Glass structural elements and load-bearing glass structures

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Abstract. This article provides an overview of scientific and technical literature on the design and calculation of load-bearing structures made of laminated glass. Since glass is one of the most fragile materials, additional control methods are required for the production, installation and operation of glass structures, because one small defect can reduce the strength of the entire structure several times. The analysis of multilayer glass, its calculation and design for use in construction is presented. The thickness, the number of layers, the presence and type of the intermediate layer, all this affects the strength characteristics of the entire glass structure. The problem of the lack of a Russian regulatory and technical base that would regulate the design of load-bearing glass elements, such as columns, beams, shells, etc.

1 Introduction
At present, glass in construction is often considered as part of the building envelope, however, means, methods and regulatory technical documentation for glass load-bearing structures are being developed. The possibility of using glass as supporting structures is being considered, using the example of columns, beams, as well as curved and mesh shells. The properties of load-bearing glass structures, various types of glass, options for strengthening it, joining with other materials, etc.

2 Review of sources
Transition "Skywalk" (Hanover, Germany) is an example of glass panels in curved shells in the form of a system of cylindrical panels. Considering the load-bearing properties of the cladding, significant savings could be achieved at the expense of glass thickness. During the tests, it was found that the carrying effect of the shell remained sufficient even in the event of a crack in the glass. In all-glass shells used as load-bearing structures, the elements experience relatively high compressive stresses, so only glass bars or relatively thick glass panels can be used. Another example of the use of glass as a structurally supporting element is the Talus du Temple glass pavilion (architect Dirk Jan Postel, 2001, France). The walls are connected to the base and roof using steel corners with neoprene gaskets. The structure has proven its durability, having endured two strongest storms during its existence. An example will also be the glass dome of the open-air amphitheater in the Zaryadye Park, architectural bureau «Diller Scofidio + Renfro» (Fig. 1.). The glass staircase of the shopping and entertainment
center (Krasnoyarsk, Russia) (Fig. 2). The staircase of the shopping center is a reinforced glass panel, resting on the central part of the spiral staircase structure.

To create columns, the author in article [1] offers both completely glass elements by gluing glass strips together, and various combinations of glass joining, also by gluing glass to steel, plastic or wood. Considering glass beams, beams of solid tempered glass and beams of glass in combination with other materials are proposed. The shells are considered as curved and reticulated, because they can carry heavy loads compared to straight shells. It is proposed to use glass, both with the use of additional materials, such as steel, wood or plastic, and the possibility of using glass without any additional reinforcement as load-bearing structures. Glass columns and beams will allow not only to increase the space, but also to give it lightness and elegance. A nonlinear analytical (exact) model was developed for the analysis of composite beams under transverse bending load in article [2]. The model reproduces the elements responsible for the relative sliding between layers (shear connectors and interface) with an elastoplastic intermediate layer that softens the deformation. In addition to slippage, the model predicts stresses due to a given load and ultimate load for delamination of two-layer composite beams. To assess the influence of various geometric and material parameters, a number of parametric studies are carried out, the main results of which are presented together with an interpretation, for example, the dependence of the bearing capacity, stresses and deflections on the local nonlinear load. The study also proved that the lower and upper bounds of the shear joint (respectively, fully flexible and infinitely rigid shear connectors) imply no lower and upper bounds for response.

Equations for the effective thickness of multilayer glass beams [3] are derived from the analytical model. Some static experimental tests were performed on multiple laminated glass beams under distributed loading to validate model predictions. The static response of laminated elements, such as beams and laminated glass plates, can be modeled using analytical or numerical models, in which glass is usually modeled as linear elastic and polyvinyl butyral (elastic spacer) as linear viscoelastic material, respectively.

