The role of aesthetic principles in the designing process of bridge structures

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Abstract: Designing of bridge constructions is an engineering issue. Among the many aspects of relevance, safety, production technology and economy are crucial – aesthetics, regrettably, tending to be ignored. It must not be neglected, though, that full comprehending and including all the principles of aesthetic design of bridges are necessary in the initial as well as final designing phases. These rules are useful as the guidelines for composition and combining the structure's elements into a whole while checking the overall concept.

Keywords: aesthetics, designing, bridges, structures.

1. Introduction

The notion of bridge aesthetics is connected with higher-tier feelings, as peculiar to humans since time immemorial [1]. Aesthetics-related considerations are associated with the functionality of structures; they shape the space, arousing the sense of harmony owing not only to outward appearance: they impact man's psyche and culture as well. Constructing bridges is an art, one that calls for special attention, since bridge structures become, as a rule, lasting elements within their surroundings and environment, 'accompanying' us for several dozens of years.

Bridge engineering has lately been dominated by technological development and economic drivers [2]. Bridges reflect today the society's civilisational development [3]. 'Aesthetic design' is understood very broadly at present: apart from the beauty of the object as such, the concept seeks to observe the basics of form. In terms of functionality as well as construction and materials used, a bridge ought to be matched with its surroundings, not intervening in its environment in any manner whatsoever. It moreover should be in harmony with the surrounding environment, or even enrich it, in certain cases. Quite importantly, the effect of changes appearing with time on the perception of the bridge ought to be prevented. Bridges are, normally, more astonishing structures compared to other architectural elements; they are prevalent and accessible as works of architecture also for those who are not interested in art. Bridges each have their individual character. Apart from transport and communication, they play a social role as well [4].

This essay shows the development of the notion of aesthetics in relation to bridge structures. Briefly discussed are the main assumptions of aesthetics, along with aspects of architectural construction designing, together with the factors informing their aesthetic reception.

2. Aesthetics as a notion

Aesthetics is defined as a science of beautiful objects and arts, part of its scope being considerations of aesthetic experience. European aesthetics originated in ancient Greece and has been developing till our day. This continuous development is not free of moments of severity and resistance, breaks and turns. The most violent turns followed the collapse of the Roman Empire and subsequently appeared in the Renaissance era. Apart from influencing the aesthetics, these changes affected the entire European culture. The developments in question make legitimate the identification of three periods in aesthetics: ancient, mediaeval, and modern [5].

Ancient aesthetics spans around a thousand years, and forms the foundation of European aesthetics. It was prevalently developed by the Greeks; later on, other nations have made their contributions.

The notions and concepts developed within the aesthetics founded by the Greeks were original and, to an extent, took shape before the era of philosophers; as such, they were much different from those commonly used today. 'Beauty' referred to anything that aroused recognition. The idea of beauty was pretty broad, extending not only to views and sounds but also personality traits, for instance. The Greeks considered the concept of beauty a material and intellectual good. It was them, it is generally assumed, to have created the Great Theory. Plato believed that beauty was something worth living for, and placed it on equal footing with truth and good. Thus, the three greatest values were established: truth, good, and beauty – the triad that has ever since remained part of the European thought. Beauty would be based on the matching of proportions, and on a relation of the simplest numbers. In music, the Greeks would fundamentally use the intervals of octave (1:2) and fifth (2:3); it was particularly in the human body that they found the proportions of 1:8 and 1:3; in architecture, 5:8 [6]. "Every domain of art has its own, peculiar types of relations between elements constructing a work of art. In architecture, for that matter, the relations are spatial, as opposed to temporal relations in music. In bridge design/construction, like in architecture, the beauty of a bridge is mainly founded upon the number and lengths of spans, the slenderness of supports and of the load-bearing structure" [4].

The Middle Ages have preserved the ancient theory and view of beauty. St Augustine was of opinion that beautiful things are such per se, rather than because they please somebody. According to this thinker, beauty is measure, form, and order (*modus*, *species*, *ordo*). The age of Boethius (fourth century) begot the mediaeval formula of beauty: commensurability of members (*commensuratio membrorum*). The theory of beauty was dualistic in the mediaeval age. Some claimed that proportion is the foundation of beauty; others would say that clarity and appropriate proportion is an inherent part of beauty. Everything comes from God's will, it was believed; a work of art is born in the artist's soul, his tools, and the shaping of matter.

