formally established, and they are considered as the individuals appointed to the control of the compositional and formal aspects of the building. In a similar way, engineers are considered the repositories of building construction techniques. To the former, 'artistic' skills are referred, while from the latter more 'executive' skills are requested. A role separation which has been further consolidated in 1794 with the establishment of the École Polytechnique, which would definitely establish not only the conditions for an increasingly pronounced cultural and scientific contrast between architecture and engineering, but also the formalization of different ways to interpret the processes which modify reality (Deswarte and Lemoine, 1980). This duality implicated, on a process level, the creation of a contradictory, or perhaps ambiguous, project culture. This led architecture and engineering to become apparently separated entities, while they are actually bonded by a reciprocal correspondence and correlation aimed at finding, through the project, moments of discussion and blending. Occasions that in history proved to be a 'common ground', a space to explore and where a 'border epistemology' can be ex-

perimented (Morin, 1993, p. 67). A dimension where alternative ways can be promoted in order to create correspondence in the contents that an architectural project has to express; situations where a dialogic relationship between architecture and engineering can be reinforced and the mutual role of the two disciplines can be legitimated, also defending their character and function. From a phenomenological point of view, Campioli (2015, p. 67) writes: «Architecture and engineering, in a dialogic point of view, are not merely juxtaposed, but are one essential to the other. This allows maintaining duality within unity, through the association of two terms which can be considered complementary and antagonistic».

In recent history, with the occurrence of a lack of the self-referentiality that architecture and engineering can reach, the more interesting outcomes have been celebrated. Situations where it has been possible to reach, through the project phase, new expressive forms, promoting innovative actions related to the complexity of construction. If, on the one hand, the history of modern architecture is characterized by unbearable divergences between architectural and engineering knowledge², on the other it is marked by numerous occasions when the final quality is the result of the explicit contamination between these two disciplines. Moments in which architecture demands have become one with engineering reasons, reaching – if not a true symbiotic relationship – at least a construction unitarity.

The search for form and structure is attributable to high-value intellectual and scientific figures: Robert Maillart, Pier Luigi Nervi, Eduardo Torroja, Eugène Freyssinet, Félix Candela. Designers. Designers who had the undeniable merit of bringing to the attention of the project discipline the expressive potential of the static and constructive components, the new materials and innovative technologies, thus promoting the importance of pursuing, through the design and process action, the maximum interaction between formal identity and construction technique (Margolius, 2002). These hybridizations are present in some paradigmatic interventions which left their mark on the history of construction, like Jørn Utzon's Sydney Opera House in 1957, whose construction was made possible thanks to the unique role of Jack Zunz, an engineer at Arup & Partners, or the Parisian Centre Georges Pompidou in 1971, designed by Renzo Piano and Richard Rogers, where the involvement of Peter Rice, also an engineer at Arup & Partners, turned out to be decisive for the realization of the building³. Occasions on which it was possible to cross the disciplinary borders, proposing new formal narratives and figurative expressivities between technical experimentation and linguistic research. Design outbursts which produced advancements in the conception and definition of architecture and reformulated the creative and generative process intended for the morphological research together with the static analysis. In the interaction between architecture, engineering and industry, Richard Buckminster Fuller and Konrad Wachsmann led the discipline towards a prolific debate about the topics of mass production. The former did it through the experimentation related to unification and prefabrication, as can be seen in the Packaged House System's patent of 1942. The lat-

ter experimented, in the Dymaxion House of 1929 and in the Geodesic Dome of 1954, the potential of reticulated space structures, tensegrity systems and large-scale industrial production.

