Glass – structural material of buildings

Marcela Karmazínová and Jindrich Melcher

***Abstract*—**In the period of several last decades, glass is used not only as a transparent filling of building openings, but also as the statically and dynamically loaded civil engineering structural component. Structural glass is brittle material without elastic or elasto-plastic behaviour, so the missing pliability of the material cannot help to decrease the influence of the local stresses concentration. Also the deformations of the slab structures can significantly exceed the slab thickness, so it is necessary to apply the theory of the large deflections, i.e. geometrically nonlinear theory of the 2nd order of thin slabs. Thus, the design of load-carrying structures made of structural glass requires diametrically different approaches than in the case of conventional building materials. The paper presents some examples of the arrangement of load-carrying structural systems and inclusion of the glass components into the buildings, structural details and used basic materials. Significant parts of the verification of the reliability of structural glass systems are experiments and loading tests realized for the real load and boundary conditions and for the real composition of used materials corresponding to the verified structure. In the paper, basic typical failure modes of the components made of float glass and laminated float or tempered glass with intermediate foil. Also the examples of realized buildings using load-carrying components of structural glass are mentioned, respectively also their damage and crash.

***Keywords*—**Structural glass, float glass, tempered glass, material property, building, civil engineering, failure.

I. Introduction

THE basic classic materials of building load-carrying structures (masonry, concrete, steel, timber) are more significantly complemented (in the last period) by structural glass, which is not only traditional filling of smaller window openings, where their dimensions (thickness) arising from the long term practical experience has not been usually verified by the static assessment. Emerging trends in the architectonic creation of the buildings requiring large glazed areas of civil structures, but – on the other hand – also the possibilities of their realization related to the development of the production technology of the large scaled glass components, bring new challenges for the industry of the glass production, as well as for structural engineers.

Similarly as traditionally in the case of load-carrying civil structures, glass requires – in dependence on the support type, load intensity and material properties – the verification of the reliability, durability and effectiveness, as it is, in civil engineering practice, necessary in the case of other structural materials.

For the reasons mentioned above, the attention is paid to the research, realization and development of methods for the design and resistance of the load-carrying structures made of structural glass, over the world. For further development of the usage of load-carrying structural glass in civil engineering structures, it is important to develop the new technologies and procedures of the glass production, which are ensured by many significant producers of the diverse assortment of glass components, as well as respective supply companies.

II. Materials and Composition of Structural Glass Elements

A. Annealed Glass, Float Glass

The basic type of building glass, which can be modified and treated by tempering, staining, sandblasting and cutting, is clear float glass. The input raw material for its production is silica in the form of sand, soda in the form of carbonate and sulphate, and limestone as a stabilizer. Flat clear glass is an input raw material for the wide range of the usage of glass in building structures (interiors and claddings of buildings). The basic overview of the heat-strength treatments of float glass with appropriate technical terminology is shown in Fig. 1.

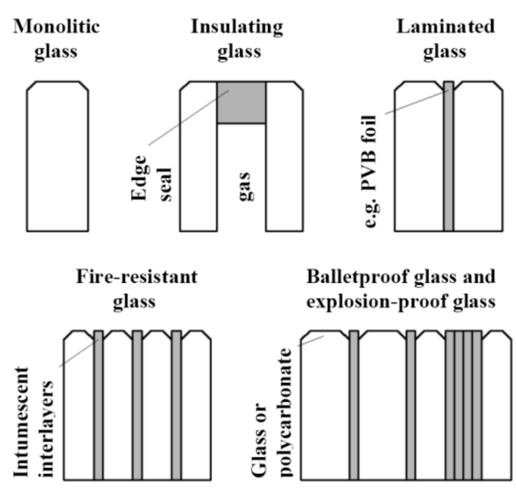

Fig. 1 composition and terminology of structural glass components

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B. Fully Tempered Glass, Toughened Glass

The increasing of the mechanical resistance of float glass can be reached using the technology of heat-toughening (tempering) that means glass is heated to the specific temperature (about 650 °C) and subsequently it is cooled by the sharp airflow. Due to the cooling, inside the structure of heat-strengthened glass the tensile stress occurs, while on the surface the compression stress occurs.

Thus, the physical properties from the viewpoint of the strength are significantly changed. In the case of breaking, glass will break into small pieces, so the risks of personal injury and property damage are minimized. The new distribution of the stress in toughened glass affects the essential change of glass properties.

Fully-tempered glass will obtain the resistance to the strike, and further, the flexural strength and thermal resistance up to 200 °C will be increased. Thanks to these properties, this glass is classified as safety glass. Glass must be finally machined (drilling holes, grinding edges, etc.) before tempering, because its further machining after toughening is not already possible.

The usage of heat-toughened glass requires significant attention from the viewpoint of the elimination of safety risks associated with keeping technological limits of dimensions and shape of the component, initial deformations and failures, details of bearing on the support structure, and so on. The special problem can also be spontaneous explosion of heat-toughened glass.

