FACTA UNIVERSITATIS
Series: **Architecture and Civil Engineering** Vol. 11, N° 1, 2013, pp. 35 - 45
DOI: 10.2298/FUACE1301035S

ARCHITECTURAL GLASS: TYPES, PERFORMANCE AND LEGISLATION

UDC 666.185:620.9(083.74)=111

Jelena Savić#, Danijela Đurić-Mijović, Veliborka Bogdanović

University of Niš, Faculty of Civil Engineering and Architecture, Serbia
#jelena.savic@gaf.ni.ac.rs

Abstract. *Glass is an ancient building material, which facilitated penetration of light into buildings. Once it was used exclusively for window panes, whereas nowadays there are examples of structures made of glass only. Apart from the traditional non-bearing application in engineering, it is progressively used for construction of bearing elements.*
The progressively stricter regulations dealing with energy efficiency of the buildings gives rise to application of special characteristics glass of high performance, but also to the more intensive research in this field. The adequate choice of the glass type can to a great extent improve the energy efficiency of the building.
The paper gives a literature review of today's available architectural glass types as well as their characteristics and developing tendencies. Also a review of standards, both national and international once is provided.

Key words: *architectural glass, types, special coatings, energy efficiency, structural use, future development, legislation.*

1. Introduction

It is difficult to conceive the contemporary architecture without glass. In combination with modern technologies and materials such as steel, concrete, aluminium and other materials, this ancient building material [1] very successfully contributes to extraordinary appearance of buildings. Regardless of it being used for windows, façade or interior partitions, glass connects the space, improves the quality of space, transmits sufficient light, and the contemporary types of glass may contribute to energy saving. It is known that energy saving is one of the most important architectonic challenges of our age. The heat loss through the glass surfacing on the façade or the roof has been significantly reduced owing to modern glass production and processing technologies. Also, more than ever before, there is a concern about the safety of the users and the structure itself. Glass must nowadays conform to the high standards regarding safety of the users and passers-by, thus they

Received February 7, 2013

are made resistant to shocks and abrupt temperature changes, and in chase they are damaged or shattered, they would not break in. The manufacturers tried in this way to keep the risk of injury to a minimum.

Glass nowadays is an integral part of many facades and roofs. This material can be easily shaped and installed, crating in this way the structures which are gripping and dominating. However, apart from esthetic criteria, a contemporary structure must meet a number of criteria which are necessary for creation of adequate comfort within a structure. In order to improve the comfort of the occupants by an increase in the quality of interior space and optimization of natural resources, it is necessary to conceive of a building with an "interactive" envelope.

When selecting the type and use of glass in a project, one looks for an optimal balance between aesthetics and function. The wide variety of architectural glass commercially available coupled with the versatility and creativity one can explore with the material makes the design process exciting and challenging. The transparency and translucency of glass has historically given an aesthetic quality to architecture like no other material. It gives a building the ability to change, to move, and to create certain environments. The way in which light transmits through a piece of glass in building can be a powerful design tool for an architect. Glass can reflect, bend, transmit, and absorb light, all with great accuracy. Most architectural glass is partially transparent with little reflectance and absorbency. There are hundreds of glass compositions as well as different coatings, colors, thick-nesses, and laminates, all of which affect the way light passes through the material.

Fig. 1. Contemporary glass may adapt to variety of architectural forms

2. TYPES OF ARCHITECTURAL GLASS

The development of the float glass process in the 1950s allowed the economical mass production of high quality flat glass and virtually all architectural glass is now produced by this process. The focus of intensive research and development aimed at maximizing its tree most attractive traits: the ability to transmit light, block heat and safety issues. These efforts have engendered a number of significant advances, from the introduction of uncoated spectrally selective glass to the rise of multi-cavity insulating glass units. Safety issues have a high importance on glass applications, because of potential life safety hazard to pedestrians and building occupants. Today, the vast majority of new windows, curtain walls and skylights for commercial building construction have insulating glazing for energy efficiency and comfort. Nevertheless, high-quality glass products also give the opportunity to design load-bearing structural elements or systems constructed primarily of glass, such as staircases, floors, walls and bridges.