In the specific field of the structural expressiveness of thin-shell systems, the morphological experimentations carried out in the Kresge Auditorium by Eero Saarinen in 1955 stand out. The Auditorium was realized in Cambridge, on behalf of MIT and in collaboration with the New York-based Ammann & Whitney engineering firm. There were also the Deitingen Service Station by Heinz Isler in 1968 and, among the infrastructures, the Musmeci's Basento Bridge in 1971: works where form and structure achieve a complete constructive synthesis, according to the specificity that Giò Ponti (1955, p. 2) described with great lucidity in an article appeared on *Domus* and entitled *Engineering and Architecture*: «They belong to engineering those forms which are generated and developed [...] by the repetition of identical elements and which could [...] extend and grow, [...] in theory forever. Not having a dimension of their own – that is, a finite and closed form – they are not architecture. These forms, I thought at the beginning, belonged to the construction industry, to building; today I think it is more correct to say that they (some of them appearing beautiful to me) belong to something higher, something that can be sublime too, but that is not architecture: today I think it is more correct to say that they belong to Engineering, a demanding and beautiful discipline which distinguish itself from Architecture (art) because it (Engineering) is progressive and Architecture, art, is not. Engineering is eclectic, Architecture is not: engineering accepts, experiments and absorbs [...] the best that technique and production can offer [...], creates technical works, repeatable, multipliable and superable, one subsequent to the other, continuously getting better». On an educational level, the dimension of structural data can be promoted by experimenting some constructive systems which, through their simplicity, force a student to think about forces and weights. Tensegrities and spatial reciprocal frames, ancient but still modern systems, are the ones that, more than others, can transform into useful preparatory tools for a 'form-finding' education.

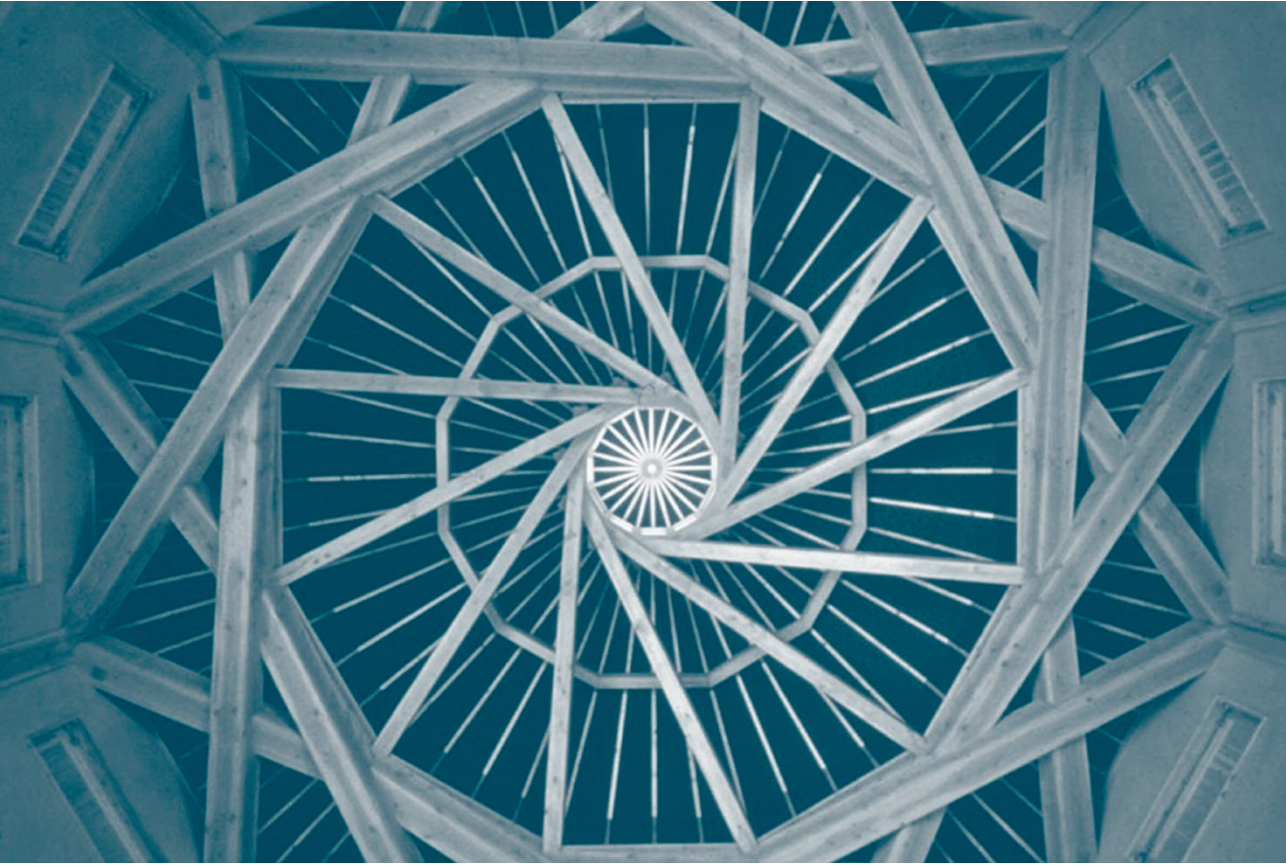
Reciprocal frames – Reciprocal frames are spatial systems composed by three or more beams that hold each other, forming a closed circuit. Their arrangement, mainly of the grid type, allows to span over long distances without using intermediate supports, and that is the reason why they are historically used for planar roofs. Their configuration allows spanning lengths greater than the dimensions of the single beams constituting the whole, thus making it possible to bypass the technological and constructive limits of the traditional systems. The use of reciprocal frame structures had already been documented by authors like Villard de Honnecourt and, later, Sebastiano Serlio (1978, or. ed. 1566) and Leonardo da Vinci himself, in the *Codex Atlanticus* (Gioppo and Redemagni, 2000). In the last years, this structural system has been studied in a more organic way by John Chilton (Chilton and Choo, 1992; Chilton, Choo and Popovic, 1995) and Olga Popovic Larsen (1996, 2008), who analyzed its geometric, constructive and structural principles.