The Renaissance resumed the ancient theories of beauty, perceived as measure, shape, and order. Leonardo da Vinci believed that beauty is not only observable by human senses but also consumed by the mind. Harmony was the most sublime expression of beauty. Many a philosopher considered the issue of beauty by making new observations and drawing new conclusions, as recapitulated and summarised by W. Tatarkiewicz [1].

The nineteenth century saw two theories of beauty emerging: in G.W.F. Hegel's approach, beauty is a revelation of an idea; B. Croce, for a change, saw beauty as an expression of the psyche. The conviction that beauty is subjective led to the formulation of a view whereby it is one's aesthetic experience, rather than beauty, that is the basic concept of aesthetics. Two currents have emerged in the views closer to our day: the aesthetics of

expression and the aesthetics of contemplation. It is expressing one's inner life through art that matters the most: as V. Kandinsky wrote, any form is an expression of spiritual content.

The twentieth century saw a departure from the classical rules of beauty and, consequently, quit the idea of masterly performance. Symmetry, balance, cohesiveness and coherence, and unity, have been replaced by asymmetry; balance has turned into unstable equilibrium. Decomposition has become prevalent; genres and types of art have become integrated, and technological development taken advantage of; aesthetics has become generalised. Avant-garde and artistic conventions triggering the sort of reception of aesthetics that is permeated with shock or provocation have become omnipresent.

3. Experiencing aesthetics

Architecture as well as construction tend to beget feelings or sentiments as part of conceptual and design activities, and in the use of a building or structure. The intensity and scope of this experience is determined by a variety of factors that influence, to a larger or smaller degree, both the designer and the user/consumer.

3.1. Experience-forming factors

Three processes, describable as 'perceptual image', 'implementation reckoning', and 'classifying opinions', can be specified as far as architectural sentiments are concerned (Fig. 1 [5]); each of them being, possibly, positive or negative.

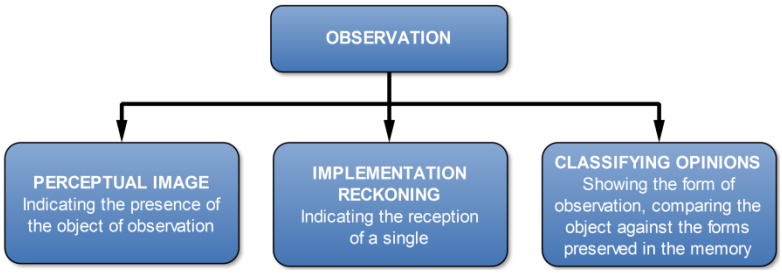

Fig. 1. Architecture perception experience, according to [5]

Observations, things spotted/perceived, imply diverse feelings that appear one after another or overlap at various time intervals, contributing altogether to an experience, whilst remaining mutually independent. Reception of a stimulus may trigger a pleasant sentiments whereas the feelings related to the 'implementation reckoning' or 'classifying opinion' may be completely neutral, or even unpleasant.

3.2. Architectural feelings

Referring to architecture-related feelings, or sentiments, their causes call for adequate attention. The potential of responding by feeling and perception may be stimulated by any of the following (and, within each, of any sort of):

The interior effect

Having entered into an interior separated from its surroundings, any human feels that such a particular space is, in a sense, part of a personality – his/her own, or someone else's. The illusion is based on the fact that the surrounding environment meets the functionality conditions and, what is more, has been chosen by the perceiving individual and subsequently adjusted to his needs, tastes or inclinations, concepts or perceptions; in particular does it

reflect, basically, the man's self-image. This effect is referred to as identification of the environment with the personality. Bridge structures are equipped with a dual interior: upon the bridge's surface and beneath it. Both interior spaces are open, in contrast to other types of construction. The space 'on' the bridge is an antidote of closed spaces; the world is seen from high above and appears completely open.

Contrasts

The contrast between a structure and its surroundings, or between a structure and its elements, sharpens one's perceptiveness, enchains attention, enlarges the scope of stimuli, thus stimulating the response capability, in terms of both sentiments and perception. New technologies, materials, structures of unheard-of scale, and extravagant solutions all trigger the contrast effect. Bridge structures arouse the reaction of contrast perception because of, for instance, the smooth-profiled lines of roads or tracks visible within them. At times, a contrast may be perceived because of an error related to the useful purpose or specific construction conditions. The fact stands out, moreover, that contrast effect tends to fade away if perceived frequently.