Architectural glass comes in three different strength categories [2]: annealed glass, heat-strengthened glass and fully-tempered glass. **Annealed glass** is the most commonly used architectural glass. It has good surface flatness because it is not heat-treated and therefore not subject to distortion typically produced during glass tempering. On the downside, annealed glass breaks into sharp, dangerous shards. Heat-strengthened and fully-tempered glass are heat-treated glass products, heated and quenched in such a way to create residual surface compression in the glass. The surface compression gives the glass generally higher resistance to breakage than annealed glass. **Heat-strengthened glass** has at least twice the strength and resistance to breakage from wind loads or thermal stresses comparing to annealed glass. The necessary heat treatment generally results in some distortion compared to annealed glass. Like annealed glass, heat-strengthened glass can break into large shards. **Fully-tempered glass** (toughened glass) provides at least four times the strength of annealed glass, which gives it superior resistance to glass breakage. It is float or plate glass that has been heated and rapidly cooled, increasing its inherent strength and ductility. Similar to heat-strengthened glass, the heat-treatment generally results in some distortion. If it breaks, fully-tempered glass breaks into many small fragments, which makes it suitable as safety glazing under certain conditions. It is used for windows that are exposed to high wind pressure or extreme heat or cold (Fig. 2a). Properties of annealed and fully-tempered glass [4] are comparatively provided in Table 1.

Table 1. Properties of Glass

	Annealed glass	Toughened glass (fully tempered)
Strength	59–150 N/mm^2	7–28 N/mm^2
Young's modulus	70 kN/mm^2	70 kN/mm^2
Density	2.4 kg/m^3	2.4 kg/m^3
Thermal coefficient of expansion	8.8*10^{-6} K^{-1}	8.8*10^{-6} K^{-1}
Poisson's ratio	0.22	0.22

The following are specialized glass types that are made with different qualities to enhance their performance [3]:

- **Laminated glass** (Fig. 2b) involves sandwiching a transparent sheet of polymer, such as polyvinyl butryal, between two or more layers of flat glass using an adhesive. Because it can prevent the fall-out of dangerous glass shards following fracture, it is often used as safety glazing and as overhead glazing in skylights. It is a durable and versatile glass with plastic interlayer which provides protection from ultraviolet rays and attenuates vibration, and gives laminated glass good acoustical characteristics. Can be used in a variety of environments.
- **Insulating glass** consists of two or more lites of glass separated by a hermetically sealed space for thermal insulation and condensation control. The airspace between the glass lites can be filled during the manufacturing process with either dry air or a low-conductivity gas, such as sulfur hexafluoride or argon. The thermal performance of double-glazed or triple-glazed windows can be further improved by the addition of

a low-emissivity coating on one or all of the layers of glass. The air space also reduces heat gain and loss, as well as sound transmission, which gives the insulating glass superior thermal performance and acoustical characteristics compared to single glazing. Most commercial windows, curtain walls, and skylights contain insulating glass.

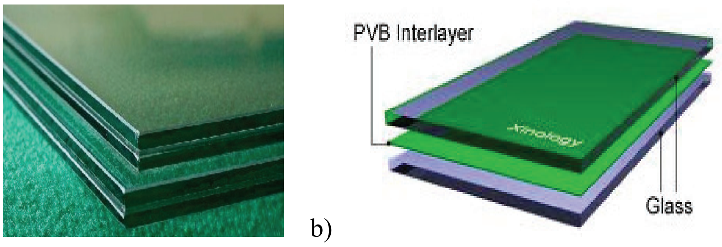

Fig. 2. Appearance: a) tempered glass, b) laminated glass

- **Coated glass** is covered with reflective or low-emissivity (low-E) coatings. In addition to providing aesthetic appeal, the coatings improve the thermal performance of the glass by reflecting visible light and infrared radiation.
- **Tinted glass** contains minerals that color the glass uniformly through its thickness and promote absorption of visible light and infrared radiation.
- **Wire glass** involves steel wires rolled into sheets of glass. A wire mesh is inserted during the manufacturing of plate glass, allowing the glass to adhere together when cracked. It can qualify as safety glass for some applications.

