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## RATIONAL STRUCTURE – THE INTUITIVE PLAY OF FORCES

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### RACJONALNA STRUKTURA – INTUICYJNA GRA SIŁ

#### Abstract

Bridges and roofs with a string structure can be included in this group of modern buildings that spectacularly embody the supporting structure. This architecture is an example of model extraction of plastic shapes, revealing the qualities of the material and the play of forces in the exposed structure.

Currently, a more accurate knowledge of the actual work of the structure indicates that synthetic moulds are excellent in terms of structural performance. Therefore, the criterion of form authenticity, basic for wire structures, guarantees their artistic value. It can be concluded that buildings in which string structures are used are a case in which the real rationality turns out to be identical to the visual rationality.

*Keywords: bridges, roofing, string structures, architectural form, aesthetics*

#### Streszczenie

Mosty i przekrycia o konstrukcji cięgnowej można zaliczyć do tej grupy nowoczesnych budowli, które spektakularnie ucieleśniają strukturę nośną. Ta architektura wydaje się być przykładem modelowego wydobywania plastycznych kształtów, ujawniających walory tworzywa i grę sił w eksponowanej konstrukcji.

Obecnie dokładniejsza znajomość rzeczywistej pracy konstrukcji wskazuje, że formy syntetyczne są doskonałe pod względem wydajności konstrukcyjnej. Toteż kryterium prawdziwości formy, podstawowe dla konstrukcji cięgnowych, gwarantuje im wartość plastyczną. Można uznać, iż budowle, w których zastosowano konstrukcje cięgnowe, są przypadkiem, w którym racjonalność rzeczywista okazuje się tożsama z racjonalnością wizualną.

*Słowa kluczowe: mosty, przekrycia, konstrukcje cięgnowe, forma architektoniczna, estetyka*

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## 1. Expression in architecture

An emotional response can be stimulated by the expression of any form. Since Greek times, the geometrical regularity of architecture, as well as the regularity of nature, has been regarded by many aesthetes as the essence of beauty.

The architectural expression of a building or its part can be called a set of features affecting the visibility of the property of this building. We consider the expression of any parts of the building as well as its entirety. Expression is a tool of architectural composition that aims to evoke aesthetic impressions by visualizing the building's properties: purpose, physical and strength properties, the balance of forces, the way of constructing the design concept and composition<sup>1</sup>.

The basis for determining the correctness of expression is the aesthetic experience, the ability and correctness of reading aesthetic impressions and their dependence on forms. Expression of the structure is aimed at increasing the intensity of impressions received through the senses depending on used architectural forms. It uses the scale, geometrical dimensions ratio, sense of strength, balance, motion, light, shadows and colours. The expression of string structures depends on the formation of lines, surfaces, shapes and systems of forces in building elements in a manner consistent with their purpose.

The postulate of the form's conformity with the construction is closely related to the view of the artistic value of the systems of forces. According to Arthur Schopenhauer, the value of an architectural work depends on the degree of clarity with which the relationship between the force of gravity and the strength of the materials used is revealed. The forms of individual parts and their place in the whole structure are determined by the functions of counteracting the force of gravity. The shapes of the building structural components are determined by the functions that these elements perform. Knowledge of the function is necessary to understand the forms<sup>2</sup>.

Schopenhauer, postulating against the futility of solutions, meant not so much their practical uselessness as their artistic worthlessness. Because the aesthetic experience provided by architecture is the result of the perception of the laws of nature, architectural objects that do not take them into account or even falsify them are devoid of value. This also applies to individual building elements.

Also interesting are Schopenhauer's views on the question of materials used for building, which are designed not only to reveal their properties, but also to make them easily discernible. The laws that govern the structure of the building must reach the viewer. The awareness of the inauthenticity of the material can ruin the positive feelings of aesthetic contemplation.

These views have become very common nowadays. Schopenhauer's validity is confirmed both by the terminology he uses (according to which purely architectural means as much as construction), as well as statements about the role of construction in architecture<sup>3</sup>. Only such a construction in which the load and support are strongly contrasted is satisfactory in terms of aesthetics<sup>4</sup>. Buildings where string structures are used can be considered a great example

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<sup>1</sup> J. Sławińska, *Ekspresja sił w nowoczesnej architekturze (Expression of forces in modern architecture)*, Warsaw 1997.

