EVALUATION OF GLASS IN DESIGN OF LOAD BEARING STRUCTURES

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ABSTRACT

Transparent glass staircase landings platforms are one of the load bearing structural components which do t not have established design practice by national or international codes. Experimental tests are practically only option to assess the behavior of glass and to certificate it. Glass may be assumed as isotropic material; mechanical properties do not depend on direction for orientation thus easy for modeling. The main issue once designing staircase landings assumptions of critical stress in particular as tensile and in certain extend bending strength of glass is not a constant value. This stress level depending on glass type, location of the load and glass laminate panel compilation. This paper presents the assessment of the existing design practice in contrary to physical experiments of single glass stair landing plate. In order to perform an optimization task, different kinds of glass samples have been tested in 4-point bending using testing equipment INSTRON 8802. Bending test settings are correspond to LVS EN 1288-3 standard requirements and based on similar research performed earlier at DTU Netherlands. The results demonstrated that the glass mechanical and physical properties such as Young's modulus, the Poisson ratio and the density, of the annealed and tempered glass are practically the same nevertheless the bending stress is dependent on glass type.

Key words: glass, 4-point bending, tempered glass, annealed glass, finite element analysis

INTRODUCTION

In 21st century the glass is not anymore considered just as a material for producing household goods, but becoming a material widely utilised in load bearing structures. This is due fact that production quality has improved dramatically and building industry has progressed like never before.

Initially glass as material is obtained liquid cooled to the rigid state without crystallizing. Raw materials for glass production are 75% silicia (SIO_2), sodium oxide Na_2O from soda ash, lime CaO, and several minor additives. (Button, 1993) In the production process all ingredients were heated at a temperature much higher than 1200^0C. (Button, 1993) The main advantage of the application of glass is its high mechanical and physical properties. At the same time glass is well known for its fragile and brittle/ instantaneous collapse behaviour which does not encourage designers to sufficiently exploit glass material.

This is due fact that at higher levels of stress most materials deform plastically, that is the atoms or molecules in the structure become rearranged or crystals slide past each other. These materials can often accommodate large strains without failure, although they may be permanently deformed. (Button, 1993) The structure of glass cannot accommodate this plastic deformation, so the stress-strain curves for glass show perfect linearity. (Button, 1993) Such behaviour is easy to simulate in modern analysis codes, however requires robust and reliable knowledge of glass failure stress levels.

General ceramic including glass material properties are described by U.S. researchers Marshall W. and Rudnicki A. (Marshall et al.) which are basis of defining character of the glass. Mathematical calculations for determination of mechanical properties from 3 and 4 point bending tests, assuming that samples have a square cross-section have been developed by Davies G.S. (1972) (Davies, 1973). Moreover, this approach has been extended for circular cross-section by Kittl.P (1978), Medrano R.E and Grills P.P (1978) (Kittl, 1980). There are several alternative bending methods, for example, one of the most specific test method is "Brazil" disk test method, described by Handros G. (1974) and Oh. K.P. and co-authors (1973) (Migliore et al., 1996).

Glass brittle failure is the reason why it is necessary to clarify the failure strength of glass in bending. Delft University of Technology had developed a whole series of glass bending tests. F.A. Veer (Veer, 2007) main research related to the bending strength for different types of glass samples in 4 point bending, setting the average failure stress values, which depend on the sample size. Bending tests values can be employed for load- bearing structural calculation, which display actual situation for glass's behaviour.

For tailor made glass designs, one may require curved glass which do change the mechanical performance of the glass. J.Belis, et. al. have set an experimental study investigating curved glass to design for design "cold bending" processing (Belis et al., 2007).

Recent research by Maria Froling (Froling, 2011) has demonstrated the advanced strength design approach for laminated glass, applying numerical solid-shell element of the commercial finite element software ABAQUS and established the maximum principal stresses for laminated glass samples with holes for bolt binding.