3. SPECIAL GLASS COATINGS

Glass provides high compression strength and perfect transparency – but also the possibility to alter its transparency through the integration of materials which have a switchable light transmissivity. Today's coating technologies, as well as the possibility of reinforcing glass with different stiffening materials; open a nearly endless range of new ways of using glass. Glass and façade manufacturers now offer a wider range of affordable glazing system solutions which will provide better thermal and solar control without sacrificing daylight, and perhaps control surface temperature at the inside face of the glass to maintain human comfort.

Self-cleaning or easy-to-clean glass [5] uses titanium dioxide coatings as a catalyst to break up organic deposits. It requires direct sunlight to sustain the chemical reaction and rainwater to wash off the residue. Anorganic deposits are not affected by the coatings.

Photochromic coatings [6,7] incorporate organic photochromic dyes to produce self-shading glass. Originally developed for sunglasses, these coatings are self-adjusting to ambient light and reduce visible light transmission through the glass. They provide a more evenly (in terms of time) distributed illumination of interior space regardless of exterior variations and they are typically used to provide shading.

Glass with **electrochromic coatings** [6] utilizes a small electrical voltage, adjusted with dimmable ballasts, to adjust the shading coefficient and visible light transmission.

Upon switching off the power, they retain the same degree of dimming. In this way it is possible to control the shading of the façade, and thus illumination and temperature of the interior (Fig. 3). Like photochromic coatings, they are intended to attain lighting energy savings.

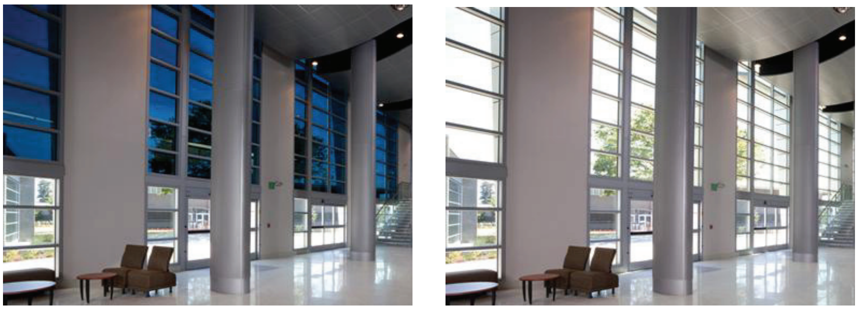

Fig. 3. Electrochromic coatings

Thermochromic laminated glazing (TLG) enables to regulate daylight, automatically adapting dynamically to the continuously changing climatic conditions, aids in reducing the energy needs of a building and providing thermal comfort. Neither electrical power nor driving unit are required. The polymeric interlayer of TLG is doped with complexes of transition metals, which change their coordination and transmission or color of the film under influence of light and heat fluxes (Fig. 4).

They are favorable for regulation of interior temperature [6] in comparison to the photochromic glass, because the external temperature and degree of illumination need not be directly mutually dependent, especially in winter.

Fig. 4. Sunlight responsive thermochromic glass: (a) windows are tinted by direct sunlight; (b) windows are clearer as they are only exposed to indirect sunlight

4. Potential for Future Development

To attain, new social, economic and technological ideals architects and engineers of today must improve the quality of buildings and establish new principles of conceptual design of buildings. The quality of interior space and the impact of a building on its surroundings depend strongly on the physical interface that separates the outer environment from the inner building space. The conception and realization of this envelope are therefore of prime importance.

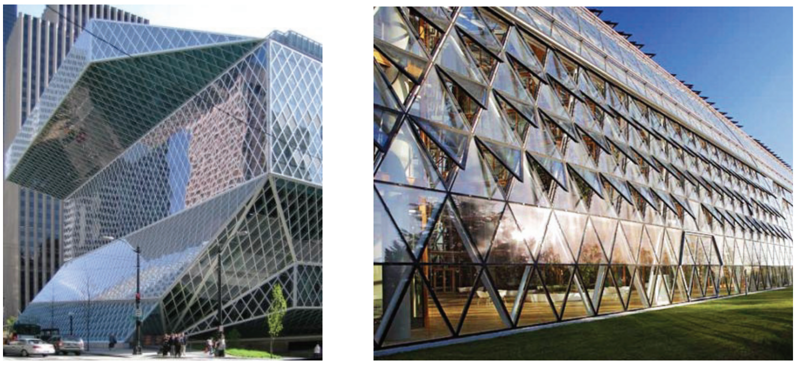

Fig. 5. Glass combined with contemporary technical systems for ventilation, shading and collecting of the Sun energy