<sup>2</sup> J. Sławińska, *op.cit.*, p. 13.

<sup>3</sup> *Ibidem.*, p. 14.

<sup>4</sup> *Ibidem.*, p. 16.

of such architecture. In them, the supports and strings are clearly opposed to the forces that load them.

It is well-known that modern architecture, in placing the postulate of “sincerity”, is more concerned with revealing the course of forces than any of its predecessors. In buildings where string structures are used, the directions of the structural system result from the action of gravity and constitute the foundation of both static considerations and calculations as well as an intuitive sense of balance.

## 2. Expression of modern structures

Aestheticians and researchers of historical architecture, regardless of the trend they represent, have in general become aware of the significance of the expression of gravity as a specific means of expression. However, in general wordings we rarely find any mention of force expression, because it was not always dominant in architecture itself. In modern art, we observe the phenomenon of transferring pressure to this issue. The development of new construction technologies is connected with the enormous possibilities of displaying the artistic values of the construction. In modern architecture, although it is not absolutely pioneering in the use of force expression in comparison with previous periods, there has been a revolutionary breakthrough in this respect<sup>5</sup>.

Modern constructions and materials at the beginning of the twentieth century enabled a significant increase in the cubature and span of objects. In contrast to small buildings, where the exhibition of the structural system cannot be a source of emotional sensations, in structures organizing large spaces, such as bridges and halls with large spans, it is automatically put in the foreground.

Mastering new construction technologies influenced the spread of previously unknown constructions, significantly expanding the richness of structural forms, to which we can undoubtedly include string structures. Their erection was not accompanied by concern for the satisfaction of artistic emotions, but these buildings often caused such reactions. This fact became the basis for a conscious desire to emphasize the artistic values related to new construction systems.

We observe that changes in construction techniques always affect aesthetic evaluations of force expression. The preference for light constructions, consistent with the requirements of construction techniques, but temporarily exposed to the disqualifying aesthetic assessments of unaccustomed recipients, contributed to the emergence of a new sense of security and stability of the building, and consequently new aesthetic assessments.

Innovation in terms of the expression of strength taught us to see the beauty of new forms before they became so common that the recipients got used to them, and their perception was not accompanied by some anxiety. It turned out that the impression of something that is incompatible with the intuitive sense of balance is an important source of positive emotions. The new approach to force expression not only disqualifies solutions that break with the traditional sense of balance and endurance, but it is in these solutions that particularly valuable and immediately revealing advantages are noticed: expressiveness, uniqueness, dynamism.

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<sup>5</sup> *Ibidem.*, p. 33.



The properties of innovative construction systems were therefore used not only because of their functional advantages, but also as an independent and rich source of artistic emotions.

To sum up, positive aesthetic evaluations relating, for example, to engineering structures arise and consolidate in the wake of the development and dissemination of this type of building. Changes in preferences and ratings are delayed compared to transformations in the construction industry itself, but gradually catch up with them.

### 3. Expression of string structures

Experiments in the field of structural design come down to the search for real solutions in correlation with the current state of the art. And because searching is an important field for satisfying people's passions, new solutions become not only a means to realize useful goals, but also represent artistic values; however, it is very difficult to determine where the boundary between the artistic and rational value of architecture lies. Due to the fact that structures are constantly changing, countering the force of gravity is carried out in an increasingly different way. The likes and dislikes are also transformed. The symbol of new aesthetics are those buildings that do not seem to burden the earth, but to float on it. Forms of hanging structures are examples of buildings not overloading the ground with their weight. Their characteristics are common: fluidity, tension, lightness. The dynamism of modern architecture, by overcoming the close connection of the building with the earth, leads to an apparent negation of gravity and evokes the illusion of floating and liquidity of the forms.

The elements of the building in which the string structures are used give the impression of staying in a state of suspension or constant tension – hence an impression of dynamism and suggestion of movement. In these structures, dematerialisation is manifested as a tendency to overcome gravity and massiveness. Tracking available only on the basis of the intuition of the course of forces, of the uniqueness of the balance of these objects, determines their particular grace and artistic value.