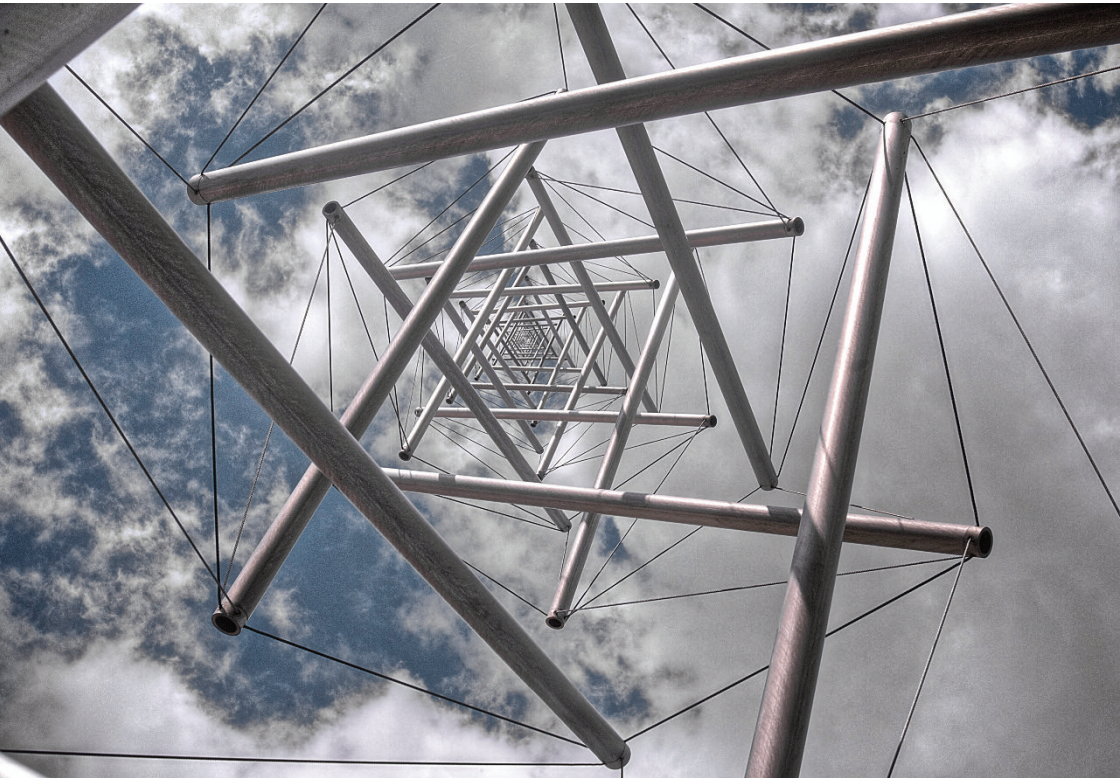
The main criticality of reciprocal frames is their structural robustness. Because of the reciprocity principle itself, in fact, there are no predefined paths for acting forces, as happens in traditional frame structures. Every element supports and is supported at the same time, in a circularity of forces and weights, as stated in other studies (Pugnale and Sassone, 2014). The lack of a hierarchy between elements and the consequent lack of structural redundancy can lead to a collapse of the system, especially when a single component suffers a structural failure. These aspects should be taken into account when reciprocal frames are going to be studied and used. In relation to this, noteworthy are the studies and the experimental tests carried out at the University of Bergamo by the research group of Attilio Pizzigoni (2008). During this research, a ‘short beam’ profile to be adopted in reciprocal frame roofs has been perfected. Starting with a modular element, several tests have been conducted to determine the breaking strength and the ultimate resources available to the entire system, in order to demonstrate the feasibility and practicability of such design solutions. In literature there are several examples of reciprocal frame roofs, like the ones used in 1952-53 by Louis Kahn for the Mill Creek Public Housing Project in Philadelphia, which was unfortunately demolished. Visually stunning is the Japanese Seiwa Bunraku Puppet Theatre (Fig. 1), designed by Kazuhiro Ishii in 1992. In this case, the reciprocal frame structure is clearly visible in the elegant roof over the exhibition hall, with structural elements having a length of about 8 meters, where the wooden beams, intersecting each other, reveal the basic principles of reciprocity. More recent works can be seen in some temporary pavilions, like Shigeru Ban and Cecil Balmond’s Forest Park Pavilion and the renowned Serpentine Gallery Pavilion by Álvaro Siza, Eduardo Souto de Moura and Cecil Balmond (Fig. 2). In this last case, the wooden elements constitute the pavilion’s envelope, which seamlessly goes from the roof to the walls.