The problems mentioned above are in detail discussed, for example, in the sources [4] and [5], which define the basic causes of the failures of glass:

- the breakage of glass due to the temperature shock;
- the failure of glass due to the assembly mistake;
- the failure of glass caused by the poor machining;
- the condensation in the interspace of insulating double glass or triple glass;
- the spontaneous explosion of heat-toughened glass.

In the cases, when the risk of the spontaneous breakage of glass with nickel sulphide (NiS) inclusions is inadmissible, it is recommended to use so-called “heat-soak” test of already heat-treated glass panes. So it is practically avoided the usage of glass, which can crack without previous warning due to anomalies caused in the tempering process.

C. Heat Strengthened Glass, Partly Toughened Glass

The next type of heat-strengthened glass is semi-hardened partly toughened glass. Its mechanical properties of soda-lime-silica glass do not change during the progressive heating at least up to 200 °C and they are not influenced by the temperatures below freezing.

In the production process, glass is subjected to the special heat treatment, which is different from usual heat toughening. The temperature of glass heating and the time of the whole treatment process are different. Then, the result is glass with increased mechanical resistance (compared with float glass), and in the case of breakage, the pane is broken to the larger pieces. The resistance to the heat stress is also higher. The advantage is, that this type of glass has no nickel sulphide inclusions (NiS) and resists to the temperature difference of up 100 °C.

D. Laminated Safety Glass

Laminated safety glass is composed of two or more panes of tempered or heat-strengthened glass with the usage of intermediate foil inserted in autoclave at the temperature of about 140 °C and the pressure of 0.8 MPa. Most often used intermediate foils are polyvinyl butyral (PVB) or ethylene vinyl acetate (EVA) foils. The thickness of the foil is, according to the type, 0.38 mm or 0.76 mm.

In the case of breakage, safety glass remains glued to the foil and the personal injury and property damage are avoided. In the cases, when one of glass is not damaged, the wholeness of glass pane is maintained.

Safety glass has the application there, where it is required avoiding injury, to protect against burglary and firearms and noise protection. The combination of laminated heat-toughened glass is also used for walkable glass slabs.

Safety laminated glass with acoustic effect uses PVB foil and reaches improved characteristics for avoiding the noise spreading. The properties of this glass depend on the specific composition and combination of the glass panes and foils. The maximal value of the sound attenuation is 45 dB.

III. Principles of Design of Structural Glass Components

The default illustrative comparison of the static behaviour of glass, steel and concrete is evident from stress-strain diagrams for these materials drawn in Fig. 2. The course of those diagrams indicates the response of the relevant material to the load.

It is evident, that structural glass is ideal elastic brittle material without elastic-plastic or plastic behaviour, and thus, pliability (ductility) of the material cannot decrease the influence of the concentration of local stresses in the case of intensive loading.

From the viewpoint of the design of structural details and connections, it is necessary to eliminate the direct contact of glass and supporting steel structure, for example using plastic washers, inserts, eventually sealants or backed silicone profiles, which allow to exclude failures arising from the rigidity of locally loaded glass component.

In addition, the deflection of slab structures – particularly in the case of one-layer panes – can significantly exceed the slab thickness, so for the static analysis it is necessary to utilize the theory of the large deflections, i.e. geometrically nonlinear 2nd order theory of thin slabs, instead of the classic Kirhoff’s theory of thick slabs. In this case, the flexural effects are supplemented by the membrane components of the load in the slab plane.

The principles of the design of the load-carrying structures with the application of structural glass require markedly different approaches than in the case conventional building materials.

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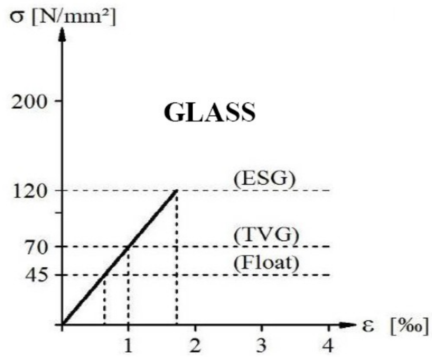
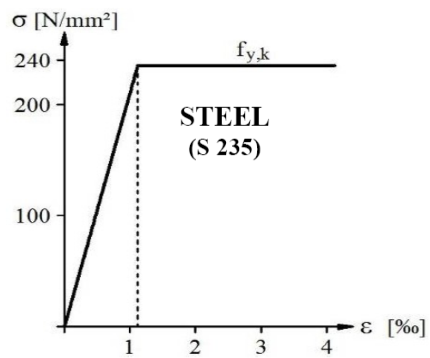
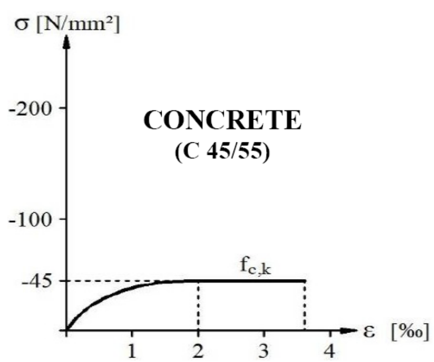


(a)



(b)



(c)

Fig. 2 characteristic stress-strain diagrams of (a) glass, (b) steel, and (c) concrete

Basic material, mechanical and physical characteristics of soda-lime-silica glass are mentioned in Table 1.