Considering **market issues** it is obvious that growth of demand for glass is not only a consequence of economic growth but also regulations concerning safety, reduction of noise and growing demands in terms of energy efficiency of buildings. However, the lack of standards regulating use of glass in engineering can, in perspective, reduce the growth of glass use in construction.

The main growth drivers that will influence the flat glass consumption in buildings and civil engineering respond to several contemporary demands, presented in *Table 2*.

Table 2. Growth drivers for future flat glass consumption [8]

Demand	Growth Drivers
Energy saving *(heating)*	Energy saving legislation and building regulations, reduction of energy loss from buildings and energy labeling of windows.
Energy saving *(cooling)*	Energy saving legislation, reduction of air-conditioning load in buildings. Preventing non air-conditioned buildings from overheating
Safety	Increasing legislative requirement for safety glass
Security	Requirement for transparency combined with security/safety features
Fire protection	Compliance with fire regulations combined with requirements for good light transmission
Acoustic	Increasing noise levels caused by traffic, aircrafts etc progressively covered by legislation
Self-cleaning	Reduce use of detergents and improve safety of cleaning works on high-rise buildings. Product range now extended to incorporate self-cleaning features

Safety issues occurring in contemporary glass structure are the result of the lack of knowledge of glass properties and other materials forming a composition with it, and designing, production or construction flaws. It is important to consider them so that they could be avoided. The basic measures taken to protect the glass structures [3] are:

- Application of chemically tempered glass with the polycarbonate core, allowing additional safety and durability;
- Application of multi-layered glass, with at least one layer of semi-tempered glass, which will prevent the unwanted displacement of glass panel in case of breakage;
- In case of point supported glass façades, prevention of failure chain reaction by independent support of glass panels in vertical rows, with regular distribution of stress in case of breakage of some of the panels, transferring the load horizontally to adjacent panels;
- In case of point supported glass facades, if possible, provide a central suspension point for the topmost panel in a row, providing an absolutely vertical position;
- In case of multi-layered glass, it is good practice to use one additional layer on the glass than what is required by the static design.

Fig. 6. Structural use of glass

Glass structural design standards are essential to limit the number of structural failures that arise from avoidable negligence resulting from poor design or construction practice due to the lack of a harmonized standard.

The research in the field of enhancing glass as a building material, its properties and processing methods has resulted in a range of various products, which is huge stimulation to expand its use in architecture and beyond. **Technical issues** for the growing application of glass in civil engineering require to establish and harmonize certain criteria of its production, processing and installation. The upgrade of the current situation, where different standards are in use in different countries, can be achieved by the harmonization and development of the single European standard.

Table 3. Main issues related to the further development of standards to help the practical application of the knowledge gained in the application of glass as structural products [8]

Item / Issue	Level of solution /perception
Availability of materials	High
Versatility of products	High
Technology level	High
Cost	Moderate
Codes, standards and specifications	good, but still insufficient: lack of harmonized design standards
Supportive data banks	Fair
Understanding of behavior	weak, perceived unreliability
Knowledge of structural mechanics	relatively high
Knowledge of design methodology	Insufficient
Knowledge of detailing	Poor
Confidence in reliability of structure	Low

5. Current Status of Standards and Regulations

Regulations are the result of experience and research and should undergo updating in order to create an adequate framework for designing, construction and production. When it comes to civil engineering, regulations are very extensive and difficult to consider. In most cases, it is necessary to consult several reference documents in order to fully understand the observed problem. As for the architectural glass, it is important to mention that there are several leading international standards such as the U.S standard E1300-07, British BS 6262 and European pre-standard prEN 13474. The American standard is recognized in the countries which do not have their own glass standards; the British standard is relevant for the British and Irish market where construction of glass-aluminium facades is very prominent, while the European pre-standard is an attempt to harmonize the design of glass structures for the entire European market [9]. This would facilitate designing, application and monitoring of architectural glass. The globalization of the construction market comprising construction products, engineering and construction services requires international standards families in order to avoid inconsistencies due to the use of various national standards.