Tensegrity structures – Tensegrity systems share several properties with reciprocal frames, like circularity and recursivity. Recent studies by Biagio Di Carlo (2008) show their analogies and similarities. This kind of structures, adopted for several years in installation art (Fig. 3), is making an increasingly frequent appearance on the international architecture scene (Dal Co, 2018). Sculptor Kenneth Snelson defined them as ‘floating compression structures’, in a way recalling their equilibrium form, which shows the lightness, both visual and structural, that so fascinates contemporary architects. Among the engineering studies, several definitions of tensegrity structures have been provided, starting with R. Buckminster Fuller, Kenneth Snelson and David G. Emmerich, who claimed its authorship. It was through Kenneth Snelson’s first tensegrity models (Fig.

Fig. 1 - Next page. Kazuhiro Ishii, The reciprocal frame structure of the exhibition hall roof in Kazuhiro Ishii’s Bunraku Theatre complex, Seiwa, Japan, 1992 (credit: The Architectural Review).

Fig. 2 - Álvaro Siza and Eduardo Souto de Moura with Cecil Balmond, Serpentine Gallery Pavilion, London, 2005 (credit: Arup Photograph 2005 S. Deleu).





4) that R. Buckminster Fuller developed the concept of tensegrity. The term derives from the contraction of the words ‘tension’ and ‘integrity’, meaning ‘tensional integrity’. The mesh of the elements in tension makes the entire system deformable, so that, if a certain pressure is applied on one or more elements, the structure experiences a deformation and then returns to its initial configuration as soon as the perturbation stops.