In modern hanging constructions, we observe the principle of optimal structural efficiency, i.e. the maximum effect with minimal expenditure of funds, which has the nature (as emphasized by its supporters) of a general aesthetic and moral quality. This aspect does not concern either financial resources or the amount of human energy consumed during construction, but refers to the sum of elastic energy accumulated in structures. The “saving” achieved in this way obviously exerts a decisive influence on the appearance of the object, making it surprisingly light and often original in its form, so that you can see aesthetic values in it.

The moderation and the saving of the means of artistic expression slowly and hesitantly gained recognition as values desired in the architecture of past eras, but they have never been as highly valued as in modern architecture. The changeability of norms in art remains in connection with changes in other human activity and principles observed there. One of the

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Ill. 1. Great Belt Est Bridge, source: photo by the author

Ill.2. Millennium Stadium, Cardiff, United Kingdom, source: <https://www.sofascore.com/news/millennium-stadium-will-host-the-champions-league-final-2017/sports-stadia-millennium-stadium-cardiff/-2018.06.11>

Ill.3. Grande Bigo, Genoa, Italy, source: photo by the author

important features of the string structures in question, which testifies to high artistic values, is their synthetic nature. These structures differ mainly in flat (e.g. hanging bridges) or spatial (cubature) works. However, all types occupy a certain part of the space in which the work takes place – and in a sense all are spatial.

The constructor's intuitive effort has an enormous role in the design of buildings that use string structures. The intuition here is the ability to predict the spatial shape of the course of force streams and to choose the appropriate structure; nevertheless, it leaves a huge field for the constructor's fantasy, so that his work acquires certain features of artistic creativity.

String structures are mainly used (apart from bridges) (Ill. 1) in single-space buildings: stadiums (Ill. 2), stations, exhibition (Ill. 3) and industrial halls. In such buildings, important things happen in human life. The characteristic buildings are perpetuated in memory, especially when they dominate the surroundings and become city landmarks and at the same time symbols of the present day. They implement a long-standing postulate of the synthesis of technology and art. Usually, at the design stage, these objects are extremely difficult for constructors, but soon become one of the most famous and most appreciated works of modernity. This tendency is commonly noticed in the case of suspended and cable-stayed bridges, which, apart from their obvious essence of road continuity, are objects with a high value of gravity.

### 3.1. Sports facilities

In sports and entertainment facilities, there can be no question of placing supports in the zone of the pitch or stage. It is also obvious that there must be no elements restricting visibility within the audience. In this case, the use of string structures for suspending the roof is a purposeful and logical solution. Such solutions, apart from the obvious compatibility with the function, also have a symbolic meaning – the lightness of the structure coincides with the field of sport or elements of the performing arts practised. String structures have a specific meaning – lightness, dynamism of the elements' system and the course of forces perfectly harmonize with sport, which adheres to expression and lightness combined with extraordinary strength. That is why string structures used to hang a roof over an object audience or over entire objects are so well received by all users. We observe here a logical sequence of applications: the construction interacts with the function and further with the ideological expression of the building. It could be said that the structure of the roofing is reflected in the penetration of beauty and utility.

Among the roofs of suspended stadiums, several contemporary implementations deserve special attention. These constructions have been shaped in a special way. Compressive forces are transmitted by poles spread out around the perimeter of the stadium, or by arcs stretched over the object, being the only rigid elements of the structure. The rest of the construction is made of string and flaccid textile or lightweight plastics. In many cases, the function of the inner ring and stiffening beam is also taken over by ropes.

Millennium Stadium, Cardiff (Wales), United Kingdom<sup>6</sup> (Ill. 2)

Authors: HOK and LOBB Partnership.

Cooperation: O'Brien Kreitzberg – project coordinator.

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<sup>6</sup> Specifications see: [www.eurostadiums.com](http://www.eurostadiums.com).

Construction: WS Atkins.

Implementation: 1999.

The location of the stadium in the Arms Park, in the centre of Cardiff by the River Taff, has many advantages. The facility offers numerous recreational and entertainment opportunities, which revive the city centre throughout the year, not only on the days of events. The location of the building allows viewers to come to public events by means of public transport or even on foot. For this reason, a network of roads and walking paths around the facility was developed and made available from the north.