Table 1 characteristic values of soda-lime-silica glass

Quantity	Symbol	Value and unit
Density (specific weight)	ρ	2 500 $kg \cdot m^{-3}$
Young's modulus of elasticity	E	70 000 $N \cdot mm^{-2}$
Shear modulus of elasticity	G	30 000 $N \cdot mm^{-2}$
Poisson's coefficient	μ	0.23
Coefficient of thermal expansion	α	$9 \cdot 10^{-6}$ K^{-1}

The philosophy, methodology and procedures of the design of load-carrying structures for the basic materials (concrete, masonry, steel, timber, steel-concrete) are in detail elaborated and introduced in the unified European Standards (Eurocodes).

In general, for structural glass, all the principles defined in EN 1990 – Eurocode: Basis of Structural Design and EN 1991 – Eurocode 1: Loading Actions, where the principles for the loads by snow, wind, dead load, live load, etc. are mentioned, are valid.

Normative uniform European document allowing the static design of load-carrying systems with the usage of structural glass is however in the stage of the proposal and it is not definitively approved. Therefore, in this paper, informative data only, following the concept of selected procedures for the design of building structures with the usage of structural glass are mentioned, in the meaning of prepared normative documents arising from the methodology of limit states.

A. Strengths of Structural Glass

The basic characteristic strength of float glass f_{kg}, as a basic material property, can be given as the value of

$$f_{kg} = 40 \text{ N/mm}^2 \, . \tag{1}$$

The characteristic strength f_k of the component made of structural glass can be determined according to the formula

$$f_{Rk} = k_{mod} \cdot k_{sp} \cdot f_{kg} \, , \tag{2}$$

where k_{mod} is the factor of the type and duration of the load, which reaches the values in the range from 0.29 to 1.00;
k_{sp} is the factor of the type of the surface of glass component, which reaches the values in the range from 0.32 to 0.55.

The basic characteristic strength of heat-strengthened glass can be given as the value of

$$f_{kg} = 70 \text{ N/mm}^2 \, . \tag{3}$$

The basic characteristic strength of heat-toughened glass can be given as the value of

$$f_{kg} = 120 \text{ N/mm}^2 \, . \tag{4}$$

The characteristic strength of the components made of structural heat-treated glass can be in principal determined according to the same formula as for float glass, i.e. formula (2), where, similarly as in the case of float glass, k_{mod} is the factor of the type and duration of the load and k_{sp} is the factor of the type of the surface of glass component.

B. Resistance of Structural Glass Load-Carrying Systems

The verification of the resistance of load-carrying system with the usage of structural glass for the ultimate limit state can be performed according to the design reliability condition:

$$E_d \leq R_d, \tag{5}$$

where E_d is the design value of the load effect;
R_d is the design value of the resistance of the structural component or system.

The design strength f_{Rd} of the structural glass component can be determined according to the formula:

$$f_{Rd} = f_{Rk} / \gamma_M, \tag{6}$$

where the value of the reliability safety factor γ_M is recommended to take as

$$\gamma_M = 1.2. \tag{7}$$

From the viewpoint of the serviceability limit state, the permissible values of the deflections δ_{lim} are given as (up to)

$$\delta_{lim} = L / 100, \tag{8}$$

where L is the span of the component between supported edges.

All the indicated design factors, material characteristics and reliability coefficients will be more in detail defined after the approval of the prepared European document EN 13474 Glass in Civil Engineering.

In conclusion of this paragraph, it should be noted, that it is not recommended to use and design the thickness of one layer of load-carrying structural glass less than 3 mm and greater than 25 mm.

IV. Selected Examples of Realizations and Studies

The development of the use of the building load-carrying systems with the application of structural glass is further indicated by the selection of illustrative examples of buildings and project studies realized over the world, but also in the Czech Republic.

Fig. 3 stairs in Audio-Video Shopping Center, New York

The glass stair, suitably integrated to the interior of the Audio-Video Centre in San Francisco, is shown in Fig. 3 (photo J. Melcher). Glass does not prevent the vista to the internal space of the building. The stair grades, as well as the vertical supporting structure stiffened by supporting transverse ribs, are designed and made of glass. Transverse stiffening ribs are necessary, with respect to the insurance of the resistance of the high slender wall subjected to the vertical compression load.

