Structural design in the Warsaw school of architecture

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Abstract. The architectural design process requires the collision between art and technology. Their clash leads to an interaction which shapes the building, whose interdisciplinary content is subjected to a multifaceted assessment. Structural design is the technical discipline, which has the greatest impact on the form of the object being designed. It is concerns itself not only with the important material and technological decisions, but above all the structural idea, which greatly affects the function, artistic expression, etc. In the history of architecture many of the iconic buildings are characterized by an unconventional structure with an impressive geometry, span or material technology. Regardless of whether their author was an architect with structural intuition, or a civil engineer with a high sensitivity to beauty, and whether the building was created as a result of cooperation between industries – the "emergence" of the structural form, is invariably a creative process requiring multi-criteria evaluation, compromise and a coherent vision. There are many examples of objects that have arisen through the synergy of architecture and structure - including the J.S. Dorton Arena sports and entertainment hall in Raleigh opened in 1952, which was designed by the architect Maciej Nowicki, or the impressive search for bio-morphic reinforced concrete forms by eminent architects and engineers such as Felix Candela, Pier Luigi Nervi, Otto Frei or Eduardo Torroja. The interactions between architecture and structure are very important part of the design process that should come at the beginning. The difficulty in running a creative and co-dependent process results from the original vision of the structural form, often arising from a momentary inspiration, while thinking about the technical side is still far in the future – unless it is an intuitive reflex dictated by a proper habit and previous positive experiences. From this perspective, the process of educating young architects and preparing them to search for innovative architecture through rational technical solutions seems to be interesting. Supporting the creation of such habits and experiences has been the aim of the Warsaw school of architecture since the beginning of its existence, ie from 1915. The Interdisciplinary, practical education based on knowledge and historical achievements was the underlying idea which guided the founders and later the lecturers of the university, including Józef Dziekoński, Oskar Sosnowski, Stefan Bryła and many other eminent professors. The care for the integration of art and technology continues even today and it motivates the development of new subjects as well as the vision for education. Particularly noteworthy in the context of the interdependence of architecture and civil engineering is the subject created by prof. Adam Pawłowski – structural design, which is carried out continuously since the late 1960s. The paper deals with the selected curriculum topics and presents both the original teaching method as well as its effects on the structural design subject from the Warsaw school of architecture, pointing to the creative interdisciplinary aspect of the learning process.
1. Introduction
Architecture is the art of building; so it is not only described by the object itself - the finished work, but also by the creative process of building creation. When looking at a building, we analyze not only its form through our subjective perception of beauty – but we also pay attention to the material or the construction technique, which can be verified more objectively – through time and rational thinking.

When Le Corbusier first stood on the Greek Acropolis, he wrote that the Parthenon is an exceptional product of technology. Le Corbusier described this building as a “terrible machine" [1] - a machine that is cruel and terrifying in its transparency and unrelenting honesty. He explained that the rise of the Parthenon was based on the same sense of imagination and cool reasoning that led to the production of cars and aircrafts - combining the creative element with the available technology. In the process of creating architecture, it is important to integrate many disciplines which affect the beauty of the tectonic solutions - and the unity between art and technology is crucial. It creates the basis for architecture. This unity is especially important for the education of young architects. From its beginning in 1915 the Warsaw school of architecture has set itself the overarching objective of integrating technical and humanistic fields. In the program of the Faculty of Architecture of the Warsaw University of Technology from 1915 you can read: "The program that we draw here aims to educate architects in the highest concept - the broad artistic culture and serious professional knowledge are its guiding threads (...). This program is to be the first beacon in the works of the new university, and its further development will depend on the abilities of our successors [2].

The concept for the curriculum was created by the teachers who were professors and practitioners, civil engineers and architects; among them were S. Noakowski, C. Przybylski, O. Sosnowski, J. Dziekoński, M. Lalewicz. The character of the teaching curriculum of the Warsaw school of architecture was shaped on one hand intellectual and creative potential, and on the other hand by the socio-economic and political conditions. Because of war, the first phase of shaping and stabilizing of the curricula of the Warsaw school of architecture lasted for about six years. Professor Stanisław Noakowski, who was the dean then, described the first decade of the scientific unit’s work: “The department is primarily characterized by the intentional balance of the two factors of the academic architectural education: artistic and technical, which stems from the very essence of architecture – art and technology together” [2].