The most interesting and the most difficult part of the building was the roof. The Millennium Stadium is today one of the largest sports facilities in the world, it measures 222.4 m by 181 m, with a completely closed roof. Thanks to this, it can function regardless of the season and weather. The roofing consists of a covering part of the stand, hung on four ninety-metre high masts and two movable plates with dimensions of 55 by 76 metres each. These boards are, if necessary, slid onto the playing field, creating a tight cover at a height of thirty-three metres. The assumption of such a roofing entailed the need to carry out additional acoustic tests of the stadium. These mainly concerned whether the closed roof would cause sound distortion during concerts.

Steel pylons were made in the shape similar to an inverted letter “V”. They have arms with a tubular cross-section, connected with each other by a horizontal concentration. A stiffening beam structure was suspended to each pylon. Suspension cables have a 2 x 6 cable system, three in parallel arrangement. Extraction (compression) ropes were made as 2 bundles of 6 cables in a parallel arrangement, located obliquely to the pylon. Anchoring them took place in the lower part of the pylon, in its separate pillars.

The composition of the building is determined by the contrast of the two elements of the form. Transparent pylons made of tubular profiles, placed in the corners of the stadium, have been juxtaposed with the mass of extensive roofing. The rigging system, in its abundance and variability of directions, emphasizes the dominance of supports in the entirety of the architectural assumption. The vertical and diagonal directions of the suspension elements oppose the horizontal lines of the roof and façade. From this plexus of forms emerges one general figure, which is more than just the sum of individual parts.

### **3.2. Exhibition pavilions**

The unique set of requirements set for the exhibition pavilion architecture also creates a unique set of architectural features. The opportunity to search for new solutions and to draw immediate conclusions from their accuracy and shortcomings, with a high speed of design and implementation – stimulates the development of those forms of construction that best meet the requirements of exhibition pavilions. It is not accidental that the characteristic structures in exhibition are string structures, which are characterized by the attractiveness of form, ease of prefabrication, assembly and disassembly, lightness and frequent economy.

Grande Bigo (open exhibition pavilion), Genoa, Italy<sup>7</sup> (Ill. 3)

Author: architect Renzo Piano.

Construction: architect Peter Rice, Alister Lenczer, David Kufferman.

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<sup>7</sup> Specifications, see: [www.canobbio.com](http://www.canobbio.com).

Implementation 1992.

The port of Genoa, from whence the ships of the Columbus expedition sailed, became in 1992 the place to celebrate the 500<sup>th</sup> anniversary of the discovery of America and an exhibition entitled “Columbus, ships and the sea”.

The image of an old, busy port and sailing was at the basis of the architectural concept of the exhibition.

The powerful steel structure designed by Renzo Piano resembles a port crane. The main bearing column, reaching 60 m from the sea level, is strongly inclined and connected with rope lashings with successive pillars whose tops are located at 42 m above sea level. In order to ensure the geometric invariance of the regimes, the pylons are deflected in opposite directions creating specific “counterweights” in relation to each other. The rope lashings holding the poles in the state of equilibrium were attached under the surface of the water. A beautiful construction, resembling a sculpture was created in this way.

The tent, measuring 400 x 30 m (with an area of 12,000 m<sup>2</sup>), has been suspended to two pylons, deviating from the vertical by an angle close to 45°. The roofing consists of four sheets of stretched shells reinforced with fiberglass based on three parallel arches. The diaphragms are fixed to the arches at only a few points, which resulted in openings illuminating the interior.

The adopted structural solution of the object indicates rather the subordination of the project to the predetermined artistic effects. Certainly, historical considerations have determined it – a reference to 15th-century port cranes. The object is characterized by an extremely dynamic architectural composition. The forms of individual structural elements are determined by the overriding function of counteracting the force of gravity. The shapes and location of these elements follow the static idea, which designates them a strictly defined role they are to play in the chain structure. The tamed forces, as if stopped in motion, are depicted by lines, shapes and directions of masts and strings. Their distribution in space determines the effect of the search for an architectural form.

