EFFICIENT STRUCTURAL FORMS AS A RESULT OF ARCHITECT AND ENGINEER COLLABORATION

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Abstract
Structure is an essential element of most architecture works, but beyond its main function to carry loads, it can also enrich and animate the architectural space. The architect, in cooperation with the engineer, may expand awareness of the architectural potential of the load-bearing system and design efficient structural forms that are based on the natural flow of forces and are simultaneously functional, unique, and aesthetic. The article shows how to design such forms and attempts to demonstrate that they can have a positive impact on the originality and beauty of an architectural object.

Keywords: collaborative design, shaping forms, efficient structures

INTRODUCTION

Two main designers of an architectural object are the architect and the engineer. The architect creates the design in accordance with the requirements of the client. His main task is to accommodate the space to the needs of usability, function, and aesthetics. The engineer tries to construct the object which the architect devised. His main duty is to guarantee that the design is safe by selecting structural materials, determining structural members, and meeting all appropriate regulations. The architect is more interested in the look and functionality of the architectural work, whereas the engineer is primarily concerned with ensuring that the structure is structurally strong, durable, and economical. Although the roles and responsibilities of both professions overlap in the area of structural design, they usually do not design the structure together at the same time. Traditionally, the architect prepares first a preliminary layout of the structure. Based on this layout, the engineer specifies the type of the structure to be used, the size and the material of its individual elements. Much better results can be achieved through the cooperation of the architect and the engineer from the beginning of the design process. For this process to be successful, both must mutually understand the main rules governing their disciplines. Hence, the architect should have a basic knowledge of the principles of structural behaviour, in order to have a greater impact on the structure at the initial stage. On the other hand, the engineer must realize and respect the functional and aesthetic meaning of the architect's work. These two professions can then cooperate fully over the structural form. The engineer can compromise if he gets acquainted early with the architect's vision, and the architect does not have to feel constrained by structural limitations. The design that is the result of such a close relationship between them not only leads to an economic and functional structure but also can enhance the aesthetic attraction of the architectural object.

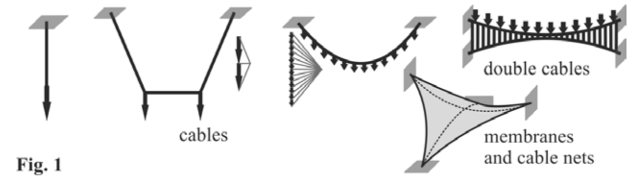
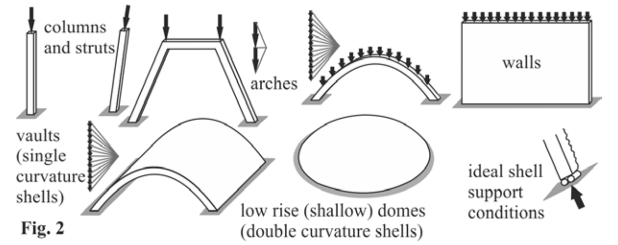
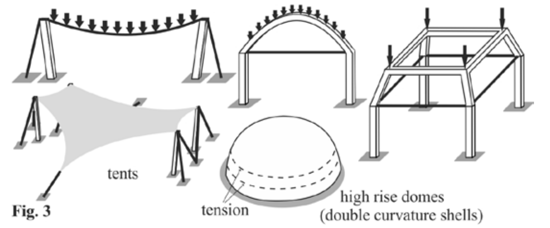
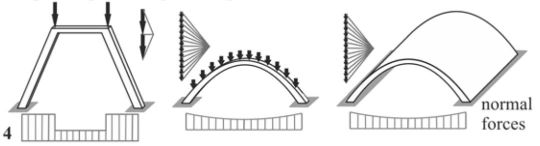
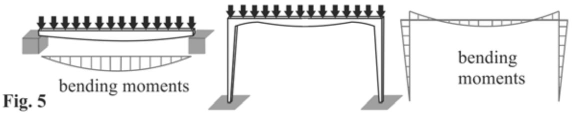
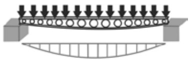
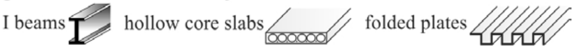
Issues of the cooperation between the architect and the engineer in order to adopt forms of architectural structures to their structural behaviour are raised by many authors. Olsen and Mac Namara engage in interdisciplinary discussions on team-building and problem-solving between architects and engineers to prepare them to work together by establishing common goals and values [C. Olsen and S. Mac Namara 2014]. Siegel encourages architects and engineers to design in harmony with structural principles and examines the influence of construction techniques on architectural design [C. Siegel 1974]. Schlaich writes that *"architects and engineers can learn a lot from each other. The architects can learn from the engineers about the interrelation of form and load-bearing behaviour, about the aesthetics of a pure, efficient structural form. The engineers can learn from the architects about the social and ecological aspects of building, about how to proceed from analytical to synthetic thinking"* [J. Schlaich 1996, as cited in E. Allen and W. Zalewski 2010, p. 614]. Macdonald believes that an appreciation of the role of structure is essential to the understanding of architecture [A.J. Macdonald 2001, p. xi]. He claims that collaboration between the designers of the architectural thing influences in a positive way on the design, and the engineer should be a member of the team of designers which evolves the form of the building [A.J. Macdonald 2001, p. 114]. Ching, Onouye, and Zuberbuhler write that architectural structures should unite with form and space in a coherent manner [F.D.K. Ching et al. 2014, p. 14]. They think that to understand the impact of structural systems on an architectural design, one has to be aware of "how they relate to the conceptual, experiential, and contextual ordering of architecture" [F.D.K. Ching et al. 2014, p. 15]. Charleson writes that "architects and structural engineers have to work closely in developing designs from early concepts to the final design and construction" [I. Margolius 2002, p. 17]. "They should be equal parents to their child" [B. Addis 1994, as cited in I. Margolius 2002, p. 17].

1. HOW TO MAKE AN ARCHITECTURAL STRUCTURE MORE EFFICIENT?

The main objective of a structure is to transfer loads with maximum efficiency. Issues related to the efficiency of structural forms are too extensive to elaborate them fully in the paper, so they are discussed only in general. A decisive role in the cost of a structure plays the material cost, so the amount of material can be taken as a measure of structural efficiency. The weight of material which must be guaranteed to give elements appropriate strength and rigidity is dependent primarily on the distribution of normal stresses caused by acting loads. Therefore, the optimal shaping of structures consists mainly in adapting the structural forms to normal stresses, regardless of the scale of the structure and the type of material. The structural efficiency estimated in terms of material use depends primarily on the topology and overall geometry of the structure in relation to the arrangement of applied loads and also on the geometry of longitudinal profiles and cross-sections of structural elements (see Table 1). The relationship between structural forms and their efficiency is discussed in many books [A.J. Macdonald 2001, p. 37-46], [E. Allen and W. Zalewski 2010], [M. Salvadori and R. Heller 1975], [M. Salvadori 1980].