Each of the mentioned standards is composed of a set of design standards in connection with product and testing standards.

In the EU regulations, three groups of regulations can be singled out, which must be considered when designing elements and structures of glass [3]:

1. General standards, related to designing and construction in general,
2. Standards relating to glass as a building material,
3. Standards relating to glass structures.

Particular attention must be paid to the last group of standards relating to: safety and security of the structure, fire safety, acoustic comfort, thermal comfort, water vapor diffusion, water and air permeability.

The national standards in this area are fairly poor and based on the international standards. As there is a multitude of structural elements of glass, it is necessary to define and structure this field by a number of standards and regulations. The structural application of glass and static designs for glass facades and structural safety of glass buildings are not the subject of national standards.

In Germany, one of the leading countries in this field, there is a number of standards and rules, as a DIN 18008 which provides rules for design and construction as well as specifications for required experimental verifications [3]. In Germany, technical rules for glass construction are available and include technical rules for glazing acting as anti-drop device/railing (TRAV), technical rules for linear supported glazing (TRLV) and technical rules for point supported glazing (TRPV).

Fire-proofing is a very important characteristic when it comes to contemporary materials. Two most important European standards dealing with these issues are: DIN 4102 and ISO 834-10. In national regulations, SRPS ISO 3009:1993 [10] regulates fire-proof characteristics of glazed elements.

Acoustic comfort, as a part of engineering physics, represents the youngest field of research as opposed to other – classical topics in civil engineering. The acoustic comfort is defined by the standard SRPS EN ISO 140 and SRPS EN ISO 717, dealing with laboratory measuring of insulation capacity R and determination of the level of sound-proofing in buildings. The national standard SRPS EN 12354-1-6:2008 [10] defines the level of sound-proofing of buildings on the basis of acoustic performances of building elements.

Thermal comfort is a developing area and it is very interesting. In the field of thermal protection, there are the following standards: EN 13790-thermal performance of the structure, EN 13830-thermal aspect of curtain walls, EN ISO 10077-1-includes the method for design of thermal characteristics of thermal insulation glazing, EN 1279 1-6 regulates the field of thermal insulation glass. In the national regulations the current standard is SRPS EN 1279-1-6 related to construction glass, which is taken from and partly translated European standard EN 1279 1-6. The standards treating the methods of calculation of thermal transmission coefficient (U value) are SRPS EN 673 - Determination of thermal transmittance-calculated method, SRPS EN ISO 10077 1-2 - Thermal performance of windows, doors, shutters - Calculation of thermal transmittance. Since 2008 in the national standards there has been the regulation SRPS EN 13947 defining calculation of thermal transmittance of curtain walls. The calculation includes: different types of glazing, e.g. glass or plastic; single or multiple glazing; with or without low emissivity coating; with cavities filled with air or other gases; frames (of any material) with or without thermal breaks; different types of opaque panels clad with metal, glass, ceramics or any other material. Thermal bridge effects at the rebate or connection between the glazed area, the frame area and the panel area are included in the calculation.

Water vapor diffusion, represents an important characteristic when the external partitions are concerned, whereas, in national standards it relates only to massive structures. The European standard EN ISO 13788:2001 deals with this problem and calculation methods.

Since recently, the field of glass facades was arranged in terms of permeability to air and water due to variations in pressure. The standards covering this field are SRPS EN 12152, 12153, 12154 and they specify requirements and classification of air permeability of both fixed and openable parts of curtain walling, also defining the method to be used to determine the air permeability and defining the requirements and classification of water tightness performance of curtain walling.

6. Conclusion

On the basis of the previous statements, it can be concluded that the contemporary architecture is particularly interested in glass, and it is being more extensively applied in architecture as a result of improvement its production technology. Accordingly, there is a great number of glasses in use today, depending on its purpose, and the application potential is larger. Apart from its traditional role, the glass is progressively used as a structural, load bearing material.