### 3.3. Industrial halls

In industrial halls, string structures are used to suspend the roof in order to reach the space released from the supports. In this way, the freedom to shape the spatial interior is achieved. Limiting the number of supports to the necessary minimum is desirable in the case of production runs, which are subject to frequent changes.

Freedom of shaping the interior space of the object is the main goal of architects designing such buildings. Thus, in this case we observe an extremely well-established compliance of the applied construction in relation to functional needs. As is known, such compliance is one of the basic principles of creating a building with a positive visual perception. The main postulate of modern architecture is also fulfilled, so that the applied construction solution results from a consciously planned function.

In industrial buildings where string structures are used, there is often a certain independence between the load-bearing structure of the building and its external appearance, i.e. between the bearing structure and the roofing covering it. The external façade may prevent full observation of the structural layout of the object. However, this circumstance is even an additional point. The observer may be surprised by the durability of the building, prompting him to find elements of structures invisible outside.

#### 4. Artistic values

One can try to say that the beauty of architecture is an inherent result of faultless technical solutions. Today's builders, guided by the principles of rationality, usability and economy, create objects in which there are no previously known artistic values (although this was not in principle the intention of the creators).

An aesthetic evaluation factor participates in the formation of each spatial building concept. Even if the designer is the only author, his aesthetic sense is influenced by the widespread forms of art using mass media. The use of some construction systems undoubtedly promotes the appearance of self-made artistic values. Tension structures are especially favoured in this respect. Especially famous for their artistic qualities are suspended and cable-stayed bridges. These bridges are usually devoid of any decorative elements, unnecessary from the point of view of utility and construction functions. Meanwhile, these types of bridges are more popular than other projects, with a unique and elegant reputation. It is worth adding that according to Giedion, bridges cannot be the result of only technical requirements, because they must be in compliance with the artistic compositional rules in the visual arts. Undoubtedly, however, the function of the bridge imposes systems that give an image of cohesion and structural work. The considerable span of the bridge – and consequently the transfer of large forces – enhances the artistic expression.

Another interesting example of buildings distinguished by spontaneous expression of the structure are large spans, including those where string structures were used. The large span and shape are conducive to the synthetic organization of space and create positive impressions.

The rationality of maximum structural efficiency escapes direct perception. However, the uniqueness of forms and any originality of constructional solutions arouses widespread interest. Some string structures, causing amazement and anxiety, lead to special interest. The process of artistic perception of the architectural work is long-term and multistage in time. At first encounter, the delighted observer generally does not realize the source of his emotions. The mystery of the forms, however, stimulates further exploration. And here the authenticity, integrity and honesty turn out to be as necessary as the extraordinary qualities.

The choice of solution determines the general character of the building and also its aesthetic value. The analysis of aesthetic values of string structures allows us to evaluate them highly – their synthetic character corresponds to the traditional principles of consistency of composition. In them the traditional rules combine with originality – a feature particularly appreciated in contemporary value systems. Spatial order harmonizes with increased dynamics and, consequently, with clarity. The existing analogy with organic forms (spider's webs) is an element of the humanization of the engineering solution, while the expression of the course of forces in the strings is associated with modernity – fast movement, the pace of today's transformations, using the benefits of technology.

Buildings that use string structures can enjoy widespread approval. Their features, such as: mysterious lightness, hidden force, elegant shape, are perceivable in general perception. Some of them are characterized by such compositional compactness that any change could disturb this composition – these structures are approaching perfection.

Against the background of contemporary art, from Impressionism to today and against the background of social development in this period – only such architects have existed as creative personalities who, having honoured the functional and structural requirements,

achieved their own autonomous form in the spatial objects they design, thanks to which they are recognizable.

Some architectural environments look for the synthesis of great spatial constructions and sculptures. Spaniard Santiago Calatrava Valls is very well known in Europe. His critics compare his works to symphonies. Norman Foster, Richard Rogers, Nicolas Grimshaw, Renzo Piano, Wojciech Zabłocki – these are just some of the names of architects known for the use of innovative constructions positively assessed for the unique power of expression.

Buildings that use string structures, regardless of the intentions of their creators, remain invariably delightful sculptural constructions – signs of their time.

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