Fig. 4 Juilliard School in Lincoln Center, New York

The structures in the areas of Lincoln Centre in New York stiffened by twisted rope are illustrated in Fig. 4. Partition peripheral or external walls or, eventually, railing fillings without significant effects of the basic loadings (vertical load, wind, and so on) shall be assessed according to the technical document ČSN EN 12600 Glass in Civil Engineering – Shuttle Test – Method of Impact Test (ČNI Prague, 2003) and ČSN 74 3305 Protective railings (ČNI Prague, 2008).

High glazed peripheral building walls – with respect to the significant effects of the wind load (compression or sucking) – shall be necessarily stiffened by the steel load-carrying structure, which create the support system of peripheral glass cladding.

(a) (b)

Fig. 5 (a) wall in Waterloo Station, London; (b) hall of International Forum, Tokyo

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In Fig. 5 (a) (photo J. Melcher), the structure of the glazed wall in the area of Waterloo Station in London, with the steel support structure, which is created by the truss system with ties and struts placed both outside and inside the building, is shown. In Fig. 5 (b) (photo J. Melcher), the structure of the glazed wall of so-called Glass Hall in the areas of the International Forum in Tokyo, with steel support structure, created by the truss system with ties and struts placed inside the building, is shown.

From the shots mentioned the arrangement of the relevant structural system is evident, and mentioned examples indicate large diversity of the composition and structural design of load-carrying systems with the usage of structural glass.

The illustration of the successful usage of structural glass in the Czech Republic is the oblique façade of the store Sykora Home Prague [6] in Fig. 6. The wall of the façade is along the top line inclined from the vertical plane. The laminated glass panels are through the targets anchored to the steel load-carrying structure created by lattice crosspieces, which are supported by steel columns inclined in parallel with the façade. The lattice tube crosspieces are supported by the system of rectifiable parallel ties DETAN.

Fig. 6 structure of oblique façade of Sykora Home building, Prague

The example of the usage of structural glass for the roofing of the platform of bus station near the railway station Ostrava – Svinov is shown in Fig. 7. The work has been ensured by the company METALPROGRES Inc. Tetčice, and on the base of this, the experimental programme [7], [9] of the verification of load-carrying capacity and deformations of the panels made of structural glass corresponding the real composition and supporting of test specimens, has been realized. Relevant loading tests are more in detail mentioned below in the chapter 5.

The roofing component made of two-layer tempered glass with intermediate foil showed the possibility of the fall of glass slab to the covered space in the case of the failure around metal targets. With regards to otherwise favourable deformation and strength characteristics of proposed composition of roofing panel, it can be effective, to eliminate this problem by supplementary technical modification, which will exclude the fall of the failed specimens. The proposed modification lies in the inserting protective rope (see Fig. 7) under glass slab. The rope is anchored to the shackles in the axis of the bolts of circle connecting plates, and it is lead diagonally and further along the line connecting four support nodes of glass slab. The utilized steel rope had the diameter of 5 mm; in general it is enough to design the rope according to the corresponding self weight and the number of the hangings. The failed pane composed of laminated tempered glass is detained by the protective rope, it remains undivided thanks to the stiffening effect of the foil and in addition, it is capable of transport and manipulation when replacing.

Fig. 7 roofing of platform of bus station, Ostrava - Svinov

In the period of the last years, the usage of the large-scale glazed façades of buildings has been significantly spread. Their necessary stiffening, in relation to the adverse effects of compression and sucking of the wind, is ensured by the transverse glass ribs, so-called fins, which are inserted, in parallel in the certain distances, into the façade system.

Various possibilities of the composition of the glass walls of the mentioned type are documented by the examples of the realizations over the world, but also in the Czech Republic.

(a) (b)

Fig. 8 (a) South Bank University, London; (b) Holiday Inn, Paris

Fig. 8 (a) shows the shot of the structural glass wall stiffened by transverse glass ribs in the building of London South Bank University. Another example of the similar solution of the restaurant glass wall in Holiday Inn Hotel in Paris is shown in Fig. 8 (b) (photo J. Melcher). Further, the solution realized in Burj Al Arab Hotel in Dubai is illustrated in Fig. 9, and finally, the glass wall in the building of Harbour Grand Kowloon Hotel in Hong Kong is in Fig. 10 (photo J. Melcher).

Fig. 9 Burj Al Arab Hotel, Dubai

Fig. 10 Harbour Grand Kowloon Hotel, Hong Kong

From the structures of the similar type realized in the Czech Republic, it is documented the glass façade stiffened by transverse ribs, which lines the stairs tower of the new building of the Faculty of Civil Engineering of Technical University of Ostrava, as indicated in Fig. 11 (photo J. Melcher). This work was tasked by the company TOLZA, Ltd., Brno. The tests of the connection of the transverse rib to the façade of the type of “metal plate – glass” with the usage of two-component silicon sealant, have been performed, as illustrated in Fig. 12.