The adjustment of the structure to the natural flow of forces gives the biggest economic benefits in the case of obtaining the greatest possible number of only tensile or compressive elements for a dominant loading case, usually self-weight (the first method in Table 1). The distribution of normal stresses acting over any cross-section of such elements is uniform. The stresses with a constant intensity can be carried more efficiently than non-uniform stresses because an equal distribution allows full use of all the material in the element. Flexible structures – cables, chains, double cables, cable nets, membranes – develop tension stresses only and deform in a way dependent on the magnitudes and locations of applied loads, taking shapes of funicular polygons (Fig. 1 in Table 1). Examples of tensile structural elements are shown in Fig. 10. Compressive structures – arches, vaults, domes – must be rigid, and their geometry must be adjusted to the pattern of applied loads based on the rule of the inverted chains (Fig. 2 in Table 1). Their longitudinal axes should be the mirror images of the funicular shapes adopted by cables. Moreover, their ends must be adequately supported. Their supports must be capable of providing force reactions to the compressive normal forces transmitted to them. Regrettably, if the shapes of the compressive structures with single curvature are not the true funicular forms for the loads, or if the loads change, then the bending non-uniform stresses occur in the structures, and there is a risk of their strength failure. However, double curvature shells are considerably more complex and can carry a wide range of different loadings through membrane action without introducing bending [S. Adriaenssens et al. 2014, p. 9]. Nevertheless, all compressive structures must be given a certain strength to resist bending stresses. Furthermore, tensile structures can be only destroyed by rupture, while compressive structures have two failure modes: crushing and buckling. Hence, compressive structures should be made thicker than tensile ones and are structurally less efficient. Examples of structural elements acting mainly in compression are given in Fig. 11. Many structures are composed of both tension and compression elements (Fig. 3 in Table 1 and Fig. 12). Such structures carry loads combining the compressive strength of rigid elements (arches, columns, struts) with the adaptability of flexible ones (cables,

Tab. 1. Shaping structural forms to enhance their efficiency

Method of shaping	Purpose of shaping	Structural behaviour of elements	Structures assembled of different elements (line and surface, flexible and rigid)
1) adjusting structure to load (funicular shapes) and proper supporting	uniform distribution of normal stresses in cross-sections	tensile elements	 **Fig. 1**
		compressive elements	 **Fig. 2**
		tensile and compressive elements	 **Fig. 3**
2) improving longitudinal profile	constant normal stresses in longitudinal profile	tensile elements	rarely applied
		compressive elements	adjusting the depth of longitudinal profile to normal forces  **Fig. 4**
	constant maximum normal stresses in longitudinal profile; most of the material in high normal stress regions of longitudinal profile	bending elements	adjusting the depth of longitudinal profile to bending moments  **Fig. 5**
			removing under-stressed material from the interior of longitudinal profile  **Fig. 6**
			both methods  **Fig. 7**
3) improving cross-section	most of the material in high normal stress regions of cross-section	tensile elements	not needed
		compressive elements	due to normal forces not needed
			due to buckling: moving material away from the centre of compression (line elements ) and the line of compression (surface elements ) **Fig. 8**
		bending elements	removing under-stressed material adjacent to the neutral axis of cross-section **Fig. 9** 

membranes). A lot of architectural objects with main structural elements only in tension or compression are demonstrated in Adriaenssens et al. [S. Adriaenssens et al. 2014], Charleson [A.W. Charleson 2015], Eekhout [M. Eekhout 1989].

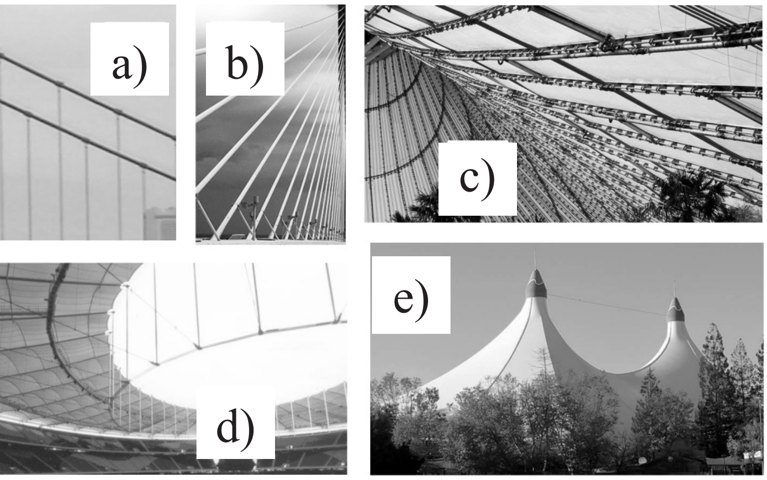


Fig. 10. Tensile elements in structures: a) main cable and hangers of the suspension Golden Gate Bridge in San Francisco (USA), photo by R. Chojnacka; b) cables of the cable-stayed Sunshine Skyway Bridge, spanning Tampa Bay (Florida, USA) (source: http://annrobiefashion.com/im-back-or-my-florida-vacation/); c) cables of roof of Khan Shatyr Entertainment Centre in Astana (Kazakhstan) (source: http://binscorner.com/pages/t/the-biggest-tent-in-the-world-amazing-st.html); d) double cable roof of Bukit Jalil National Stadium in Kuala Lumpur (Malaysia) (source: http://www.archiexpo.com/prod/hightex/product-58335-1641302.html); e) membranes of Shoreline Amphitheatre in Mountain View (California, USA), photo by R. Chojnacka; fig. by the author.

The efficiency of structural forms can be enhanced by a proper distribution of the material in the longitudinal profile (the second method in Table 1). Compression-only or tension-only structures can have varying cross-section areas adjusted to their normal forces so that normal stresses remain constant along the longitudinal profiles (side views) of elements. However, the tensile structures with varying cross-sections are very rarely used. Examples of compressive structures whose cross-sectional areas change according to normal forces are given in Fig. 4 (Table 1) and Fig. 13. If the depth of the longitudinal profiles of bending elements is varied according to the intensity of bending moments then maximum normal stresses along the element lengths can remain constant (Fig. 5 in Table 1 and Fig. 14). The author used this method of improving structural forms in the articles about furniture design [A. Kozikowska, 2010a p. 45-55], [A. Kozikowska 2010b, p. 56-65], [A. Kozikowska 2013a, p. 69-78], [A. Kozikowska 2013b, p. 18-29], [A. Kozikowska 2015a, p. 5-19], [A. Kozikowska, 2015b p. 20-34], [A. Kozikowska 2017, p. 24-35]. The efficiency of bending structures can also be corrected in such a way that material is removed from under-stressed centres of the elements leading to castellated structures and trusses (Fig. 6 in Table 1 and Fig. 15). Both methods of improving the longitudinal profile can be applied together for bending elements leading to trusses and castellated structures with changing depth of longitudinal profiles (Fig. 7 in Table 1 and Fig. 16).

A frequently used practice to increase the efficiency of structural elements is to change shapes of their cross-sections (the third method in Table 1). Cross-section shapes of tensile and compressive elements do not need to be corrected due to normal stresses because all the material is fully utilized in their cross-sections. However, cross-sections of compressive elements can be improved due to the possibility of buckling (Fig. 8 in Table 1). Bending elements have a linearly-varying normal stress distribution in cross-sections, and only their outer fibres can be fully stressed. Therefore, the under-stressed material can be moved away from the neutral axis. In this way, I-section bars, hollow core slabs, and folded plates are created (Fig. 9 in Table 1).