MATERIALS AND METHODS

FEM solution

For the highest design reliability, particularly when applying a material which is not commonly utilized by civil engineers, one of strategies is to employ a detailed design finite element engineering simulation software. This creates an alternative to physical test as set up of a numerical model has to be prepared as close to the actual physical model as possible. The finite element method (*FEM*) software *ANSYS 11.0* was utilized for simulation as it has sole potential for design of various complexity structural components. In *ANSYS* code the model is divided into finite elements for analyzing thin to moderately thick shell structures (Figure 1), in the current research the 4-node *SHELL 181* elements.

The main goal was verify the numerical results against the experimental test data.

A single glass sheet has been tested initially and then manufactured glass laminate decks composed from two to three glass sheets. Mechanical properties which has been assumed in numerical simulation were density *ρ=2500kg/m3* (prEN 13474-3, 2008), Young Modulus *E=70kN/mm2* (prEN 13474-3, 2008) and Poisson's ratio *ν=0.23* (prEN 13474-3, 2008).

Experimental investigation

All glass panels have been tested in 4- point bending set up according to LVS EN 1288-3:2001 (LVS EN 1288-3, 2001) at the Riga Technical University, Institute of Materials and Structures (*IMS*). For bending tests was utilised *INSTRON 8802* testing machine (Figure 2), which can perform tests in tension, compression, bending and fatigue. It can be set up to do static and dynamic loads up to a maximum load of 250 kN.

Glass panel samples of size L_p= *1100 mm±5mm* long and b_p=*360mm±5mm* wide were cut from a single glass plate with a thickness of 10 mm (h_p). These were industrially cut on cutting machines and finished by grinding and polishing as required for the best quality glass product. The distance between supports was assumed to be constant of 1000 mm and the distance between the loading points set 200 mm.

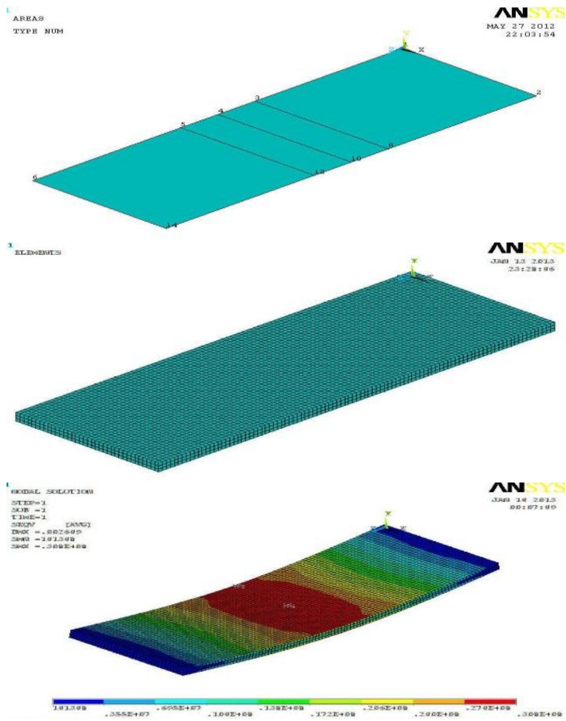


Figure 1. a) model geometry; b) FE meshed structure; c) deformed state

All specimens were divided in three groups for tests (Figure 2a): annealed float glass without polishing edges (*AN*); annealed glass with polishing edges (*AP*); tempered glass (*T*).

After estimation of the mechanical behaviour of each type of glass samples, these sheets were laminated in given combinations (Table 1). A glass laminate test set up is given in (Figure 2b).