The program of the studies evolved along with the changing political situation in Poland as well as the development of new trends in architecture. However, these changes usually took place within particular departments - without affecting the structure of scientific units and the profile of the university. For example, modernism has had a significant influence on the form of conducting architectural design classes, which introduced functionalism and constructivism as an obvious element of a modern way of understanding architecture. Prof. Stanisław Hempel among others, introduced a basis for these changes which revolutionized the methodology of teaching civil engineering subjects. Most importantly, the subjects teaching management, economy, and construction were integrated which led to a reduction of the required hours and led to the creation of new disciplines, such as the “urban design section". As an experienced engineer and constructor, Stanisław Hempel, was well aware of the need for a wide educational profile of architects-engineers. S. Hempel studied at the Technische Universität in Graz (bachelor) and later at the Warsaw Polytechnic in the industrial construction department. After World War II, he worked at the Faculty of Architecture of the Warsaw University of Technology as the head of the department of wooden constructions and as a lecturer of reinforced concrete and statics. In addition, he was a professionally active civil engineer, the author of, among others: a reinforced concrete hall for the PZL in Mielec in 1937 (back then it was one of the largest in Poland), Spire in front of the People's Hall in Wrocław (in 1948 for the Wystawa Ziem Odzyskanych). S. Hempel also participated in restoration projects (reinforcement of construction) of selected tenement houses at the Warsaw’s Old Town Square (1938-39), and also cooperated in the reconstruction of the structure of the Poniatowski Bridge in Warsaw in 1945-46. Combining a professional career with
scientific and didactic work is an advantage of the professors of the Warsaw school of architecture, and professional building experience is desirable among teachers at this university to this day.

An important event in the history of the development of the technical disciplines at the Faculty of Architecture was the appointment of prof. Stefan Bryła as the head of the construction department in 1933. At the same time, the technical subjects were divided between two departments - the general construction department and the structural design department. The number of hours allocated to technical disciplines was increased, which was caused, among others, by the developments in construction and material technologies. Professor Stefan Bryła, who was a long-time teacher at the Warsaw University of Technology, who was its dean in 1938-39, is another prominent personality of the university. As a graduate of many international schools, including: Lviv Polytechnic, technical university in Charlottenburg (near Berlin), École des Ponts et Chaussees in Paris and the University of London, he became acquainted with the problems of education as well as with the new trends in teaching architecture. His professional experience gained at construction sites i.a. in Germany, France, England, Canada and the USA shaped his knowledge of civil engineering of those times. Professor S. Bryła was the author of, among others, the world's first road bridge made entirely in welded technology, over the Służewia River near Łowicz. In 1928, he developed the world’s first regulations for steel structures’ welding for construction for the Ministry of Public Works. Also the structure of the iconic 60-meter "Prudential" skyscraper built in Warsaw in 1933 (the tallest building in Warsaw in the interwar period) was designed by prof. S. Bryła. Outstanding achievements in the construction and experience in design translated into the quality of teaching and education methods of prof. Stefan Bryła, focused on gaining practical skills. At the same time, a characteristic element of education at the Faculty of Architecture of the WUT was that students had to do the semester projects in succession, with different professors. This provided the opportunity for the student to get acquainted with several approaches to design work and helped to make the decision on the choice of the specialty. In connection with the above, from the very beginning of the Faculty of Architecture, individual departments were directed by eminent specialists with strong personalities.

Difficult occupation conditions in 1939-44 forced the teaching staff to conduct underground education - meetings were held in private apartments in small groups. At the same time, the burden of mastering the material was moved onto the student's independent work, which verified the existing teaching methods. Unfortunately, many eminent teachers died during the war; among them: Oskar Sosnowski, Stefan Bryła, Rudolf Świerczyński, Aleksander Bojemski and Marian Lalewicz. As a result of the losses suffered, the young architects and practitioners, who were the pre-war pupils of the Warsaw school of architecture, took over the responsibility of educating the young architects - who could then rebuild Warsaw.

The young professors, who were simultaneously active in the work of Warsaw’s reconstruction, created a program focused on technical issues. A program which assumed the necessity of quick studies, concise transfer of practical knowledge in the necessary scope. It was only after the first half of the 20th century that the post-war teaching program underwent modifications, establishing three distinct groups of subjects: technical, humanistic and design. The emphasis was continuously placed on integrating many disciplines in teaching and creating architecture: "an important feature in the architect's work must be the ability to see, evaluate and balance all factors that condition the creation and proper functioning of architectural work. It is also necessary to be able to predict the effects of architectural and construction activities both in their economic effects and in their impact on the natural and social environment" [2]. These ideals, among other things, guided the methods of education of the Warsaw school of architecture in the subsequent years of its activity - and they seem to be still valid today. In education, it is important to provide the theoretical foundations and to teach independent and rational thinking. All these elements are needed for further creative work of an architect. Work which consists of the search for new quality, including the beautiful design of architectural forms. An additional skill
is the ability to follow new material developments, new construction technologies and new work tools - being flexible in the continuous economic and social changes, etc.