The greatest structural efficiency is achieved in funicular structures which resist loads mainly through uniform normal stresses and whose longitudinal profiles are adopted to normal force diagrams. However, the compression-only or tension-only structures require high quality design, analysis,` and manufacturing. Hence, they especially demand a solid understanding of structural mechanics and a close collaboration between the architect and the engineer. Bending structures are simpler to analyse and design than funicular structures, but they are less effective in the transmission of loads. The adjustment of their longitudinal profile shapes to bending moment diagrams is dependent on the type of the structure, shapes of their elements, and acting loads. Therefore, optimal longitudinal profiles of bending elements should be designed for each project separately through the cooperation between the engineer and the architect. The improvement of cross-section shapes is easier, depends mainly on the type of structural behaviour (bending or compression) and does not require such a large commitment of designers. If both normal stresses – flexural (bending) and axial (compression or tension) – occur in a cross-section, resulting stresses are the algebraic sum of both contributions. However, in such cases, bending usually has a decisive influence on structural forms.

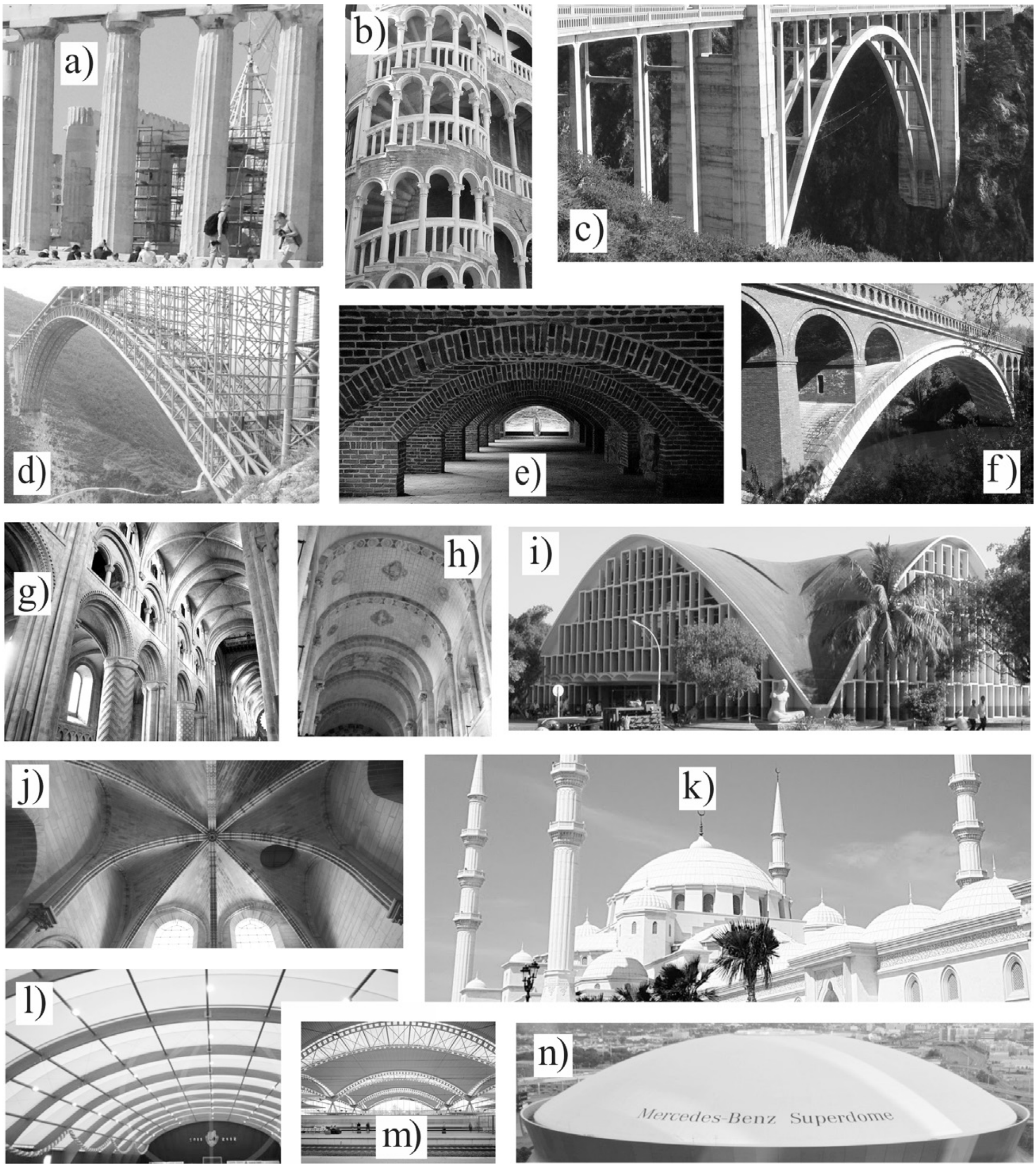


Fig. 11. Compression elements in structures: a) columns of Parthenon in Athens (Greece), photo by R. Kozikowski; b) arches and columns of Palazzo Contarini del Bovolo in Venice (Italy), photo by R. Kozikowski; c) arch and columns of the Bixby Creek Bridge on the Big Sur coast (California, USA), photo by R. Kozikowski; d) arch and columns of Xiaohe River Bridge in Enshi (Hubei, China) (source: https://en.wikipedia.org/wiki/List_of_highest_bridges#/media/File:Xiaohe_Bridge-1.jpg); e) arches and walls of Baltimore Basilica Crypt in Baltimore (Maryland, USA) (source; http://photography-on-the.net/forum/showthread.php?t=693565); f) arched vaults and walls of Pont Antoinette bridge in Sémalens (France) (source: https://fr.wikipedia.org/wiki/Pont_Antoinette); g) arches, vaults and columns of Galilee Chapel at Durham Cathedral in Durham (England) (source: https://roundaboutlondon.wordpress.com/tag/corbridge/); h) vault of Basilica of Saint-Sernin in Toulouse (France) (source: http://www.sacred-destinations.com/france/toulouse-st-sernin/photos/xti_2337pl); i) shells of Main Hall of Royal University in Phnom Penh (Cambodia) (source: https://structurae.net/structures/main-hall-of-the-royal-university-of-phnom-penh); j) arches and vaults of Notre-Dame Cathedral in Paris (France) (source: https://commons.wikimedia.org/wiki/File:Notre-dame-de-paris-vue-interieure-salle-nord.jpg); k) domes and columns of Sheikh Zayed Grand Mosque in Abu Dhabi (UAE), photo by R. Kozikowski; l) arches of sport hall (source http://www.plastecomilano.com/p/v.php?r=tendostrutture-acciaio-legno); m) arches and columns of railway station in Leuven (Belgium) (source: http://www.ingegneri.info/news/strutture/la-copertura-a-vele-della-stazione-ferroviaria-di-leuven/); n) dome of Mercedes-Benz Stadium in New Orleans (Louisiana, USA) (source: http://loyaltytraveler.boardingarea.com/2016/06/28/hotel-review-hyatt-regency-new-orleans/); fig. by the author.