However, glass, even multilayer glass, is one of the most fragile and vulnerable materials. Load-bearing structures made of glass require more attention to their strength, and in order to prevent low-quality products from getting to the construction site, it is necessary to create additional verification stages at the production stage. Various types of installations for testing glass samples are discussed in article [4]; laminated safety glass, which is subdivided into impact-resistant glass, penetration-resistant glass and bullet-resistant glass. An improved device for testing impact resistance is proposed. This
method of evaluating the quality of glass samples could be used to evaluate glass support structures. The methodology proposed in [5] is confirmed by experimental tests on multilayer glass plates with a uniformly distributed load. A little earlier, the concept of effective thickness was proposed to simplify the static calculations of laminated glass using a monolithic model with an equivalent bending stiffness equal to that of the laminated element. Due to the temperature-dependent changes in the properties of the laminated glass introduced by the viscoelastic polymer intermediate layer, a different effective thickness must be determined for each different temperature. This feature implies a large number of evaluations for each of the possible working situations.

Presents an analytical model [6] of a multilayer glass plate (two outer glass layers and a polymer intermediate layer). Its mechanical behavior is described by a system of three exact and explicit equations. The equations are solved for a simple bearing rectangular plate, with a transverse uniformly distributed static load. However, a solution for other constraints, shapes and loads can be obtained without changing the model, but simply by adjusting the mathematical form of the functions with which the equations are solved. The model is a design and evaluation tool. It allows you to check and refine finite element models and semi-empirical formulas. Since it is analytical and explicit, the model provides a better understanding of the mechanical behavior of the laminated glass plate.

The possibility of using laminated glass is described in article [7]. The author considers the possibility of designing supporting structures made of glass and methods of calculation and design. The bearing capacity of spliced structural glass beams under bending action is considered [8], which is investigated using finite element modeling. As geometric features arise in spliced structural glass beams, stress concentrations arise that are a key issue in bearing capacity due to the brittle failure mode of the glass. Simulations show that these stress concentrations are highly dependent on the stiffness of the intermediate layer material, which, in turn, is highly dependent on temperature and load duration. In the case of low interlayer stiffness, stress concentrations are also low, but the zone of influence of the joint is large. In the case of high interlayer stiffness, the area of influence of the joint is small, and therefore the force in the connected panel must be transmitted in a small area, resulting in high stress concentrations.

Therefore, in order to obtain a safe design, different loading scenarios must be considered with different assumptions regarding the stiffness of the interlayer material. The process of designing an "I"-shaped glass column has been analyzed [9]. The results show that the bearing capacity efficiency is better in the case of the first group, but the design for the critical reaction forces of the second group is safer. The article [10] assesses such a glass element as a column. This column is considered from an economic point of view, it is concluded that a glass column will be much more expensive and more laborious to manufacture and install than similar samples from steel and reinforced concrete. Glass has good compressive strength, corrosion resistance. The strength characteristics will correspond to the theoretical ones if the material is homogeneous and without geometric inaccuracies.

An equation of the Euler theory for the buckling of monolithic beams [11] is proposed, which extends to multilayer laminated glass beams using effective stiffness. This proposal is based on the idea of calculating the thickness (depending on time and temperature) of a monolithic element with bending properties equivalent to those of a laminated one, that is, the deflections provided by an equivalent monolithic beam are equal to the deflections of a multilayer model with a viscoelastic core. A finite element model was assembled to validate the proposed methodology for any boundary conditions. Later, methods of increasing the fire resistance of glass while maintaining its operational properties were considered [12].

For glass support elements, the place where the force is transferred from the slab to the glass part of the column or beam is very important. It is especially important to take into account the transfer of load from horizontal elements to other parts of the structure and to prevent the gradual collapse of the building or its part due to the collapse of one glass column. The methodology of calculation and design of supporting structures made of glass [13], as well as design of joints, is proposed. At the moment, the most common connection is bolted. Such a connection assumes the presence of holes to the structure. In this case, a point contact occurs between the bolt and the hole surface along one line,
which is unacceptable, since the load transfer area takes on the minimum possible value, the already high stress concentration in the hole becomes even higher. The article describes an experiment that was carried out with two beams, which were connected to each other using a system of metal ties, and the glass sheets in each beam were connected using ultraviolet bonding. In the places of the bolted connection of the elements, it is assumed that some kind of polymer gasket would ensure the distribution of forces over the area of the hole.