2. Professor A. Z. Pawłowski – interdisciplinary design in the creative search for structural forms

The continuation of the idea of interdisciplinary design at the Faculty of Architecture of the Warsaw University of Technology can be seen in the works of the Department of Structural Design in the 1970s. One of the prominent figures from that period is prof. Adam Zbigniew Pawłowski – a civil engineer, associated with the Department of Structural Design since 1952 as an assistant, then as an assistant professor, and from 1991 acting as the head of the unit. The professor is the author of many publications, including publications in the field of high-rise buildings. Versatile professional works include an impressive number of completed projects, including, in cooperation with Bogusław Chyliński (Kępa Potocka’s skyscrapers, 1965), Witold Benedek and Stanisław Niewiadomski (University of Gdańsk’s buildings, 1972), or Konrad Kucza-Kuczyński and Andrzej Miklaszewski (church in Siedlce). Professor A. Z. Pawłowski is also the author of the Warsaw Financial Center construction project from 1998. (design: arch. J. Skrzypczak with his team and Kohn Pedersen Fox Associates), and co-author of the modernization project of the National Museum in Warsaw, 2008 [3]. In addition to the design activities, Professor A. Z. Pawłowski is the author of over 120 expert opinions and concepts for building security in the country and abroad (France, the Netherlands, Belgium, Algeria and Libya). The expertise of high-rise buildings in Warsaw: Rondo I (designed by SOM), Złota 44 (designed by Daniel Libeskind), Cosmopolitan (designed by Helmut Jahn) deserve special mention. Prof. A. Z. Pawłowski eagerly shared his professional and scientific experience with students, constantly searching for an appropriate formula of teaching structural design to architects.

One of the revolutionary changes that prof. A. Z. Pawłowski introduced was the creation of the Structural Design subject. It developed on the idea of interdisciplinary design of a structural form – the creative search for “rational beauty”. The subject was conducted during the seventh semester, constituting a summary of teaching in the field of building structures at the Faculty of Architecture of the Warsaw University of Technology, i.e. wooden and masonry structures (3rd semester), reinforced concrete structures (4th and 5th sem.) and steel structures (6th sem.). The curriculum consisted of 48 didactic hours. The first part, the introductory seminar - took 15 hours, and the next 33 were dedicated to design classes. The introductory part consisted of lectures (under Prof. A. Z. Pawłowski’s supervision) which run parallel to the seminars. During the seminars students in groups of 5-8 prepared an analysis of selected issues: small high-tech architectural-structural forms, large span steel structures, CLT structures, cable and membrane structures etc. An important element of these analyzes was the presentation and discussion on the most outstanding designs of the last decade - interestingly, the students presented and analyzed the above objects by making hand-drawn sketches. The second part – an individual design, consisted of three parts, each ending with a closure: stage I - spatial form concept with the specification of dimensions, main systems and secondary structural elements, stage II - structural and material solutions of the major and minor structural elements, stage III - development of a minimum of three details designated by the tutors.

Piotr Trębacz, one of the lecturers, wrote about the requirements for individual student projects: "The structure should be beautiful in itself, and when viewed from the inside it should create an interior. Architecture operates with solids that have interiors, which is the fundamental difference between the architectual and sculptural vision. The student-designer must see not only the planes separating the building from the environment, but in one look should embrace the structural system and its interior” [4]. Students of architecture, trained to design bold and not necessarily economic solutions, had to face a difficult challenge - limitations such as: rational cubature, material (adequate in strength and aesthetics), assembly efficiency and construction time, standardization of elements and repeatability (Figure 1, 2). In addition, it was also necessary to take into account the standard loads resulting from
usage, wind and snow loads, or seismic movements. The difficulty of the project resulted, among others, from the fact that the technological limitations mentioned above become apparent gradually. When they are taken into account at subsequent stages of the project, they may even lead to a complete change in the concept of the structural form.