Table 1

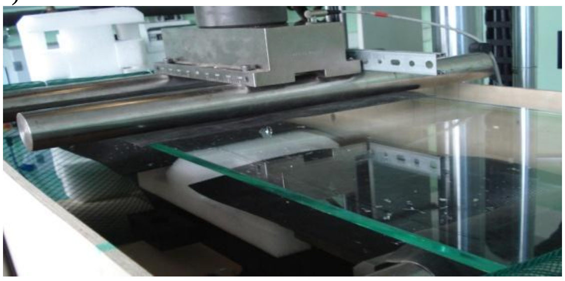
Laminated glass samples

	*T* A^+ *T*	A^+ *T* A^+	A^+ A^+ *T*	*T* A^+	A^- A^- A^-
Number of samples	1	1	1	1	2

where T-tempered glass;
A-annealed glass;
+-with polishing edges;
--without polishing edges.

The main emphasis for testing of glass laminates in four point bending set up, was establishing the strength relationship among tempered and annealed glasses. Estimated mechanical behavior confirmed that stiffness properties are similar among these two glass types.

a)



b)

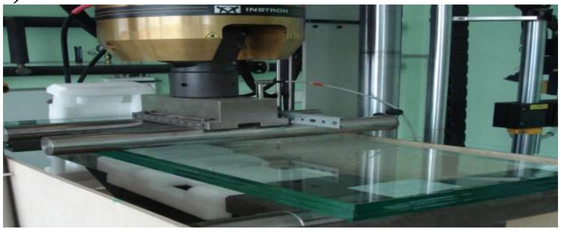


Figure 2. a) single glass sheet sample b) laminated glass sample in bending test set up (INSTRON 8802)

RESULTS AND DISCUSSION

Single glass sheet samples

Indeed it is evidently that glass is brittle and once reaching the ultimate load fails instantly. It would be of advantage if one may determinate the cause of the failure for glass only from size and shape of broken glass samples as it is for concrete samples. One of the factors influencing load carrying capacity of glass is micro cracks (Button, 1993). Conventional glass cutting is done by "scoring" and breaking which produces micro-cracks (Mangeron, 2010) an alternative is stress concentration during the transportation and handling. Even if they are up to 100 micro meters, it may be sufficient reason for the reduction in bending strength of the glass, especially vital in load-bearing structures.

During the physical experiments, before sample has been placed in bench, it has been visually examined whether annealed glass edges hasn`t been damaged during the transportation. After examining, it was concluded that no visual damage had been observed, so it can be assumed that the samples could be accepted for testing of mechanical properties.

Once brittle fracture was observed the annealed float glass samples without polished edges (Figure 3.a) crumbled into tiny, incisive, elongated fragments, forming a triangle or rectangular-shaped area at the site where the load has been applied. The sample of span length of about 30 cm in width remained solid. It suggests that this type of glass breaks in areas where stress concentrations have accrued.

Table 2

Test results for annealed glass samples without polishing edges

Number of test	Failure load F_{max} [N]	Deflection u [mm]	Young's Modulus E [GPa]	Bending strength F_m[MPa]
1AN	692	6.1	94.6	23.1
2AN	1 467	12.9	92.0	48.9
3AN	1 549	13.6	89.5	51.6
4AN	948	8.3	93.6	31.6
5AN	1 021	9.1	90.7	34.0
6AN	990	8.7	93.8	33.0

In the next step annealed glass samples were tested (Figure 3.b). It should be noted that specimen had polished edges which basically eliminates any possibility of micro cracks. Bending strength of this type of glass samples resulted in load-bearing capacity increment of 1.5 times higher than initial sample (Table 3).

This finding may suggest that the glass is one of those materials, whose behaviour of the load response depends on the quality of the glass. For samples with polished edges one may observe a small inconsistency of the results, thus one recommendation may be concluded that special attention should be given to sample preparation. Furthermore, annealed glass samples with polished edges once failed, form a set of small, elongated and sharp pieces, under load, but unlike the previous panels, these samples are of collapse were larger with size range from a few mm to 20 cm.