The reactions of 18 samples of load-bearing glass structures made of laminated glass are given in article [14]. Which were divided into three groups (columns, beams and prisms), and the loads applied to them (central, eccentric compression and bending). As a result, two categories were distinguished, the first stage of destruction - the appearance of the first cracks and the second stage - the destruction of the sample. It should be noted that the indicators of strength characteristics depend not only on the type and composition of the glass structure, the installation method, but also on the load applied to it. It has been experimentally proven that the average value of the elastic modulus of multilayer samples differs by about two times. In the direction of load application: perpendicular to the glass layers - 30,000 MPa; along the layers of glass - 60,000 MPa. The influence of the connecting polymer material and the technology of manufacturing structures is also noted. Also proposed is a method for predicting the deflection of laminated beams and plates under static loads using a linear elastic monolithic model (analytical or numerical) and equations of effective stiffness for laminated glass [15]. The equations proposed in this work were confirmed by experimental tests carried out in beams with a supporting support and in a plate resting on four corners. The method of calculating the residual life of building structures is considered [16]. It was proposed to call such a method a combined one, it is universal and can be applied in all cases of calculation.

The article [17] presents an experimental, applied study of structural beam columns made of laminated glass, subjected to combined axial compression and bending in the plane. The samples under study consisted of annealed float glass layers interconnected by a SentryGlas interlayer. The 17 tests were carried out, which investigated in detail the structural behavior of glass in terms of bearing capacity, failure mode, and strength after failure and deformability of girder glass columns. Failure modes and related mechanisms were identified during the tests; assessed the effect of axial compression, the amount of laminate and the coefficient of flexibility on structural behavior; and major stress components leading to glass breakage.

Laminated glass, which is supposed to be used as a material for supporting elements of a building structure, is most often a multilayer element consisting of two or more glass sheets with one or more intermediate polymer layers. The article [18] investigated the behavior of architectural laminated glass under lateral pressures. The investigations included material property determination, theoretical stress analysis, experimental stress analysis and destructive testing using monolithic, multilayer and "multi-layer" glass plates of several geometries. The prevalence of data and information indicates that: architectural laminated glass behaves similarly to monolithic glass of the same nominal thickness at short-term lateral pressures (representative of wind loads) at and below room temperature; the temperature at which behavior changes from being monolithic to being significantly different from monolithic at transient lateral pressures is not clearly defined but is about 49 °C (120 °F); and the architectural laminated glass behaves similarly to monolithic glass of the same nominal thickness under extended lateral pressure (representative of snow loads) at 0 °C (32 °F) and below. Later, a theoretical model of engineering mechanics was presented [19], which takes into account factors affecting the behavior of laminated glass, including temperature, thickness of the intermediate layer and its composition. The paper presents additional data on tensile strength for laminated glass with a thicker intermediate layer than in previous tests. Both the theoretical model and new tensile strength data show that the strength of laminated glass increases with the thickness of the interlayer glass, and the strength of the laminated glass decreases with increasing temperature.

An optimized mathematical model of glass is considered in [20]. It has been proven that in some parameters, laminated glass can surpass monolithic glass. This shows that bending stress in glass layers is a determining factor for the load-carrying capacity of laminated glasses, but shear in the PVB
interlayer plays an important role in the interaction of the glass layer. A parametric study of the obtained mathematical model is carried out. Based on the analysis, a mathematical model of a triplex glass beam has been developed. The model is used to optimize the structure of light layer thicknesses. The model equations are easily solved analytically for a simply supported glass beam under a uniform transverse load, since it is statically determinative and one-dimensional. An analytical model of a triplex glass beam with a simple support under a uniform lateral load is used in the optimization process to determine the layer thickness required to provide a lightweight structure. Optimization results show that the inner layer of laminated glass under external pressure must be thinner than the outer layer of glass for lightweight architectural glazing design. Optimally designed laminated glass can be even better than monolithic glass in all respects. An alternative formula is derived based on a system of three simultaneous differential equations [21]. There are three formulas for the buckling of a laminated glass column. One gives the correct lower and upper limit, the other gives the correct lower and conservative upper limit, and the third gives the zero lower and conservative upper limit. The new formula is simple and provides engineering insight. Its output gives a dimensionless parameter that controls the transition from the lower to the upper limit. Subsequently, the initial deformation of the glass layers is taken into account, translating the problem of stability into a problem of strength, so that fracture is determined by the tensile strength. This allows direct computation of voltages and verification of unity.