Figure 1. One of the student projects made as part of the Structural Design project a) ideation sketches; b) perspective sketch and c) freehand drawings of structural details [5]
The scope of the project was extensive, and the issues of integration of architecture and structural design constituted a major challenge for architecture students. But it is the art of combining a sensitive creator and a conscious engineer in one person, which since the beginning and still is was, the teaching goal of the Warsaw school of architecture. Pier Luigi Nervi, one of the most prominent civil engineers, the creator of buildings whose artistry and beauty was based on static logic once spoke about the art of building: "However, in order for our great architectural hopes to materialize, the new building techniques must go hand in hand with the sensitivity to architectural form, the architects must work with civil engineers, must value the true value of civil engineering science and refer to it with the same respect, that a composer refers to musical instruments. Only then will the architect become the initiator
and conductor of the great grandioso symphony played by the architecture of the future” [8]. P. L. Nervi was the author of many sports facilities and large span buildings. Objects of a similar scale became the subject of analyzes and design explorations conducted as part of Structural Design. The emerging new trends in architecture, including bionics deriving from the patterns found in nature, were a great challenge in the search for interesting structural forms. Since the end of the 1990s, and with the introduction of digital tools supporting design at the Faculty of Architecture of the Warsaw University of Technology, bionic patterns began to appear in student projects (Figure 3). Attempts were made to reproduce organic shapes in structural and construction elements, as well as to implement the logic of systems found in nature in the aesthetic expression of the structural forms.

Figure 3. Footbridge at Tamka Street [9]

3. Professor W. Rokicki - structural design in the era of generative modeling tools
Since 2010, Structural Design is being developed under the direction of prof. Wiesław Rokicki, who had learned under the supervision of prof. A. Z. Pawłowski and was his first PhD student. Professor W. Rokicki is a graduate of the Faculty of Civil Engineering of the Warsaw University of Technology, but since 1974 he has been scientifically and didactically associated with the Faculty of Architecture of the Warsaw University of Technology, where he obtained his subsequent academic degrees. He gained professional experience both in Poland and abroad, including: Finland, France, Belgium, the Netherlands, Italy, Germany, Greece and Hungary. Professor W. Rokicki is the author or the co-author of over 250 projects, concepts, opinions, judgments and technical expert opinions. He has supervised many investments, including the construction of the BRE Bank Headquarters at Plac Teatralny in Warsaw in 1995-97. An interesting and valuable skill of prof. W. Rokicki is his ability to combine civil engineer’s work with running an architectural studio. Rich professional experience, practical knowledge as well as the extensive scientific achievements of professor W. Rokicki translate into the way he teaches students of architecture - where the joint development of arts, humanities and technical fields, as well as the new digital modeling tools are the basic elements of the modern architect's workshop. Professor W. Rokicki co-founded and taught classes in Structural Design almost from their beginning - he
observed the effects of education as well as the changing teaching methods. One of the newer challenges was the digitization of the architect's work environment, in particular the parameterization of modeling tools.

The contemporary architects have to not only design the form and function, but should also understand the processes affecting the design of the structure. It is possible through the understanding of algorithms that describe and manage those processes of parameter based form generation. Modeling with the help of algorithms leads to the most efficient and simplest possible solutions. The use of generative modeling for load-bearing structures, especially small scale ones, greatly accelerates the process. This is evident in the examples of pavilions, canopies (platforms, bus stations), footbridges (up to 40m in length) or observation towers (up to 40m in height) where more and more non-standard structures and elements are used. This is why objects such as these are the subjects of analyses and student projects as part of the Structural Design project, led by prof. Wiesław Rokicki (Figure 4, 5, 6).

The subject is currently conducted on the 5th semester and generative modeling tools (Rhinoceros, Grasshopper, Karamba) are used to find the optimal structural form. The curriculum is still divided into two parts: introductory (analyses and group presentations) and design work – additionally, a series of lectures accompany the classes throughout the semester. The introduction of the analytical part, which consists of structural simulations in programs such as: RM Win, Robot Structural Analysis, Karamba, etc. is an important addition. The objects are analyzed in terms of loads, structure and form optimization (Figure 5c). The analyzes are carried out in the middle of the semester and usually are a turning point in the projects – the students verify their designs by checking the standard results, chosen cross-section sizes and material strength. The confrontation with technical and technological constraints at this stage of the project leads to significant design decisions, sometimes related to the change of the structural form. The formula for the subject – where the intuitive and creative is combined with calculations – makes it easier for students to reach independent conclusions and face the problem of structural design. The highest structural efficiency (such as: minimum material consumption, repeatability of structural elements, ease of assembly, etc.) can be obtained by means of the structural form, that is, at the creative stage of the architect's work [10]. This is one of the reasons why it is so important to teach architects how to design structures and to bring awareness of the technical consequences of decisions made at the early stage of concept creation.
Figure 4. Examples of student projects made as part of the Structural Design project; Pedestrian and bicycle footbridge at Książęca Street, a) detail; b) perspective view, c) plan and sections, d) static and strength analysis [11]; Canopy over the Warszawa Gdańska railway station’s platforms, e) perspective view, f) static and strength analysis [12]
Figure 5. Observation tower at Ratuszowa Street, a) perspective view; b) physical model, c) static and strength analysis; from the left: deformation chart, stress diagram, graph of limit state ratio for individual bars [13]
Figure 6. Examples of student projects made as part of the Structural Design project; a) Observation tower at Ratuszowa Street [14], b) Observation tower at the Wawrzyszew Fort [15], c) Observation tower at Ratuszowa Street [16]