One of the main characteristics of tensegrities is that, before being subjected to external loads, they are already prestressed: compression elements put in tension the other elements, and vice versa. In this way, the structure assumes a geometry deriving from the continuous balance of opposite forces. There is no unique definition of a tensegrity system. As a general rule, this system can be defined as a set of discontinuous compression elements which interacts with a continuous set of tensile elements, in such a way to define a stable volume in space. Bin-Bing Wang and Yan-Yun Li (2003) speak about tensegrity systems as self-supported reticulated structures, stiffened by a state of self-stress, where a set of cables is tensioned by a discontinuous set of compression members. René Motro (2003) provided a comprehensive definition: a tensegrity system can be intended as a system which is in a stable self-equilibrated state composed of a discontinuous set of compression elements inside a continuous net of tensioned components.

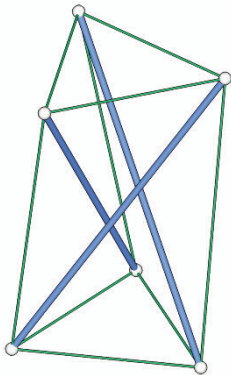
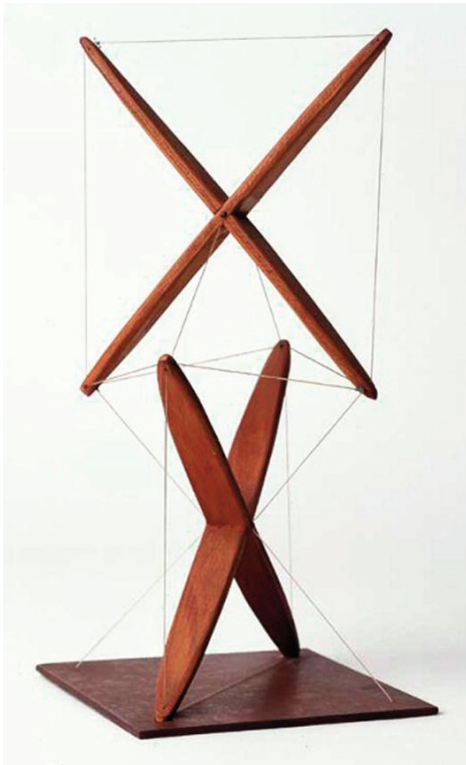


Fig. 3 - Previous page. R. Buckminster Fuller, Needle Tower (credit: C. Shonkwiler via Flickr Licence CC BY 2.0).

Fig. 4 - Kenneth Snelson, The X-piece, 1948.

Fig. 5, 6 - Tensegrity T-prism; Gerkan, Marg und Partner (Architect) and Schlaich, Bergermann & Partner (Structural Design), Tensegrity Tower, Rostock, 2003 (H.G. Esch, Hennef-Stadt Blankenberg).



Considered the great variety of achievable configurations of a tensegrity, several researchers categorized them over time, identifying sets and subsets.

Anthony Pugh (1976) was the first to propose a classification, enumerating the ways of connecting more systems in order to get more extended configurations. Among simple tensegrity units, the best known is the triangular tensegrity prism (Fig. 5), also called simplex or T-prism, generated by a right prism where cables are horizontal or vertical and bars are diagonal and connect vertices of two different levels. If a relative rotation between the upper and lower polygons is introduced, the corresponding tensegrity prism can be obtained. In order to achieve an equilibrium configuration, this rotation cannot be arbitrary, and depends on the number of bars. The very first structure realized following tensegrity concepts is The Skylon, a tower symbol of the Festival of Britain in London, built in 1951. Designed by Hidalgo Moya, Philip Powell and Felix Samuely, it presented a steel frame structure, with a shape resembling a cigar. The base of the mast was about 15 m from the ground, while the upper part was 90 m high. The main element, visible at a great distance, was supported by three cables, giving the illusion of being floating with no support, according to a characterization already proposed in Kenneth Snelson's tensegrities. The prestress applied to the cables was meant to stabilize the structure, reducing its inevitable oscillations.