Expression

The belief has prevailed since the ancient Greek times that essential about the beauty in architecture is its geometric regularity, which impacts perceptiveness through use of repeated stimuli and impulses. Perceptions seem clearer and the perceiving individual feels more perceptive. Regular though banal arrangements tend, however, to arouse negative feelings – boredom coming to the fore. Hence, regularity, without additional characteristics, cannot fundamentally define the beauty of a construction: any geometrical, dynamic, and functional features of functionality render the impression more powerful.

4. Rules of aesthetic shaping

Taking into account all the principles of aesthetic design of a bridge is a must, both at the initial phase of design, when the form and general proportions of the structure are being formed (taking shape), and at the final stage, when decisions are made as to details.

No ready-to-use templates or patterns have ever been made available that would clearly describe the aesthetic shaping approach in detail. There are, instead, the general rules whose observance normally has a beneficial effect on how the designed structure is (to be) perceived. Knowledge of these rules considerably facilitates the elaboration of correct solutions. Furthermore, they serve as an instrument with which to verify the architectural regularity at each step of the design process.

4.1. Aesthetic designing: criteria and foundations

Based on a review of the existing bridge construction practice, a set of observations can be discerned – by repeated interdependencies between the elements – and certain conclusions based thereon drawn. To bring an order into architectural forms, prevent elements of negligence in the related studies, and in view of bettering the collaboration between designers, 'principles of elaboration of architectural design of bridges' have been worked out. According to [5], these include:

The **form gradation principle** stands for the need to classify by scale and visibility of elements. Gradation ought, namely, to be observed in a manner so as to prevent the attention getting distracted by certain 'parent' or 'child' elements. Architectural forms of various grades should be supplied with elements as appropriate with them, avoiding the visibility of forms and elements of other grades. To this end, the following form groups have been developed:

- bridge-and-barrier entirety effect: it is characterised by the largest scale and is based on a clarity principle: the structure appears together with the barrier, as a cohesive whole;
- the road on the bridge and approach roads: it is essential that the bridge's scale not exceed the one of the road; otherwise, the bridge becomes less expressive. A road set above the structure arouses a better impression compared to a road occulted by the structural arrangement;
- supports and spans: it is fine if both are perceptible separately, their constituent elements remaining invisible;
- the interior space underneath the structure: this frequently neglected issue is, in fact, quite of essence. The form of this space is chiefly founded on the dimensions: height, width, and length. Interiors whose height is larger than the width tend to compare favourably with others. The way the bottom sections of spans look is often left unelaborated and limited to the constructional solutions applied. One example of correct solution in this respect is the orthotropic slab (deck) in steel bridges. It is different with girder bridges, where small curvatures of the bottom-deck surface, variable thickness of beams, slabs or midriffs ought to stand out. This allows to avoid the effect of emptiness, as otherwise caused by flat surfaces. Any curvature introduce differences in light refraction;
- bridge details.

This classification ensues from the observation of forms emerging or created resulting from dependencies between the elements involved.

Error rectification in developing a form – otherwise, the 'form excellence' rule, meant to make the form free of whatever might be considered irrational.

Elaboration of forms across the bridge elements – leaving aside any of the elements of the elaborated design produces a worse solution than conscientious elaboration across the steps.

Taking advantage of means of expression: architectural forms are not reducible to geometric forms or a play of lights and shadows. Attention should also be paid to the characteristics the observer is sensitive to. It is recommendable that all the means available are made use advantage of; these include: the shapes of the structure(s); the forces and weights; lights, shadows, and colours; the shapes and the development of the barrier and the surroundings; the road-line on the bridge's surface, approach roads, and underneath the bridge. The features of evenness, shapes and forces, symmetries and eurhythmics, the proportions of individual elements and of the entire structure, the span (range), the height and width of the spans, the distribution of the spans, and the equipment of the bridge should all be taken into account in this respect. All this contributes to what is referred to as 'regularity of composition'.