The specimens with surface treated by powder-coated Al-profile, with coating represented by polyester thermoset powder of PE GREY RAL7015 GLOSS, or eventually, powder coating of Interpol D1036 Lesk 85, showed the satisfactory adhesion of sealant to metal and glass, and the failure always occurred on the shear area going through silicon part of the specimen – for more see e.g. [8].

Fig. 11 structural glass façade stiffened by transverse ribs – Faculty of Civil Engineering, Technical University of Ostrava

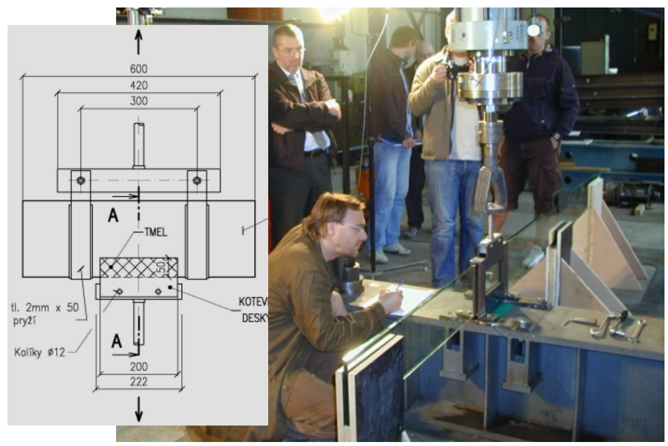

Fig. 12 tests of sealant for glass façade for Faculty of Civil Engineering, Technical University of Ostrava

The special structural group with the usage of exposed load-carrying glass components are large aquariums in the areas of ZOOs or social centres.

Fig. 13 aquarium on area of exposition of ZOO Park

The example of the aquarium in the interior of the building of ZOO Park is shown in Fig. 13. Probably due to the imperfect structural solution of the spot support of the load-carrying structure near the edge of the glass wall, the aquarium has been failed when filling by water, as evident from Fig. 14 (photo J. Melcher). The vertical wall of the aquarium composed of laminated glass with the thickness of 3 x 8 = 24 mm with inserted intermediate PVB foil had the width of 4 800 mm and the height of 2 800 mm. It was divided by vertical gaps, at the thirds of the length filled by silicon sealant. The illustrative utilization of ANSYS software (J. Kala) for the elaboration of the expertise of the crash is briefly shown in Fig. 15.

Fig. 14 damage of aquarium after filling by water

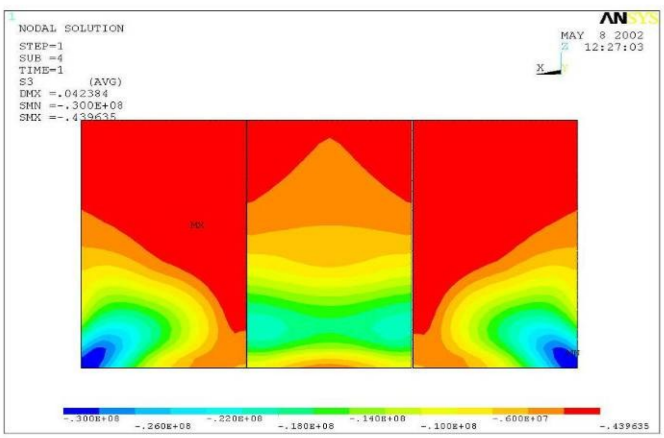

Fig. 15 illustrative utilization of ANSYS software for elaboration of static assessment

In this connection it is also interesting to mention the transparent wall of the greatest world aquarium in the shopping centre Dubai Mall in Dubai illustrated in Fig. 16.

The transparent front wall has the width of 32.88 m, the height of 8.3 m and the thickness of 750 mm. The weight of the wall is 245 614 kg. Technically it is not the material corresponding building glass, although it is sometimes marked as acrylic glass. Chemically it is the transparent thermoplastic PMMA (polymethylmethacrylate), often used as an alternative to glass, characterized by the small weight and the high resistance to the fragmentation failure. Its widening in the practice has been introduced after 1933 year under the trademark Plexiglass, later ACRYLITE®, Lucite and Perspex.

Fig. 16 aquarium in shopping centre Dubai Mall

V. Verification Experiments and Structural Glass Components Testing

The authors' workplace, i.e. the Department of Metal and Timber Structures of the Faculty of Civil Engineering at Brno University of Technology (BUT), pays long term attention to the verification of the resistance and analysis of the actual behaviour of load-carrying structural components and systems composed of steel, timber, steel-concrete, glass-fibre-concrete, glass, combined structures and also composites, eventually other materials, with considering the influence of their imperfections (geometrical, structural and constructional) – see e.g. [9], [7] and [10] to [20].