A characteristic feature of forms shaped using generative modeling tools is their biomorphism, manifested in a structure modeled after living organisms. In search for the optimal form, resulting for example from material minimization, the important role is played by mathematical models describing bionic structures. Examples of such models include minimal surfaces, chain models, Voronoi diagrams etc. The increased use of curvilinear forms in architecture requires improved methods of surface division – effective solutions in this regard can be obtained, among others, with the Finite Element Method or Delaunay triangulation. Students use such models to optimize their designs within the Structural Design project. However, the use of numerical methods of surface discretization leads to multiple solutions, which should then be verified and usually analyzed further (Figure 4e, f). Another mathematically
rational model that is often used in student projects are tensegrity structures, which maximize tensile elements and minimize the compressed ones, which due to buckling adversely affects the material – usually steel (Figure 4a, b, c, d). Tensegrity structures are on the one hand light and are characterized by low material consumption, but at the same time are difficult to design due to certain instability which requires proper balancing. Yet another approach to structural optimization of the form can be achieved through topology optimization, based on the idea form follows force [17]. The construction material is then applied only where it is actually used – by adapting the structural system to the given boundary conditions and loads in order to maximize efficiency. An important feature of topological optimization is that the design can be freely formed within the given design space, and the exploration is carried out by an evolution algorithm.

The emergence of digital structural modeling and analysis tools has significantly influenced the way in which civil engineering is taught at the Faculty of Architecture of the University of Technology. In search of savings and logical solutions, an increasingly frequent approach to design is a multi-variant concept with in-depth analyzes in several areas – including structural (construction optimization), energy, urban planning, materials etc. All these elements impact the form – its technical efficiency and artistic expression. The parametrization of elements and the design of an iterative process of "emergence" of architecture is another possibility. Regardless of the chosen technique, achieving the intended goal requires a deliberate sequence of actions and the use of appropriate tools at the right time. Optimization of the form with parametric tools requires algorithmic thinking. When it comes to the cooperation of an architect with a civil engineer it is important to create an integrated load-bearing-spatial system. The basic problem is invariably the search for a compromise between the technical and the artistic and the implementation of new optimization tools understandable to architects. The problem of correlation between architectural form and the forces acting on it becomes the basic optimization issue. This dependency also determines the directions of improvement for the digital modeling and structural analysis methods - creating new programs that combine the possibilities of parametric modeling and structural simulations. Following the developments in new architectural trends and the development of digital design tools are currently the biggest challenges facing the contemporary Faculty of Architecture of the Warsaw University of Technology in the field of civil engineering teaching. However, it should be added that regardless of this, the greatest design value remains invariable - creative and logical thinking which lead to synergistic solutions.

4. Conclusion

Architecture, like a sculpture, emerges as a result of artistic intention - the conscious choice of tools and materials. Thus, designing architecture should start with the design of structural solutions that, in harmony with the desired artistic effect, determine the subsequent disciplines and processes which form the object. By looking at architecture in a fair way – not only through the form in space, but also through the prisms of material and construction technologies elevates the creator to a higher level of consciousness – by understating the consequences of decisions it can lead to a greater creative freedom. Such an approach to the process of teaching architecture is a characteristic feature of the Warsaw school of architecture. The ability to balance all the needs related to the emergence of architecture (both functional, sensory, or those dictated by the security of users) is a difficult task, and in the era of dynamically developing digital modeling tools and changes in building and material technologies, it creates additional difficulties. This is currently one of the key challenges in teaching architecture. Optimization of the shape of the load-bearing structure becomes an indispensable element of the architectural design process, where nature is still an important source of inspiration and imitation. In addition, the quality of contemporary architecture is increasingly characterized by atypical spatial forms that arise as a result of effective engineering solutions. In the search for a new quality of structural forms, it is therefore necessary to consciously choose technical solutions - while at the same time to design effective and beautiful tectonic solutions. In the context of structural design, regardless of the method of optimal formation of gridshells, an important role is played by the creative, but also logical design,
which results from a more insightful understanding of the principles of structural mechanics. Therefore, an important element in the education of young architects today are the broadly understood processes of building optimization, with the greatest emphasis on form-finding – as it is the basic and most important skill in the work of contemporary architects.

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