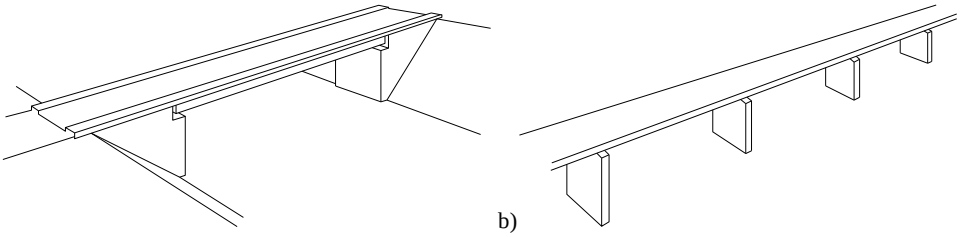

Fig. 2. 'Span bent (curved) downward', or the Zollner effect, as perceptible: (a) between the edges of the span and the bridgeheads; (b) between the edges of the span and the pillars [5]

Elaboration of such regularity includes correction or rectification of contaminated visibility. Contaminations of line consist in perceiving a shape as different than in reality. The same is true for shapes of forms or the visibility of solids, depending on the colour of their surface, background, or other elements adjacent or placed next to them. The most frequent type of visual contamination in bridge engineering is the impression that the span's bottom edge is bent downwards (as in Fig. 2 [5]).

Fig. 3 [5] shows the appropriate method of removing the span's bent edge effect: the straight lines in the external walls within the bridge's elevation are to be retained, with only the bottom surface of the spans being bent.

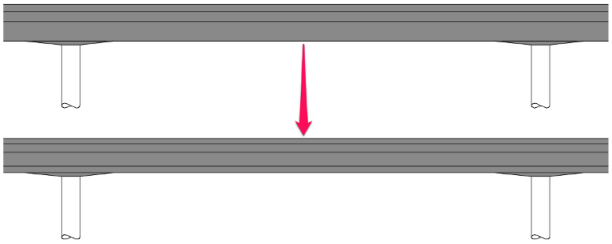

Fig. 3. Curved span edge effect rectified [5]

Convexity of the flat walls is a common illusion in visibility of the surface: the most outstanding spots in this respect are the poles and, to a lesser extent, side surfaces of beams and arches. The phenomenon can be counteracted by adding convex depressions, or by introducing an outline of adjacent constructional elements.

The density of creases sufficient for rectification of the illusion of convexity of the surface ought to be of the order of 1/10 to 1/50 of the wall's width, the wider walls always to receive shallower creases.

Primacy of communication (transport-related) forms enables to design with any intensity only the line of the road and the barriers underneath the bridge. It is an erroneous conviction that the construction of bridge is beautiful in itself. Frequently, the construction's form is overly intense and, consequently, interferes with the clarity, or 'legibility', of the whole thing. One arrives at such conclusions through juxtaposing the early and the modern solutions (Fig. 4 [7]).

Fig. 4. Earlier and modern solutions compared [7; photo: K. Śledziewski]

Formerly, bridge structures tended to be rather massive, composed of a large number of materials. Contemporary bridges are made of modern higher-resistant materials [8÷13], with use of new technologies [14÷18] enabling to make an efficient use of cross-section [19, 20].

Fig. 5. Modern bridge designs [21]

New structures display no redundant elements, which were irremovable in the early times (Fig. 5 [21]). This makes modern structures lighter and evidently less intense.

4.2. Experimental rules in bridge architecture

Experimental rules are findings whose perception influences aesthetic experience. They are formulated based on observations carried out in various conditions, by different observers, with respect to a broad scope of objects or things. Being a variety of architectural principles, the rules in question ensue from the general traits of observations and experiences. Experimental rules are uncomplicated and widespread.

Experimental rules may function as guidelines in architectural composition and facilitate the verification of conceptual solutions – these being the main two objectives of experimental rules of aesthetics. Yet, they ought not to be treated as a must-do, since the experience is the final check. The rules should be considered in a fourfold sense: object-related (objective), psychological (subjective), cognitive, and creative. The first concerns analysis of the forms of material objects; the second, reception of aesthetic experience; the third explains cognitive actions, whilst the fourth makes use of the rules cognised.

4.3. Rules based on observation and association of forms

The **entirety principle** finds that "aesthetic experience is determined by noticeability of all the elements of the form and their interdependencies" [22]. What it means is that associating a structure's geometric features with their physical and functional meaning needs being sought. The principle of entirety has many degrees to it, and extends to analysis of the structure together with its surrounding environment, the structure itself, as well as its individual elements. For this very reason, Marzyński [23] discerns the following types of aesthetics:

(a) large – town-planning and landscape-design;
(b) medium – architectural;
(c) small – finishing and details.