This tradition, which is continuously following, has been already introduced under the action of Professor Ferdinand Lederer on the authors' workplace, together with the accent to the questions of the theory, calculation methods and static and structural design of the load-carrying components and systems made of these materials.

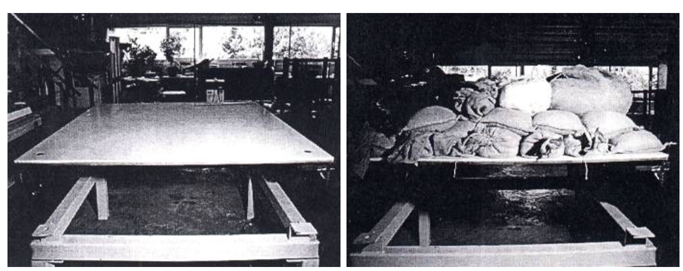

Fig. 17 traditional method of uniform loading of planar components

Within the loading of the structural glass load-carrying components, the primary problem is the realization of the full uniform load simulating compression or sucking of the wind, eventually snow load. The loading process should allow

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monitoring and recording the deflections, and also damage of tested specimens in the progress of increasing or decreasing the load.

It is evident, that the traditional method of the loading of the planar structural components by full uniform load using weighed ballast gradually loaded at the tested specimen, used sometimes even at the front foreign research or university workplaces (see Fig. 17), is imperfect and unsuitable method for the verification of the actual behaviour of the glass panes.

In the testing room of the Department of Metal and Timber Structures of the Faculty of Civil Engineering at BUT, the new efficient so-called vacuum test method allowing the uniform loading of the planar structural components, has been developed after 1980 year. Fig. 18 shows one of the first experiments of the type mentioned, used for the verification test of the resistance of glass fill of the railing of the bridge of Vysočina at Velké Meziříčí (given by the task of A. Pechal), to the uniform load corresponding the effects of compression or sucking of the wind.

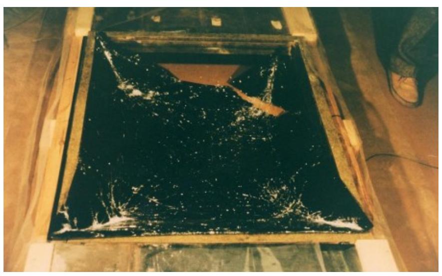

Fig. 18 loading test of railing fill – bridge of Vysočina

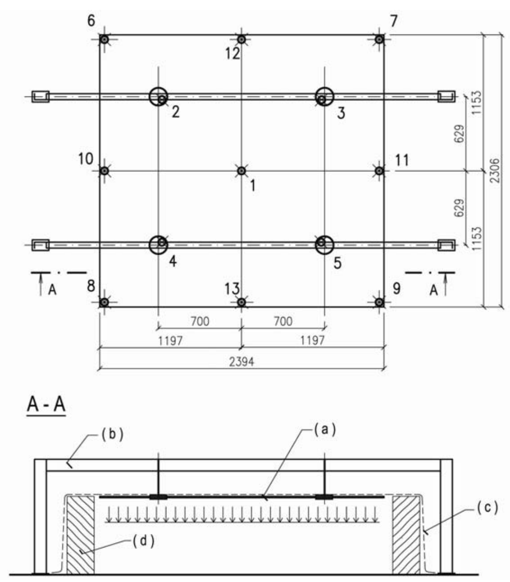

Fig. 19 scheme of arrangement of vacuum loading test of structural glass planar component

The basic scheme of the arrangement of the vacuuming in the loading test of the structural glass component is shown in Fig. 19. The component tested (a) is supported as corresponds with the real structure, for example line supports or single support nodes or targets (c), anchored to the helping frames, similarly as in the real load-carrying system. The slab specimen supported as mentioned, is installed to the separate testing box (d) represented by the rigid peripheral timber frame, and the tested specimen together with the box are covered by the transparent plastic foil (c) glued to the stiffened floor of the testing room. The floor must be stiffened, with regards to the significant effect of sucking in the closed testing box.

From the space closed under the transparent foil the air is sucked, and then, the tested specimen is ideally uniformly loaded by the effect of the atmospheric overpressure. The overpressure is measured by the electrical sensor with the digital pressure gauge, and in parallel, for checking, it is verified using the liquid barometer. The regime of the uniform loading and reloading may be simply regulated and the load intensity is determined measuring the overpressure between the external environment and the space closed by foil. The illustrative shot of the real test of vacuum loading of structural glass is in Fig. 20.

Fig. 20 illustration of arrangement of real test of structural glass

Fig. 21 failure of single-layer float glass – test specimen T1

Fig. 22 failure of single-layer float glass – test specimen T1

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Experiments verifying the actual behaviour of the glass components allow analysing the deformations (deflections) and the ultimate load-carrying capacity, as well as the failure mechanism in dependence on various material and structural composition of the glass component.