Table 3

Test results for annealed glass samples with polishing edges

Number of test	Failure load F_{max} [N]	Deflection u [mm]	Young's Modulus E [GPa]	Bending strength F_m[MPa]
1AP	1 664	13.4	92.1	55.5
2AP	1 497	13.3	89.2	50.0
3AP	1 709	15.0	92.1	57.0
4AP	2 031	17.9	91.8	67.7
5AP	1 242	11.0	104.5	41.4
6AP	1 609	14.1	117.0	53.6

Finally one may observe that tempered glass (Figure 3.c) bending strength is almost twice higher than annealed glass (Table 3). Meanwhile, one may see that once reaching the maximum bending stress the sample broke into enormous small around 2-5 mm to 2 cm "crystals", Such result was observed in five samples out of six in each set (Table 4). The modulus of elasticity of glass is typically assumed to be 70 GPa, only about a third of that of steel but five times greater than hardwood. (Wurm, 2007) It should be noted that after thermal enhancement of glass the Young's modulus doesn't change (Table2) or the difference is insignificant. For tempered and annealed glass modulus of elasticity it may be assumed exactly the same. In present research the tests average value for modulus of elasticity is 88 ±6 GPa.

Table 4

Test results for tempered glass

Number of test	Failure load F_{max} [N]	Deflection u [mm]	Young's Modulus E [GPa]	Bending strength Fm[MPa]
1T	3 764	30.3	79.0	125.5
2T	4 243	38.2	74.7	141.4
3T	3 458	30.6	72.8	115.3
4T	3 974	35.5	75.1	132.5
5T	4 390	39.0	72.9	146.3
6T	3 896	34.4	75.2	129.9

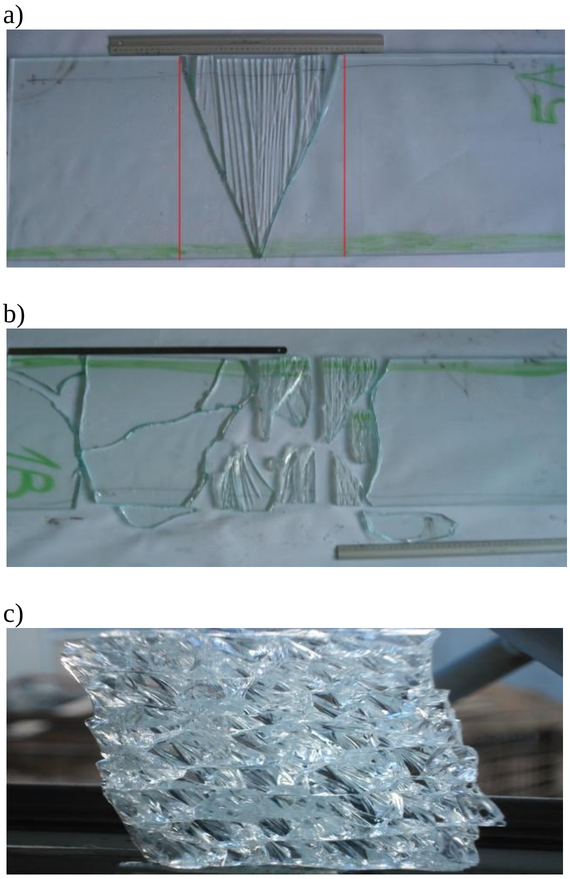


Figure 3. Samples after testing a) annealed glass without polishing edges, b) annealed glass with polishing glass, c) tempered glass

Laminated glass samples

The current Latvian legislation has not developed rules which provide a combination for glass (tempered and annealed) for load bearing structural applications. In European for design of staircase landings the choice is made to apply the annealed glass only because, the strength of the laminate is sufficient and these types of glasses do not contain nickel sulphide (Barry) in contrary to tempered glass.