Large aesthetics seeks how to place a bridge, together with approach roads, and align it with the area. Analysis of large aesthetics leads one to the issues of medium aesthetics. Moving further on, and considering the factors informing the visual perception of bridges, one comes across the small aesthetics, such as selection/matching of materials, or finish, which influence neither the shape or form, nor the structure.

Seeking to observe an order of the constituent elements, which is fundamental to aesthetic reception, cohesion of architectural form must not be neglected. Equilibrium between rational elements and architectural expression needs to be kept; otherwise, wherever any constituent is missing, the overall construction is affected (Fig. 6 [24]).

Fig. 6. Bridges harmonized with the surrounding environment [24]

The **simplicity of form principle** provides that the number of individual elements of a bridge ought to be small enough, in order that a non-complicated form be preserved. This is directly interrelated with man's capability of perceiving a small number of elements whilst ensuring a simple form. Wherever the form is overcomplicated, or overly complex, one is not capable of seeing it as a whole and gets bogged down in the interrelations, with no aesthetic experience coming out as a result.

As is the case with the entirety principle, similarity of form consists of multiple grades: rather than being limited to the whole structure, including its environment, it extends to individual elements.

The simplicity principle should not be approached in terms of restricted architectural expression or avoidance of essential dependencies but rather as a postulate to respect moderation, or restraint. Bridge structures should display the road's line and the barrier's line in the first place, the other elements of the bridge route being not as outstanding (Fig. 7 [24]).

Fig. 7. An exemplary simple form of bridge structure [24]

The **clarity of form principle** postulates that "in order for the form to arouse aesthetic impression, the associations between its elements ought to be easily perceptible" [5]. The clarity criterion complements the two previously discussed principles. Aesthetic impression is achieved through expression of forms and ease with which they are associated with the cognitive importance of aesthetics. In bridge architecture, the means bringing about this effect is the use of elements other than constructional – additional or, at times, outright antithetical. Bridge structures tend to show off arrangements that are indicative of the system of internal forces, communication lines, close interdependence between the type of construction and the materials and technologies applied as well as the construction conditions.

The former half of the twentieth century saw a rejection of traditional architectural forms, and focusing, instead, on clarity of lines of communication and force arrangement.

This is not to say, though, that arrangements, or systems, of forces are 'legible' in themselves – one example being truss bridges, common to industrial areas (but not only; Fig. 8 [7]).

Fig. 8. Exemplary truss structures [7]

The forces in the rods are of diverse values and marks, which translates into non-clarity. The multiple grades within the criterion imply that the forms of individual elements ought to indicate whether the item has been bent, squeezed, etc., and how the forces are transferred to the other links. Architectural forms also have to be legible in view of the purpose of the bridge, features of the landscape, natural and economic conditions.

The **avoidance of emptiness principle**. In order for a bridge to be of interest and attract attention, it has to have certain characteristics. Without them in place, a bridge structures can prove outright repellent. Emptiness triggers feelings analogical to boredom, weakening the ability to act due to no emotional impulses present. Lack of (in-ter)dependencies between the structure's elements, incompetence in comprehension, or lack of clarity imply emptiness (Fig. 9 [24, 25]).

Fig. 9. Exemplary methods of preventing the impression of emptiness [24, 25]

As a criterion, emptiness prevention is a variety of the criteria of genuineness (denial of cognitive endeavours; emptiness dissembling the truth) and form clarity (an empty form is illegible). Any form that has nothing to say or appears incomprehensible should be rejected.

4.4. Principles ensuing from cognitive (inter)dependencies between elements of forms

The **genuineness of form principle** implies the resolute expectation that a form arouse genuine associations, in line with the object's (structure's) purpose, operation conditions, functionality and utility. 'Genuineness' is a relative notion as far as aesthetics of bridge construction is concerned, and is dependent upon cognition. Dependent on the

cognitive conditions is also the criterion's permanency, as a given form may turn out to be non-genuine under altered conditions.

The principle in question should remain superior. It extends to the conclusions drawn based on the useful purpose and the conditions of making and operation (actual use) of the structure. The relevant conclusions include as follows:

- the bridge must be aligned with its useful purpose: this works for the traffic on and underneath the bridge and the actual development of the barrier;
- the bridge must be adapted to the natural and physical conditions: this is true for hydrological and climatic conditions as well as the choice of load-bearing structure dependent on the balance of forces;
- the bridge project has to meet the economic conditions; and,
- the bridge project has to be adapted to the social conditions.