Fig. 23 failure of laminated float glass – test specimens T3, T4

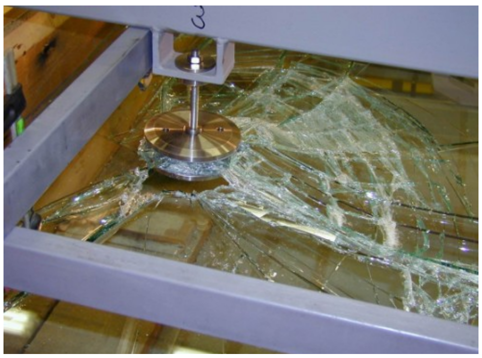


Fig. 24 typical failure around local target support – specimens T3, T4

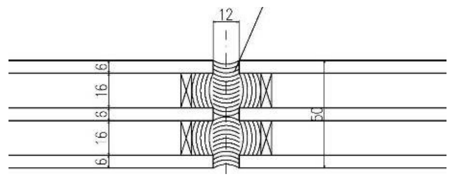
Fig. 25 failure of laminated tempered glass – test specimens T5, T6

Fig. 26 influence of safety rope on failure of specimens T5, T6

Characteristic examples of the failure of the glass specimens tested within the research programme [7], [9] are, for the illustration, indicated in figures below. Failure of the test specimen made of single-layer tempered glass (T1) is characterized by breaking up to small fragments – see Fig. 21.

The test specimen made of laminated double-layer tempered glass (T2) has been failed by tearing from the supporting targets and by the subsequent falling of the whole specimen – see Fig. 22. The essentially different failure mechanisms of the test specimens made of laminated float glass (T3, T4) and laminated tempered glass with intermediate foil (T5, T6) are evident from the shots in Figs. 23 and 24, in comparison with Figs. 25 and 26.

On the base of tests realized on the authors' workplace, the failure mechanism of the component made of structural glass of different composition arrangement is indicated further. It is the wall component made of insulating triple-layer glass in the arrangement according to Fig. 27 (a). The tests have been realized for the company GLASS EXPERTS, Ltd., Žlutice.



(a)

(b)

Fig. 27 loading test of pane made of insulating triple-layer glass: (a) composition of glass component; (b) failure of glass component

On the base of the tests realized on the authors' workplace, the failure mechanism of the component made of structural glass of different composition arrangement is indicated further. It is the wall component made of insulating triple-layer glass in the arrangement according to Fig. 27 (a). The tests have been realized for the company GLASS EXPERTS, Ltd., Žlutice.

The test specimen is the wall component made of structural float glass created by 3 parallel elements with the thickness of 3 x 6 mm, the width of 700 mm and the length of 2 470 mm, which are connected by structural silicon on the longitudinal sides. The glass part of the test specimen is on the perimeter mounted in the steel frame, the basic part of which is represented by the square hollow thin-walled cross-section with the dimensions of 60 x 60 x 4 mm.

The failure occurs suddenly, at the initiation of the fracture of glass due to the deformation in the area of the anchorage of glass panes into the rigid peripheral steel frame. The character of the failure corresponds to the unfavourable arrangement of used float glass, as illustrated in Fig. 27 (b).

VI. Experimental Verification of Stiffness Parameters of Structural Glass

Within the loading tests of the structural glass panes intended for the roofing bus station platform (see above), the verification of stiffness parameters of glass has also been performed, to verify the actual values of Young's modulus of elasticity and, in the case of laminated double-layer glass, the actual values of the flexural stiffness and from these arising the actual values of the second moments of area influenced by the non-stiff connection between glass layers given by the intermediate foil.

According to the producer of glass plated structural components mentioned above, the value of Young's modulus of elasticity of glass has been recommended as E = 70 GPa, but this is only generally considered value, which has not been verified by the producer. Therefore before the loading tests, the experimental verification of the Young's modulus has been performed at first. In this connection, as the second one, it was to verify the flexural stiffness of the test specimens with regards to their composition (laminated glass with the intermediate foil) and the production technology of glass.