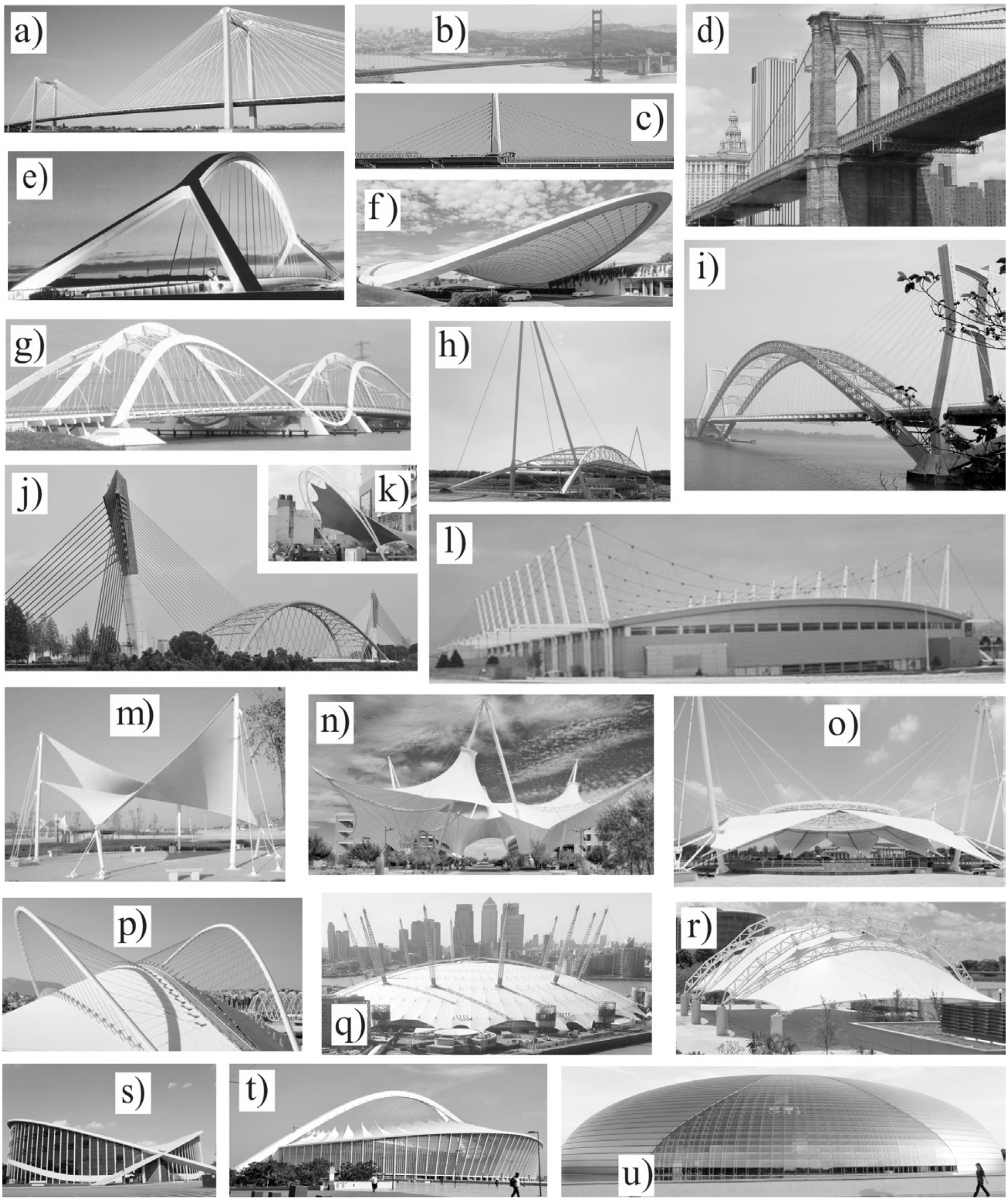


Fig. 12. Structures with elements working mainly in tension or compression: a) the Ed Hendler Bridge spanning the Columbia River (Washington, USA) (source: https://www.class-central.com/report/edx-dartmouth-engineering-of-structures-around-us/); b) the Golden Gate Bridge in San Francisco (USA), photo by R. Chojnacka; c) the Golden Horn Metro Bridge in Istanbul (Turkey) (source: https://en.wikipedia.org/wiki/Cable-stayed_bridge#/media/File:GoldenHornMetroBridge_09.JPG); d) the Brooklyn Bridge in New York (USA), photo by the author; e) Puente de la Barqueta bridge in Seville (Spain), design: Santiago Calatrava (source: http://www.steelconstruction.info/File:R7_Fig7.png); f) roof of Autostadt in Wolfsburg (Germany) (source: https://www.derbausv.de/news.jsp?id=1082); g) The Enneüs Heerma Bridge in Amsterdam (Netherlands) (source: http://www.panoramio.com/photo/7291291); h) toll gate in Souppes-sur-Loing (France) (source: https://structurae.info/ouvrages/autoroute-a-77-france/photos); i) the Lianxiang Bridge in Xiangtan (China) (source: https://zh.wikipedia.org/wiki/File:Lianxiang_bridge.jpg); j) the Seri Saujana Bridge in Putrajaya (Malaysia) (source: http://www.panoramio.com/photo/114591317); k) roofing (source: https://www.indiamart.com/mkdaylightingsolutions/tensile-structure.html); l) Utah Olympic Oval in Salt Lake City (USA) (source: http://www.teamswiderpeltz.com/2012/); m) membrane structure (source: https://pl.pinterest.com/pi-

n/276408495850396995/); n) tents (source: http://tensilefabricshade.blogspot.com/); o) membrane roofing (source: https://pl.pinterest.com/pin/326018460505674752/); p) Olympic Stadium in Athens (Greece) (source: http://www.metalsight.com/projects/athens-olympic-velodrome/); q) Millennium Dome in London (England) (source: https://en.wikipedia.org/wiki/Millennium_Dome); r) roofing of auditorium (source: https://www.indiamart.com/mkdaylightingsolutions/tensile-structure.html,); s) Dorton Arena in Raleigh (North Carolina, USA), design: Matthew Nowicki (source: https://upload.wikimedia.org/wikipedia/commons/a/a2/Dorton_Arena_West_Side.JPG); t) Moses Mabhida Stadium in Durban (South Africa) (source: https://en.wikipedia.org/wiki/File:Durban_Football_Stadium_(16231762225).jpg); u) high rise dome of National Centre for the Performing Arts in Beijing (China), photo by R. Chojnacka; fig. by the author.