Structure shaped according to physical conditions: Civil structures normally tend to be subject to certain natural dependencies such as, primarily, geological, vegetal, climatic, and physical conditions. The latter two, in particular, inform the structure's architectural shaping, the other ones influencing the type and quality, or colour and texture, of materials selected/used. The rule whereby the structure's arrangement is made compliant with the physical conditions implies the adaptation to the system (balance) of forces and climatic conditions (Fig. 10).

Fig. 10. The structure arranged according to the physical conditions. [Photo: K. Śledziewski]

Alignment with useful purpose: If aligned with the actual useful purpose, the form of a bridge positively influences aesthetic feelings. The most outstanding elements in the entire construction, and the most important factors, include the shape of the road set along the bridge and the approach roads. The use of straight lines, arches, transition curves, grade-line inclinations, and cross-falls, the shape is adapted to the specific area features and the forecast traffic. Each of these elements is visually perceptible and, if comprehensible, fosters the aesthetic impression. When designing an object or structure in line with its useful purpose, the aforementioned relevant criteria should be borne in mind; in specific:

- the entirety principle: the road to be visible along the whole section where its shape is connected with the bridge;
- the simplicity principle: any unwelcome complication should be avoided with regards to the road. It is important that the solutions applied not be contrary to the natural topography (such as e.g. reverse inclinations/radii);
- the legibility (clarity) principle: the road to be visible all along the bridge line.

There is more to this particular rule, though: first, the road should be visible from, potentially, every single point, outside the bridge space and within it. The road's section within the bridge, including the approach roads, should make up a concavity; to enable this, very small slopes, below 1%, definitely suffice. Hard to notice at times, such inclinations do contribute to the aesthetic values through improved visibility.

The **optimum form principle** translates, in practice, to actions aimed at the possibly best way to satisfy the needs within the given conditions, this being altogether referred to as optimality. As regards bridge structures, optimality seeks to adapt their expression to communication/traffic, construction, and spatial development conditions. The favourable factors include an optimum way of setting the road up to and all the way through (along) the bridge, as well as matching the bridge's siting, span and height to the system of supports, relative to the barrier. A form of bridge structure that contradicts the development of the surrounding area adversely impacts the aesthetic experience.

5. Summary

The design process ought to endeavour to respect the order, simplicity, selection/matching of appropriate internal proportions, and harmony with the surrounding environment. With these basic principles taken into account, the outcome can be really positive, whilst neglecting them may lead to a dissonant experience. The designer is obligated to act in a conscious and responsible manner, always bearing in mind the rules of aesthetic architectural shaping of bridge structures.

Hence, when it comes to shaping a bridge, slenderness of the entire structure and the supports should be sought, as should lightness combined with (the sense of) stability. Simplicity and variety of forms reduced to a minimum ensues directly from the principle of simplicity ('less' sometimes means 'more'). Massive and heavy-looking bridge structures ought to be avoided, as a rule. It should instead be endeavoured that the object assume its original and unique form, and bear a peculiar character – something that would make it nicely remembered; a view that would render the journey more pleasant and, above all, more interesting.

Among the thousands of structures constructed or under construction these days, it verges on the impossible to give every one of them a unique or original form; thus, repeating decent designs is essentially unavoidable. Otherwise, of high importance is the skill of fine-tuning the details, displaying the elements that improve the overall look, and masking those details which do not quite add to the aesthetic outcome of the solution.

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Rola zasad estetycznych w procesie projektowania konstrukcji mostowych

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Streszczenie: Projektowanie konstrukcji mostowych jest problemem inżynierskim. Spośród wielu istotnych aspektów, decydującą rolę odgrywają bezpieczeństwo, technologia wykonania oraz ekonomia. Niestety aspekt estetyczny jest często pomijany. Należy jednak pamiętać, że zrozumienie wraz z pełnym uwzględnieniem zasad estetycznego ukształtowania mostu jest konieczne zarówno w początkowej fazie projektowania, jak i w fazie końcowej. Zasady te są przydatne, jako wytyczne komponowania i zestawienia elementów obiektu w całość przy jednoczesnym sprawdzeniu koncepcji.

Słowa kluczowe: estetyka, projektowanie, mosty, konstrukcje.