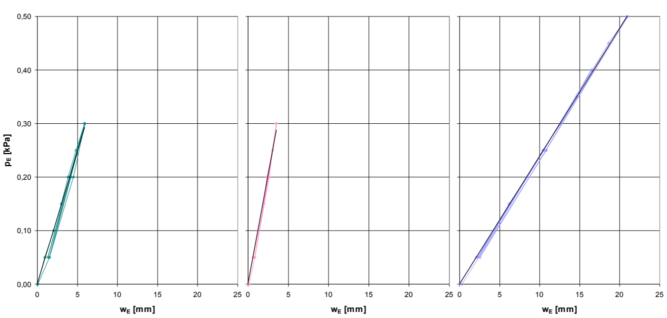


Fig. 28 relationships *"$p_E - w_E$"* obtained directly from tests

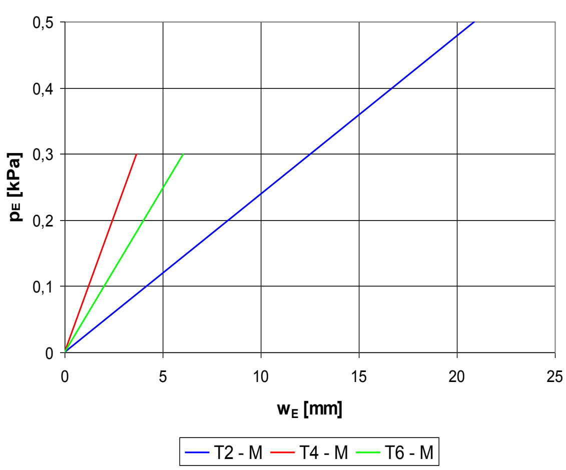


Fig. 29 relationships for stiffness derivation

For this reason, the test specimens have been supported on the shorter opposite sides of the plate, as the simply supported structural members. The theoretical span of the member was 2 294 mm. The specimens have been subjected to the uniform loading up to the load value about of 10 % of the predicted load-carrying capacity. The specimens have been repeatedly loaded and unloaded and the relationships of "load – deflection" (*"$p_E - w_E$"*) have been monitored. The *"$p_E - w_E$"* relationships obtained from the tests for all test specimens are illustrated in Fig. 28. Using the regression analysis, the linear relationships have been derived (see Fig. 29). From them, Young's modulus of elasticity, the flexural stiffness, and the effective second moment of area can be determined (Table 2).

Table 2 stiffness parameters (per width of 1 m)

Specimen	T1, T2	T5, T6	T3, T4
$E\ I_{eff}$ [Nmm^{-2}]	$8.654\cdot10^9$	$18.029\cdot10^9$	$29.568\cdot10^9$
$I = 1/12\ bt^3$ [mm^4] x)	$144\cdot10^3$	$341\cdot10^3$	$667\cdot10^3$
k ($I_{eff} = k\ I$)	1.0	**0.879**	0.879
E [GPa]	**60.1**	60.1	**50.5**

x) t is total thickness of layered glass (12 mm, 2x8 mm, 2x10 mm)

Using the relationship between the load p_E and corresponding deflection w_E in the mid-span, the effective flexural stiffness $EI_{eff,1}$ can be derived, if E is the modulus of elasticity and $I_{eff,1}$ is the effective second moment of area. For single-layer tempered glass (test specimens T1, T2), the effective second moment of area is in the form of $I_{eff,1} = \mathrm{I} = 1/12\ (b\cdot t^3)$, thus $k = I_{eff} / I = 1$, and from where the modulus of elasticity E of tempered glass can be derived directly. Using this value of the elasticity modulus for tempered layered glass (tempered glass of the same mechanical properties) with intermediate foil (test specimens T5, T6), and using the stiffness EI_{eff}, the effective second moment of area of double-layer glass can be derived as $I_{eff} = k\ I$, where the coefficient k expresses the reduction of the second moment of area I considered for the solid cross-section with the thickness of t, due to the influence of the pliability of the foil connection. Assuming, that also for laminated non-tempered glass (test specimens T3, T4) the influence of the foil on the effective second moment of area may be expressed by the same coefficient of the pliability k, then the (at least tentative) value of the elasticity modulus of non-tempered glass can be derived.

VII. Conclusions

Structural glass is already the important part of the wide spectrum of the materials of load-carrying structures of civil engineering buildings over the world and also in the Czech Republic. Nevertheless, the typical examples mentioned above cannot systematically illustrate all the possibilities of the structural composition and structural detailing from the

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viewpoint of the usage of glass in civil engineering structures, but they can indicate the modern trends of the architectonic creation of the buildings requiring the large glazed areas of civil engineering structures and also the possibilities of their realization in the connection with the development of the production technology of the large scale glass components and with the new challenges for the industry of the glass production, as well as for the structural engineers.

The paper was focused on the significant field of the design and realization of buildings with the application of structural glass including the verification of the dimensions of the glass components in relation to the material, load intensity and boundary conditions on the one hand, and the verification of the theoretical assumptions and design methods through the experiments and loading tests taking into account the influence of the initial imperfections of the real load-carrying system on the other hand.

The general philosophy and methodology of the static and structural design of buildings using structural glass arises from the similar general principles, as in the case of other materials of load-carrying structures. However, glass has many fundamentally different properties that can influence its behaviour in the structure (thermal shock, failures of glass caused by the material inhomogeneity due to the inclusions, spontaneous explosion, material brittleness without elasto-plastic or plastic behaviour and without the possibility to decrease the influence of the concentrations of local stresses, necessity of the utilization of geometrically non-linear 2nd order theory of thin slabs, etc.). This paper thus also tried at least briefly to warn to some problems mentioned above, requiring more detailed consideration and cognition.

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