In 2003 another tower-symbol was proposed: the Tower at the Fair of Rostock, in Germany (Fig. 6), designed by the architecture firm Gerkan, Marg und Partner and engineered by Schlaich Bergermann und partner. It is a structure of relevant size, composed of six simplex tensegrity modules about 8 m high, with a steel needle placed on top. Another realization is the Blur Building (Fig. 7), a temporary pavilion designed by Diller Scofidio + Renfro on the occasion of the Swiss Expo 2002 in Yverdon les Bains. The building appears impalpable, and looks like a suspended air and water cloud on the lake Neuchâtel. Inside, there is a tensegrity steel structure, designed by the Passera & Pedretti engineering firm. The building presents an elliptical plan, while the base is a bipyramidal tensegrity module (Fig. 8) obtained by reworking a study of Bin-Bing Wang (1996).

For the unity of the design process within the designer's education – What tensegrities have in common with reciprocal frames is the strong correspondence between form and structure. Their geometry is related to acting loads and the type of modules forming the structure. This forces the designer to rethink and reinvent the possible process approaches that are connected to their design. A traditional structure allows for a certain freedom to work on forms, transferring the analysis of the structural system to a second phase, according to a 'cascading' unnatural process. This implicates the separation between the figures contributing to the design of the building and the denial of the much desired 'integrated design'. The study of reciprocal frame and tensegrity systems can help, on an educational level, increase the student's awareness of the importance of the unity of form and structure within the design process. The experience promoted at the Faculty of Building Engineering of the University of Bergamo during the Architec-

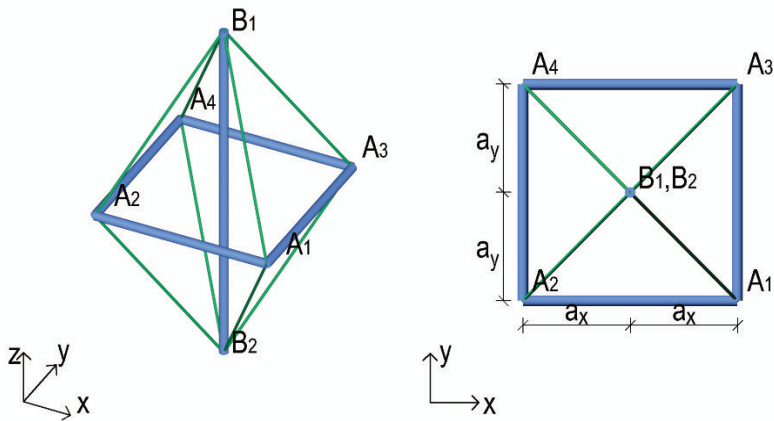


Fig. 7 - Diller Scofidio + Renfro (Architect) and Passera & Pedretti (Structural Design), Blur Building, Yverdon-les-Bains, 2002 (credit: DS+R).

Fig. 8 - Axonometric and top view of an octahedral tensegrity module.

tural Design course held by Attilio Pizzigoni is a valid proof of this method (Ruscica, Micheletti and Pizzigoni, 2010). Engineering students, always used to a mechanistic and software-dependent structural design, were asked to study in a conceptual way the

structural geometry of reciprocal frames and tensegrities, preventing them from adopting pre-established traditional structural systems. This forced the students to search for innovative structural morphologies and, at the same time, allowed them to optimize the materials used, which today is an important issue, according to the new environmental sustainability requirements.

Due to the geometrical and mechanical peculiarities, tensegrity systems cannot be studied through a traditional calculation system, but they have to be designed empirically and experimentally, with an approach that imposes a preliminary conception (it is not a simple frame). It's an approach which stimulates the students' ideational potential, making them think without any 'information technology intermediary' and without any pre-conception about the identity between form and structure, while defining the static and structural behaviour. The making of scale models of the structures conceived allows the student to observe and intuitively understand the way to reach an equilibrium configuration, highlighting the zones where the stresses are higher and where weaknesses may appear. Only when the relation between form and structure is understood, it is possible to take back that sensitivity which in the past allowed to build structural systems, even complex, where materials were adopted with real constructive and mechanical peculiarities and where intuition and experience helped achieve the magic which merges architecture and engineering.