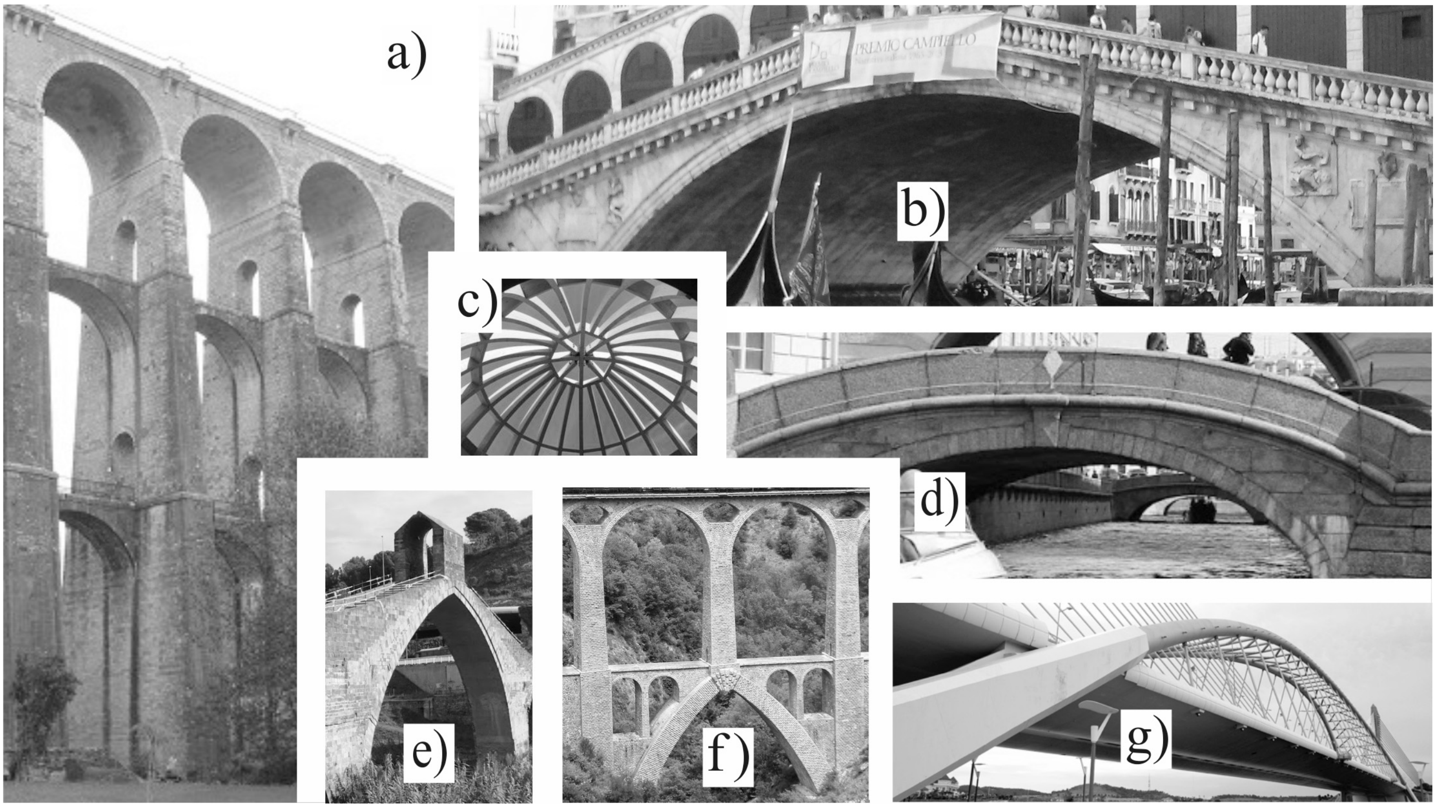


Fig. 13. Structures with compressive elements whose longitudinal profiles are adjusted to normal force diagrams: a) viaduct in Chaumont (France) (source: https://structurae.info/ouvrages/viaduc-de-chaumont); b) the Rialto Bridge in Venice (Italy), photo by R. Kozikowski; c) roof (source: http://www.rolam.ro/en/innovative-tehnologies); d) the Hermitage Bridge in Saint Petersburg (Russia), photo by R. Kozikowski; e) the Devil's Bridge across the Llobregat River in Catalonia (Spain) (source: http://loboquirce.blogspot.com/2015/11/pont-del-diable-en-martorell-bcn.html); f) Pont Séjourné viaduct in Fontpédrouse (France) (source: http://mapio.net/o/619116/); g) the Seri Saujana Bridge in Putrajaya (Malaysia) (source: http://www.bbrnetwork.com/technologies/what-are-stay-cables.html); fig. by the author.

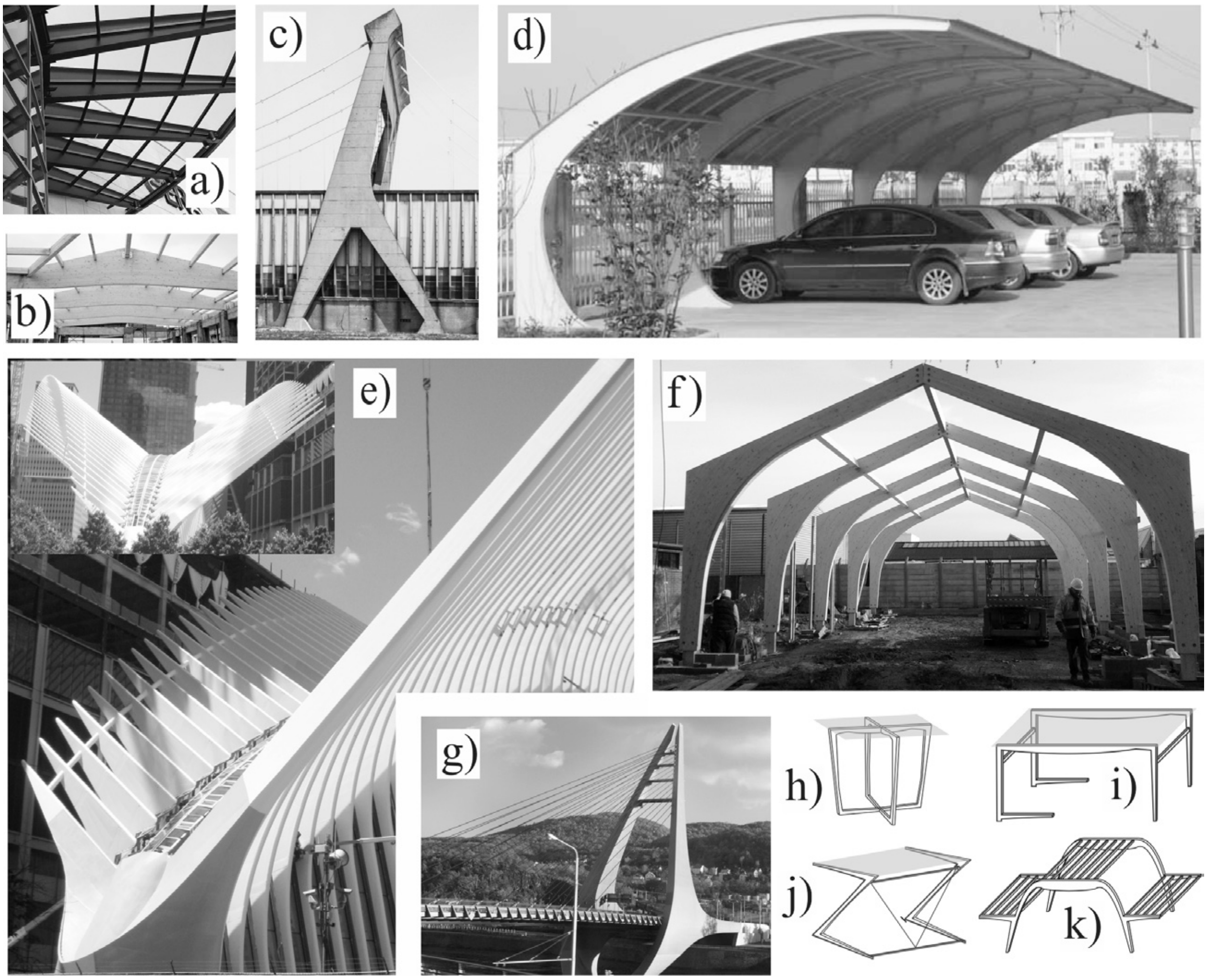


Fig. 14. Structures with bending elements whose longitudinal profiles are adjusted to bending moment diagrams: a) cantilever roofing (source: https://i.ytimg.com/vi/79adRquiVZ4/maxresdefault.jpg); b) roof (source: http://www.infoconstruct.ro/clienti/poze/SRk15-dWdjFKDjkKt.jpeg); c) factory building in Mantua (Italy) (source: http://www.ossesso.it/images/architettura/architettura-miracolo-luka-strutture-Q-03.jpg); d) car parking shed (source: http://www.fabstructure.in/kakinada/parking-shed-structure.html); e) the World Trade Center Transportation Hub in New York (USA), design: Santiago Calatrava, photo by the author; f) frames (source: http://www.bucklandtimber.co.uk/gallery/); g) the Mariansky Bridge in Ústí nad Labem (Czech Republic) (source: http://farm1.static.flickr.com/183/415232655_2ce15d296a_b.jpg); h) table, adapted from Kozikowska [2013b]; i) table, adapted from Kozikowska [2015a]; j) table, adapted from Kozikowska [2013b]; k) picnic table, adapted from Kozikowska [2015b]; fig. by the author.