An experimental study that was carried out to analyze the effect of tempering and the effect of the material and the temperature of the interlayer on the structural behavior of glass is described in article [22]. Results of this experiment: deflections can be high before glass breaks, especially in the case of one glass. The deflections of the insulating glass unit should be limited due to the tightness and watertightness, and not due to excessive deformation of adhesion due to large deformations of the insulating glass units. In-plane stresses have been shown to fail earlier than bending stresses, especially in the case of thin glass panels.

Quality control of glass structures should also apply to the material, i.e. laminated glass itself. Quality control over the production of laminated safety glass [23] is considered, as well as a comparative analysis of the traditional and axiomatic analysis of quality control in the production of laminated glass.

The topic of the polymer intermediate layer of multilayer glass and its deformability is disclosed in [24]. Due to the deformability of this layer, the rigidity and strength of the glass is usually less than that of a monolith with the same overall thickness. A practical design tool is to determine the effective thickness for deflection and stress, i.e. the thickness of an equivalent monolithic glass that corresponds to the same deflection and peak stress of the laminated glass under the same constraints and loading conditions. A new method for estimating the effective thickness is proposed. It applies to the most common design practice cases, providing synthetic tables for ease of use and immediate applicability. An overview of the standard GOST R 55988-2014 “Building structures. Expanded application of test results for fire resistance of translucent enclosing non-bearing structures”[25]. The article provides the parameters of fire resistance and classification for translucent structures in regulatory documents. Possible reasons for the destruction of sheet glass were later considered [26]. These include mechanical damage obtained during installation or during operation, as well as spontaneous destruction that occurs due to the inclusion of solid particles of nickel sulfide in the glass composition or the possible presence of particles of monolithic silicon. On the example of the Tekhnokom facade system, the indicators of fire hazard are considered [27]. As a result of the above study, compensating measures were proposed aimed at reducing the fire hazard and increasing the fire resistance of the facade system.

The study of the effect of microwave radiation (microwave electromagnetic field) is presented in article [28]. For the formation of enhanced strength properties of fiberglass products, especially in terms of bending stresses and interlayer shear, experimental studies of the effect of a microwave electromagnetic field with a frequency of 2450 MHz on the microstructure of hardened multilayer glass fiber and their bending strength have been carried out. A 60% increase in bending strength of the
samples was achieved after exposure to microwave radiation at an average power level for 2 minutes compared to controls. The reason for strengthening is an increase in the strength of the structure by increasing the contact points of the matrix and fibers during the formation of characteristic "star" structures, due to local thermal effects in the interphase zones.

3 Conclusions

This article analyzes the appearance in the Russian and foreign literature of information on load-bearing structural elements such as beams, columns or shells. Despite the fact that there are already examples of buildings using such structures, their design is still a very long, painstaking and costly process. In Russia today there is no regulatory and technical base for the design of load-bearing glass elements. There are regulatory documents: GOST R 53308-2009 “Building structures. Fire-resistance tests methods”; GOST 30733-2000 " Hard coat low emissivity glass. Specifications"; GOST 30826-2014 “Laminated glass. Specifications", which shows the calculations of glass structures, but only enclosing, but the construction industry, does not stand still and the demand of the construction market for glass supporting structures is increasing.

To design buildings with a supporting structure made of laminated glass, should know: the type of glass; this will yield important characteristics such as strength, load-bearing capacity, etc., cross-section of the glass element, type of connection, type of support, load on the element, etc. The experience of foreign colleagues in the construction and design of glass structures is much greater than in Russia. Despite the cost and labor intensity, such structures have a sufficient number of advantages for the design of glass supporting structures to begin to expand [29 -31].

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