This proves once more that, within the discipline, it is becoming increasingly important to achieve unitarity in the disciplinary knowledge of the engineer and the architect, experimenting an education that promotes the innovation of process and product, starting with an improvement of the design culture, opposing the disintegration and separation of knowledge, like Karl Popper (1958) did when speaking about the salvation of science and philosophy. During some lectures at a postgraduate course, Pier Luigi Nervi hoped for the creation of an ideal school, where it could be possible to teach 'structural architecture', which, according to his opinion, 'was a necessity, and not a trend'. He asked himself if it would be more appropriate to teach structural architecture in a school of architecture or of engineering or, even better, in an ideal school which architects and engineers could attend together, with the belief that the first who did it 'would have earned points'. This hope still presents a certain novelty.

Our times are witnessing the crisis, if not the decline, of the polytechnic culture; step by step, the disciplines, especially those related to the construction of architecture, seem to have lost their connection with reality, changing into simple guardians of a 'theoretical elsewhere'. The same theoretical elsewhere that in 1999 Edoardo Benvenuto highlighted while speaking about teaching related to the structural dimension of buildings: «our Structural Mechanics teachers are not to be blamed, because those poor guys only know a little bit of the theory of tensors, and only that; their hearth lies in this elsewhere: inside the scientific knowledge; a magnificent elsewhere coming from the theoretical spaces of mathematical analysis» (Benvenuto, 1999, pp. 609, 610). «The essence of the matter» – wrote Pier Luigi Nervi – «lies in the degree of

static and constructive competence and comprehension by designers and, in order to discover its origin, in the efficiency of the Faculties of Architecture», adding thereafter: «One of the most serious mistakes is to suppose that an architect may need a less knowledge of static-constructive matters than an engineer». In order to make the design popularization of great works and current architecture surrender to the success of an innovative culture of construction: «a comprehension of concepts so deep that these ideas (constituted by physical premises, mathematical theorems and experimental data) are merged in one synthesis and transformed in a spontaneous, almost unwitting sensitivity is necessary». Because «it is precisely the ability to feel and sense a structure as one feels a relationship between proportions or colors that constitutes the essential basis of structural design» (Nervi, 1955, p. 156).

Final considerations and possible future developments – The present notes aim to be a consideration on how the study of tensegrity systems and reciprocal frame structures can provide the preparatory bases to improve the skills and critical attitudes through which the unitarity between form and structure and the complexity of other paradigms that contemporary design culture requires can be managed within the form-finding context: lightness, essentiality, sustainability, reversibility, effectiveness, efficiency, harmony, rationality, tension, temporariness, dismantleability, etc. Solutions that, on the level of both image and the rational use of resources, make students interrogate themselves about research and the use of innovative materials, capable of achieving maximum efficiency with minimum energy consumption. Lightweight or super lightweight structures that, with their astonishing forms, promote the innovation of the formal and technological progress in construction, opening up to Non-Standard Architectures issues (Migayrou, 2003), feasible through the study of the parametric management of the project and the numerical control, according to what is identified as file-to-factory or, more recently, digital crafting.

The challenge that Architecture schools must try to win is the overcoming of a positivist matrix linear process and an instrumental use of technologies. The project embodies a very high ‘technological level’, risking to uncritically consuming itself only within the practical reasons of an articulate range of sectional solutions, without recollecting back together in a unitary or summarized prospect. The simple ‘practical approach’ – based on the pragmatic culture that ruled the processes of industrial revolution, the transformation of nature and a radical innovation of the social production relationships – is not sufficient anymore. Architecture and Engineering Schools seem to be the natural places where designers can be educated to the belief that these two disciplines have to be reciprocally essential, while preserving their identity within the unity of the design process, in order to consider the union of two academic disciplines which can be considered complementary to one another, but antagonistic at the same time.