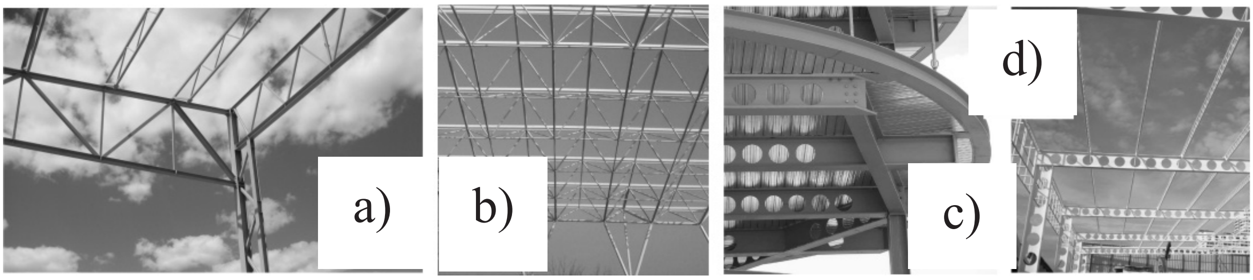


Fig. 15. Castellated structures and trusses: a) truss beams, photo by the author; b) space frame structure (source: http://www.nilka.ro/wp-content/uploads/2015/03/crangas_2.jpg); c) castellated beams (source: http://img.archiexpo.es/images_ae/photo-g/55693-7596205.jpg); d) castellated frames (source: https://www.slideshare.net/chagapon/cellular-beam-floor-roof-5112279); fig. by the author.

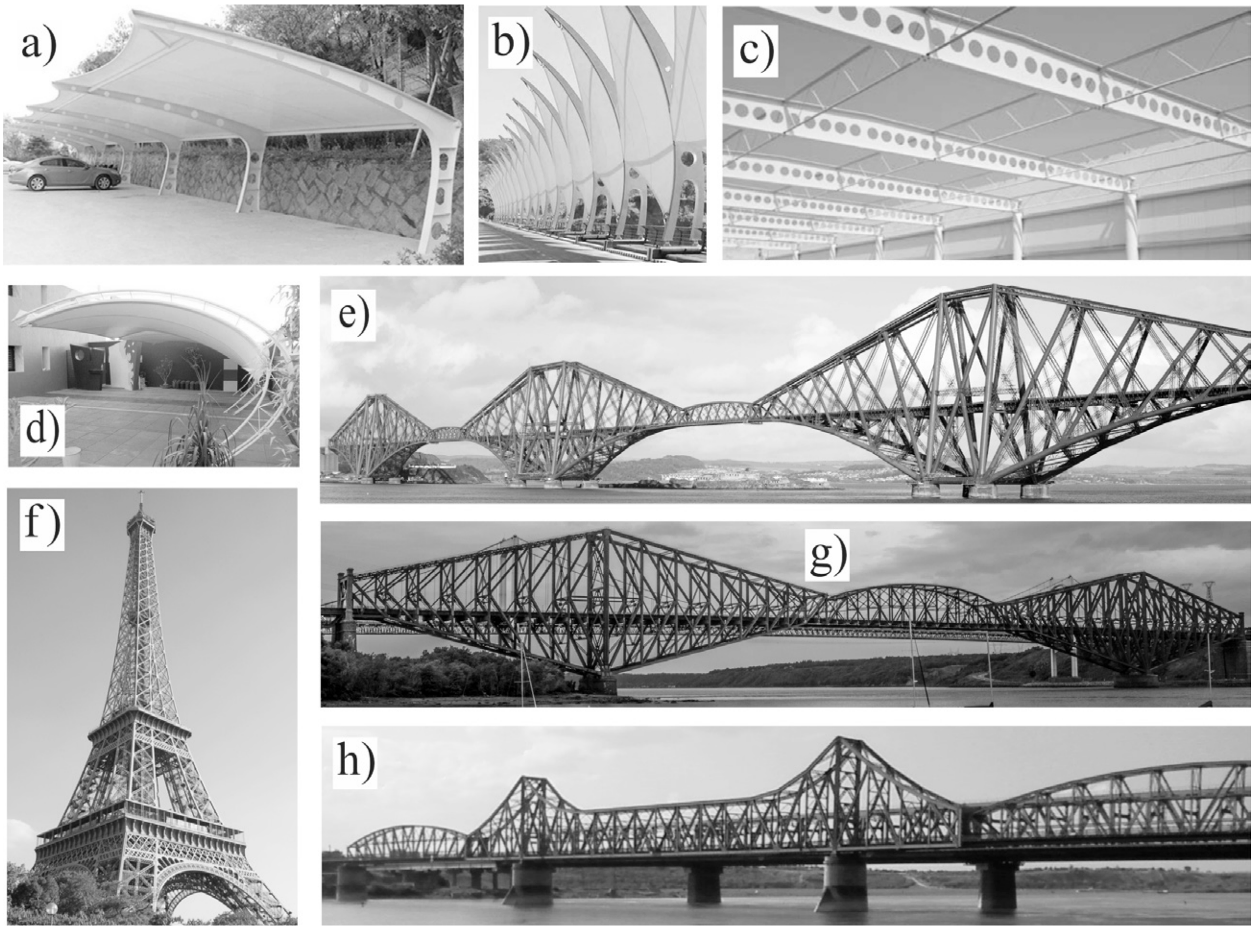


Fig. 16. Castellated structures and trusses whose longitudinal profiles are adjusted to bending moment diagrams: a) car parking shed (source: http://www.editorialespazio.com/noticias/detalle/179); b) sunshades in Aamby Valley City (India) (source: http://www.editorialespazio.com/proyectos/detalle/53); c) roof structure (source: http://docplayer.pl/9322925-Arcelormittal-europe-long-products-sections-and-merchant-bars-acb-belki-azurowe-z-otworami-kolowymi.html); d) car parking shed (source: http://sssdecors.com/images/products/car_parking.png); e) the Forth Bridge over the Firth of Forth (Scotland) (source: https://pbs.twimg.com/media/Cm6QJ2NU-kAAIr67.jpg); f) Eiffel Tower in Paris (France) (source: http://ofrancji.com/wp-content/uploads/2012/01/Pi%C4%99kne-zdj%C4%99cie-Wie%C5%BCy-Eiffla-Pary%C5%BC-Francja-by-x-oph.jpg); g) the Quebec Bridge across the Saint Lawrence River (Canada) (source: https://i.ytimg.com/vi/BcXZXj4FihU/maxresdefault.jpg); h) the Anghel Saligny Bridge across the Danube River (Romania) (source: http://static.panoramio.com/photos/original/38063989.jpg); fig. by the author.