The paper provides the review of types of architectural glass, their basic characteristics as well as the area of application. Also given is the potential for future development through the market, safety and technical issues, as well as a review of European and national standards in this field.

The number of standards being in force in developed countries worldwide shows that the glass product standardization is relatively well developed. All these standards are related to use of glass in buildings and most of them are related to structural use of glass with a few exceptions that covers energy efficiency issues. The national standards in this field cover some areas, some are being prepared, though there are areas which are not regulated at all. It is thus very important to speed up the process of harmonization of national regulations with the leading international regulations. Also, it is expected that in the future different standards from all around Europe will be harmonized.

Development of new European standards for use of glass products in civil engineering works will increase the number of structural glass applications. It will offer support to designers that will be able to realize attractive architectural ideas. The demand for structural applications, as well as several forthcoming initiatives underway to improve the energy performance of new and existing buildings, will stimulate glass manufacturers to develop innovative high-quality and high-performance, considering aspects of sustainability.

References

1. Prolović (Savić) J.: "Tradicionalni materijali u projektovanju savremenih fasada", Zbornik radova Građevinsko-arhitektonskog fakulteta u Nišu br.23, 2008. str. 311-321.
2. Vigener, N., Brown M.A. (2009), "Building Envelope Design Guide - Glazing", *Whole Building Design Guide, National Institute of Building Science*.
3. Čikić Lj. Jasna: Staklo i konstruktivna primena u arhitekturi, Gradevinska knjiga, Beograd, 2006, p.230
4. Structural design of glass: Stephen R. Ledbetter; Andrew R. Walker; and Alan P. Keiller, Journal of Architectural Engineering, ASCE, September 2006, 137-149.
5. Z. Grdić, G. Topličić Ćurčić, "Ekološki materijali – komponenta održive arhitekture", Zbornik radova Građevinsko-arhitektonskog fakulteta u Nišu br.25, 2010. str. 87-94.
6. Milošević Vuk, Đurić-Mijović Danijela:"Dvostruke fasade kao korak ka energetski održivim objektima", Nauka + Praksa, br. 13, str. 81-84, 2010.
7. Gavrilović D., Stojić J.: "Usage of "smart" glass panels in commercial and residential buildings", Facta Universitatis, Architecture and Civil Engineering, Vol 9, N°2, 2011, pp. 261-268.
8. R. Zarnic, G. Tsionis, E. Gutierrez, A. Pinto, M. Geradin, S. Dimova: "Purpose and justification for new design standards regarding the use of glass products in civil engineering works",European Commission Joint Research Centre, Office for Official Publications of the European Communities, , Luxembourg 2007.
9. T. Gere, I. Kožar: "Osnovna svojstva stakla kao konstrukcijskog materijala i norme u primjeni", Gradjevinar Vol. 60 N. 12, pp. 1043-1054, 2008.
10. Institut za standardizaciju Srbije, www.iss.rs/standard.

ARHITEKTONSKO STAKLO: TIPOVI, KARAKTERISTIKE I REGULATIVA

Jelena Savić, Danijela Đurić-Mijović, Veliborka Bogdanović

Staklo je drevni građevinski materijal koji je omogućio prodor svetlosti u objekat. Nekada korišćeno skoro isključivo za zastakljivanje prozora a danas postoje primeri konstrukcija izgrađenih u celosti od stakla. Pored tradicionalne nekonstruktivne primene u građevinarstvu, staklo se sve češće koristi za izradu nosećih elemenata.

Pooštravanjem propisa u oblasti energetske efikasnosti zgrada stvaraju se uslovi za primenu specijalnih vrsta stakala visokih performansi, kao i potreba za intenzivnijim istraživanjem u ovoj oblasti. Adekvatan izbor stakla može u velikoj meri da poboljša energetsku efikasnost zgrade.

Rad daje prikaz dostupnih vrsta arhitektonskog stakla, kao i njihove karakteristike i tendencije za dalji razvoj. Takođe je dat pregled standarda i propisa, kako nacionalnih tako i međunarodnih.

Ključne reči: *arhitektonsko staklo, vrste, specijalni premazi, energetska efikasnost, konstruktivna primena, razvojne tendencije, regulativa*