The question is not to educate hybrid figures, as is happening in several Italian Universities (Engineering-Architecture degrees), but to create the best conditions so that

these two worlds can better talk to each other, communicating and, in the best case, mixing and complementing each other, creating a common ground where experience, skills, expertise, different languages can converge in order to generate elective affinities, because only when architecture and engineering manage to merge along disciplinary boundaries, it is possible to achieve the most interesting and innovative results. The attempts implemented in the Italian Schools do not seem to ensure any success; the academic entrenchments are still too rigorous to be able to open up to a real debate and renewal. It is not yet time for a project culture capable of assuming an attitude similar to the one already occurring in human sciences, and indicated as ‘collective intelligence’, a common, enhanced and organized intellect, capable of leading to a deployment of expertise and skills in order to provide, without any simplistic reductions, well-structured answers to complex questions.

The need to consolidate the relationship between form and structure should be redefined, because «if we adapt to a more sensitive understanding of the most subtle relations between engineering and form – if we conceive composition with engineering, rather than through engineering – if we work together rather than moving away from each other, we could achieve a relationship between form and engineering that has a broader meaning for the future architecture...» (Contini, 1958, pp. 61-63). In the contemporary architectural culture it is necessary to go back to one of the main assumptions of the project research, that is the natural aesthetic expressiveness of a good constructive solution. In the project, the beauty of the structural component is proposed as the truth of the natural laws and as a measure of space. A clear concept for Pier Luigi Nervi who, while speaking to the students of the faculty of Architecture, used to ask this challenging question: «What is beauty in architecture? It does not start with a relation between masses and voids. It starts with a fundamental truth: the structure is the truth. An architecture made of masses and voids has no meaning without a truthful structure» (Einaudi, 2010, p. 139), because, in architecture as in poetry «Beauty is truth, truth beauty, — that is all/Ye know on earth, and all ye need to know»⁴. A research which was perfectly clear to Eduardo Torroja, for whom «The best work is the one that is sustained by its own form, and not by the hidden resistance of its material. The latter is always easy, while it is the former that is difficult. In this lies the merit, the fascination of research, and the satisfaction of discovery» (Pierini, 2016, p. 47).

NOTES

1) «In the construction industry the current trend is to remain inside the first category of problems (inside disciplines) or even to fragment the construction world within the single disciplines. For each of them there is only one problem to be solved: that concerning their own discipline. So, for urban planners, for structural engineers, for architectural technologists the project is always and only an urban project, a structural project, a technological project. In this way, architecture as a discipline left behind and locked up inside its purely formal logic» (Monestiroli, 2005, p. 76).

2) In 1964 Christopher Alexander wrote «The modern designer relies more and more on his position as an ‘artist,’ on catchwords, personal idiom, and intuition – for all these relieve him of some of the burden of decision, and make his cognitive problems manageable. Driven on his own resources, unable to cope with the complicated information he is supposed to organize, he hides his incompetence in a frenzy of artistic individuality. [...] the real work has to be done by less gifted engineers, because the designers hide their gift in irresponsible pretension to genius» (Alexander, 1964, p. 10).

3) Ove Nyquist Arup, founder in 1946 of Ove N. Arup Consulting Engineers and in 1963 of Arup Associates, commented about the architect’s proficiency: «with his possible technical expertise he cannot know by himself all the implications of the modern technological advances which today are involved in the construction of a building. He is therefore unable to identify by himself the right solution and he is in the grip of the various commercial interests supporting their products. The problem is the same in our field as in other fields of human activity, where the richness of new knowledge, new materials, new processes has expanded the fields of possibilities so much that they cannot be adequately analyzed by one single mind. Together with this development of means, there are new requisites to be satisfied. Our needs grow together with the means. Standards have got higher, new services have been introduced. This situation produces the specialist or the expert, and the consequent common problem of how to create the organization, the ‘composite mind’, so to speak, that can achieve a synthesis well-balanced by the richness of the available details. This, I think, is one of the essential problems of our time». (Arup, 1942, pp. 19-26).

4) Verse taken from John Keats’ poem *Ode on a Grecian Urn*, 1819.

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