2. BENEFITS OF USING EFFICIENT STRUCTURAL FORMS

Efficient structural forms not only can bring cost savings, but they can also have a positive effect on other features characterizing an architectural object. Structures adjusted to the flow of internal forces consist of thinner and lighter elements and can have a smaller number of supports. They allow wide areas to be spanned without internal supports, result in larger open spaces and give much greater freedom of interior design.

Efficient forms are still not widely used and, thanks to that, are usually perceived as original. Barnes and Dickinson write that "*they may help us to escape the wide-spread monotony and drabness in today's structural engineering which in turn will become again an essential part of the building culture*" [M. Barnes and M. Dickinson, 2000 p. 178].

Forms designed according to economic criteria can also have a great influence on the appearance of an architecture work and can make a positive contribution to its beauty. However, the concept of structural beauty is a matter of individual taste and is difficult to define. Our perception of the structural beauty is related to our familiarity with natural structures and our appreciation for them. Salvadori believes that perception "*of a structure is strictly related to our personal experience and culturally to the ex-*

perience of the race" [M. Salvadori 1980, p. 300]. The aesthetics judgment of structure has evolved over the ages; however, the structurally efficient objects have increasingly been perceived as aesthetically pleasing. Salvadori writes that "*within a short number of years our aesthetic appreciation of a given structure can change, as proven by the classic example of the Eiffel Tower in Paris*" whose initial disapproval and later full "*acceptance indicates not only an amazing reversal of public opinion but the possibility of a pure aesthetic message emanating from a pure structure*" [M. Salvadori 1980, p. 300-301]. Barnes and Dickinson think that lightweight structures may *"contribute heavily to an enriched architecture. Light, filigree and soft evokes more pleasant sensations than heavy, bulky and hard. … Thus lightweight structures with their rational aesthetics may solicit sympathies for technology, construction and engineers*" [M. Barnes and M. Dickinson 2000, p. 178]. Holgate writes that "*designers should attempt to maximize the visual appeal and emotional significance of built form. Engineers should look for character and power in build form, as much as for elegance or beauty. They should identify and draw out qualities that are inherent to the forms which arise from purely technological considerations. They will also recognize that aesthetic pleasure may be gained from many aspects of built form other than visual, particularly from skill in structural design and in the transmission of force. Engineers should educate others to take a similar delight in these aspects*" [A. Holgate 1992, p. 253]. Many authors consider shell structures to be particularly beautiful. Adriaenssens et al. write that "*more so than any other structural systems, shells have the ability to create eye-catching forms*" [S. Adriaenssens et al. 2014, p. 7]. Bletzinger and Ramm reckon that shells appear very light and graceful, meet aesthetical demands in a natural manner, and are the epitome of structural elegance [K.U. Bletzinger and E. Ramm, 1993]. Aesthetic values of optimal structures may not be easy to notice. Sandaker thinks that building structures "*are somehow part of architectural expression, and they influence the architectural space, but to be able to understand them fully requires the mobilisation not only of scientific and technological knowledge but also architectural competence and sensibility*" [B.N. Sandaker, 2008 p. 3]. However, the author agrees with the opinion of Macdonald that structures which are well designed and elegant from an engineering point of view, are exciting to those who appreciate engineering design [A.J. Macdonald, 2001 p. 72]. Structural forms which are a clear illustration of load-bearing behaviour are generally considered to be aesthetically satisfying.

CONCLUSIONS

Architecture and civil engineering professions are both engaged in the design and the construction of an architectural object. The architect must plan the object that includes a structure, and the engineer must select the suitable structure that is consistent with the vision of the architect. The close and well-integrated collaboration between the architect and the engineer is very important in this process and can result in structural forms which resist loads efficiently. The paper demonstrates how to design such efficient structural forms based on qualitative properties of the flow of internal forces. The author attempts to show that the use of such forms can also lead to the originality and beauty of an architectural object and can contribute to the enrichment of the architecture. However, the efficiency considered in terms of the weight of material should not be the only criterion when designing structures. Lightweight structures can be difficult to design, construct, and maintain. Moreover, all factors which affect structural efficiency are interrelated in complicated ways. Therefore, in each particular case, the architect and the engineer should together find the most appropriate and cost effective forms taking into account all the factors.

REFERENCES

1. **Allen E., Zalewski W. (2010)**, *Form and forces: designing efficient, expressive structures*, John Wiley & Sons, New Jersey.
2. **Adriaenssens S., Block P., Veenendaal D., Williams C. (2014)**, *Shell Structures for Architecture: Form Finding and Optimization*, Routledge, New York.
3. **Barnes M., Dickinson M. (2000)**, *Widespan Roof Structures*, Thomas Telford Publishing, London.
4. **Bletzinger K.U., Ramm E. (1993)**, Form Finding of Shells by Structural Optimization, *Engineering with Computers*, no 9, 27-35.
5. **Charleson A. W. (2015)**, *Structure as architecture : a source book for architects and structural engineers*, Routledge, New York.
6. **Ching F.D.K., Onouye B., Zuberbuhler D. (2014)**, *Building structures illustrated: Patterns, Systems, and Design*, John Wiley and Sons, Hoboken.
7. **Eekhout M. (1989)**, *Architecture in space structures*, Utigeverij 010 Publishers, Rotterdam.
8. **Holgate A. (1992)**, *Aesthetics of built form*, Oxford University Press, New York.
9. **Kozikowska A. (2010a)**, *Forma a konstrukcja mebli. Meble o konstrukcji wspornikowej*, „Architecturae et Artibus", vol. 2, no 4, 45-55.
10. **Kozikowska A. (2010b)**, *Forma a konstrukcja mebli. Meble o konstrukcji belkowej oraz ramowej*, „Architecturae et Artibus", vol. 2, no 4, 56-65.

11. **Kozikowska A. (2013a)**, *Forma a konstrukcja mebli. Meble o konstrukcji płyt zginanych jednokierunkowo*, „Architecturae et Artibus”, vol. 5, no 1, 69-78.
12. **Kozikowska A.** (2013b), *Forma a konstrukcja mebli. Stoły*, “Architecturae et Artibus”, vol. 5, no 3, 18-29.
13. **Kozikowska A. (2015a)**, *Kształtowanie form mebli o schematach swobodnie podpartych krzywych belek i wsporników przyłączonych do końców belek*, „Architecturae et Artibus”, vol. 7, no 4, 5-19.
14. **Kozikowska A. (2015b)**, *Kształtowanie form mebli o schematach zakrzywionych swobodnie podpartych belek ze wspornikami przyłączonymi poza końcami belek*, „Architecturae et Artibus”, vol. 7, no 4, 20-34.
15. **Kozikowska A. (2017)**, *Projektowanie form mebli o schematach swobodnie podpartych belek o dowolnym kształcie*, „Architecturae et Artibus”, vol. 9, no 1.
16. **Macdonald A.J. (2001)**, Structure and Architecture, Architectural Press, Oxford.
17. **Margolius I. (2002)**, *Architects + engineers = structures*, John Wiley & Sons, Chichester.
18. **Olsen C., Mac Namara S. (2014)**, *Collaborations in Architecture and Engineering*, Taylor & Francis, New York.
19. **Sandaker B. N. (2008)**, *On Span and Space: Exploring Structures in Architecture*, Taylor & Francis, New York.
20. **Salvadori M., Heller R. (1975)**, *Structure in architecture: the building of buildings*, Prentice-Hall, Englewood Cliffs.
21. **Salvadori M. (1980)**, *Why Buildings Stand Up. The Strength of Architecture*, W.W. Norton & Company, New York.
22. **Siegel C. (1974)**, *Formy strukturalne w nowoczesnej architekturze*, Arkady, Warszawa.

INTERNET SOURCES

1. http://annrobiefashion.com/im-back-or-my-florida-vacation/ (Fig. 10b) [access: 09-04-2017].
2. http://binscorner.com/pages/t/the-biggest-tent-in-the-world-amazing-st.html (Fig. 10c) [access: 09-04-2017].
3. http://www.archiexpo.com/prod/hightex/product-58335-1641302.html (Fig. 10d) [access: 09-04-2017].
4. https://en.wikipedia.org/wiki/List_of_highest_bridges#/media/File:Xiaohe_Bridge-1.jpg (Fig. 11d) [access: 09-04-2017].
5. http://photography-on-the.net/forum/showthread.php?t=693565 (Fig. 11e) [access: 09-04-2017].
6. https://fr.wikipedia.org/wiki/Pont_Antoinette (Fig. 11f) [access: 09-04-2017].
7. https://roundaboutlondon.wordpress.com/tag/corbridge/ (Fig. 11g) [access: 09-04-2017].
8. http://www.sacred-destinations.com/france/toulouse-st-sernin/photos/xti_2337pl (Fig. 11h) [access: 09-04-2017].
9. https://structurae.net/structures/main-hall-of-the-royal-university-of-phnom-penh (Fig. 11i) [access: 09-04-2017].
10. https://commons.wikimedia.org/wiki/File:Notre-dame-de-paris-vue-interieure-salle-nord.jpg (Fig. 11j) [access: 09-04-2017].
11. http://www.plastecomilano.com/p/v.php?r=tendostrutture-acciaio-legno (Fig. 11l) [access: 09-04-2017].
12. http://www.ingegneri.info/news/strutture/la-copertura-a-vele-della-stazione-ferroviaria-di-leuven/ (Fig. 11m) [access: 09-04-2017].
13. http://loyaltytraveler.boardingarea.com/2016/06/28/hotel-review-hyatt-regency-new-orleans/ (Fig. 11n) [access: 09-04-2017].
14. https://www.class-central.com/report/edx-dartmouth-engineering-of-structures-around-us/ (Fig. 12a) [access: 09-04-2017].
15. https://en.wikipedia.org/wiki/Cable-stayed_bridge#/media/File:GoldenHornMetroBridge_09.JPG (Fig. 12c) [access: 09-04-2017].
16. http://www.steelconstruction.info/File:R7_Fig7.png (Fig. 12e) [access: 09-04-2017].
17. https://www.derbausv.de/news.jsp?id=1082 (Fig. 12f) [access: 09-04-2017].
18. http://www.panoramio.com/photo/7291291 (Fig. 12g) [access: 09-04-2017].
19. https://structurae.info/ouvrages/autoroute-a-77-france/photos (Fig. 12h) [access: 09-04-2017].
20. https://zh.wikipedia.org/wiki/File:Lianxiang_bridge.jpg (Fig. 12i) [access: 09-04-2017].
21. http://www.panoramio.com/photo/114591317 (Fig. 12j) [access: 09-04-2017].
22. https://www.indiamart.com/mkdaylightingsolutions/tensile-structure.html (Fig. 12k) [access: 09-04-2017].
23. http://www.teamswiderpeltz.com/2012/ (Fig. 12l) [access: 09-04-2017].
24. https://pl.pinterest.com/pin/276408495850396995/ (Fig. 12m) [access: 09-04-2017].
25. http://tensilefabricshade.blogspot.com/ (Fig. 12n) [access: 09-04-2017].
26. https://pl.pinterest.com/pin/326018460505674752/ (Fig. 12o) [access: 09-04-2017].
27. http://www.metalsight.com/projects/athens-olympic-velodrome/ (Fig. 12p) [access: 09-04-2017].
28. https://en.wikipedia.org/wiki/Millennium_Dome (Fig. 12q) [access: 09-04-2017].
29. https://www.indiamart.com/mkdaylightingsolutions/tensile-structure.html (Fig. 12r) [access: 09-04-2017].
30. https://upload.wikimedia.org/wikipedia/commons/a/a2/Dorton_Arena_West_Side.JPG (Fig. 12s) [access: 09-04-2017].
31. https://en.wikipedia.org/wiki/File:Durban_Football_Stadium_(16231762225).jpg (Fig. 12t) [access: 09-04-2017].
32. https://structurae.info/ouvrages/viaduc-de-chaumont (Fig. 13a) [access: 09-04-2017].
33. http://www.rolam.ro/en/innovative-tehnologies (Fig. 13c) [access: 09-04-2017].
34. http://loboquirce.blogspot.com/2015/11/pont-del-diable-en-martorell-bcn.html (Fig. 13e) [access: 09-04-2017].

35. http://mapio.net/o/619116/ (Fig. 13f) [access: 09-04-2017].

36. http://www.bbrnetwork.com/technologies/what-are-stay-cables.html (Fig. 13g) [access: 09-04-2017].

37. https://i.ytimg.com/vi/79adRquiVZ4/maxresdefault.jpg (Fig. 14a) [access: 09-04-2017].

38. http://www.infoconstruct.ro/clienti/poze/SRk15dWdjFKDjkKt.jpeg (Fig. 14b) [access: 09-04-2017].

39. http://www.ossesso.it/images/architettura/architettura-miracolo-luka-strutture-Q-03.jpg (Fig. 14c) [access: 09-04-2017].

40. http://www.fabstructure.in/kakinada/parking-shed-structure.html (Fig. 14d) [access: 09-04-2017].

41. http://www.bucklandtimber.co.uk/gallery/ (Fig. 14f) [access: 09-04-2017].

42. http://farm1.static.flickr.com/183/415232655_2ce15d296a_b.jpg (Fig. 14g) [access: 09-04-2017].

43. http://www.nilka.ro/wp-content/uploads/2015/03/crangas_2.jpg (Fig. 15b) [access: 09-04-2017].

44. http://img.archiexpo.es/images_ae/photo-g/55693-7596205.jpg (Fig. 15c) [access: 09-04-2017].

45. https://www.slideshare.net/chagapon/cellular-beam-floor-roof-5112279 (Fig. 15d) [access: 09-04-2017].

46. http://www.editorialespazio.com/noticias/detalle/179 (Fig. 16a) [access: 09-04-2017].

47. http://www.editorialespazio.com/proyectos/detalle/53 (Fig. 16b) [access: 09-04-2017].

48. http://docplayer.pl/9322925-Arcelormittal-europe-long-products-sections-and-merchant-bars-acb-belki-azurowe-z-otworami-kolowymi.html (Fig. 16c) [access: 09-04-2017].

49. http://sssdecors.com/images/products/car_parking.png (Fig. 16d) [access: 09-04-2017].

50. https://pbs.twimg.com/media/Cm6QJ2NUkAAIr67.jpg (Fig. 16e) [access: 09-04-2017].

51. http://ofrancji.com/wp-content/uploads/2012/01/Pi%C4%99kne-zdj%C4%99cie-Wie%C5%BCy-Eiffla-Pary%C5%BC-Francja-by-x-oph.jpg (Fig. 16f) [access: 09-04-2017].

52. https://i.ytimg.com/vi/BcXZXj4FihU/maxresdefault.jpg (Fig. 16g) [access: 09-04-2017].

53. http://static.panoramio.com/photos/original/38063989.jpg (Fig. 16h) [access: 09-04-2017].