Table 5

Test results for laminated glass

Number of test	Thickness h_1 [mm]	Failure load F_{max} [N]	Deflection u_1 [mm]	Bending strength *Fm1* [MPa]
TAT	32.58	20 002	21.1	157.0
ATA	32.85	9 006	7.0	69.5
AAT	32.63	7 398	22.5	57.9
TA	21.30	2 825	6.4	51.9
AAA	33.29	8 513	6.8	64.0
AAA	33.28	8 557	6.8	64.4

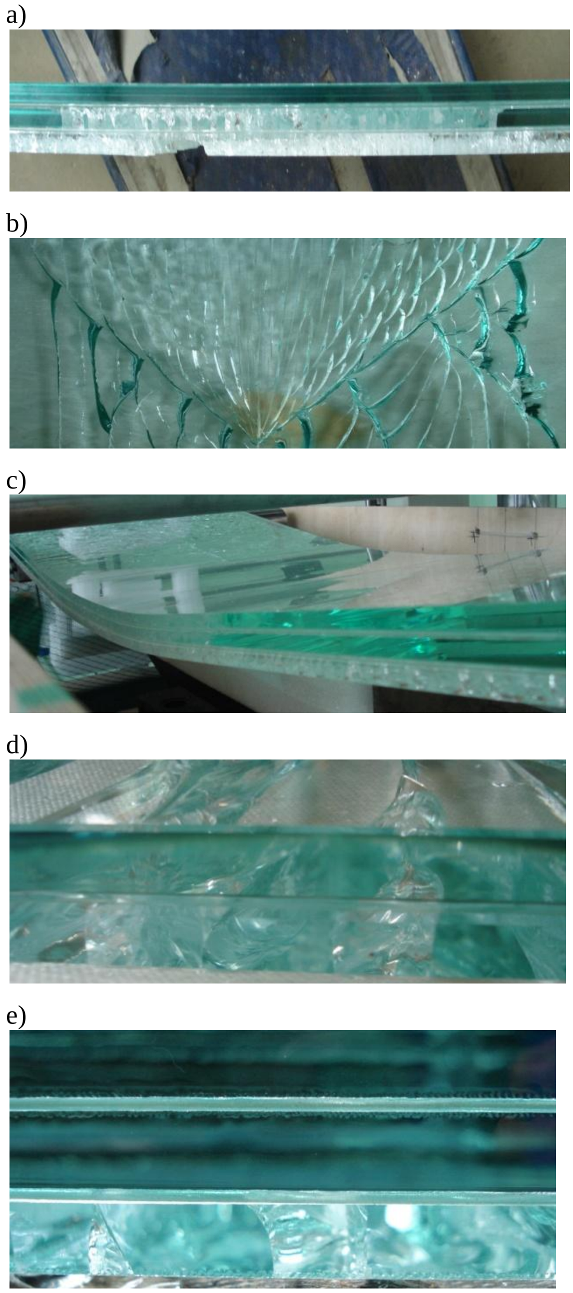


Figure 4. Laminated samples after testing a) *TAT*, b) *ATA*, c) *AAT*, d) *TA*, e) *AAA*

Laminated glasses typically consist of three glass plates bonded by a polyvinyl butyral (PVB) interlayer (Table1). This kind of combination is the

basis for glass stair step, so it was important to conduct an experiment and find the corresponding behaviour in bending.
One may observe that the best combinations are that in which in tension zone tempered glass sheet was placed (Table5).Such a solution provides tension zone stability (Figure 4a, 4c).
Once inserting an annealed glass between two tempered glasses (Figure 4a) as middle layer is unable to hold high bending strength which was generated in the top and bottom tempered glass sheets. All laminate samples has crashed in a they characteristic manner as described in previously test (Figure 4b, 4d).
Figure 5,6,7 summarise verification among the physical test and numerical model showing that the calculation is identically corresponding to single sheet glass (Figure 5) panel only. A laminate consisting of two (Figure 6) or three (Figure7) sheets, should be modelled involving a thin polymer thin film as there is no sufficient stiffness if adhesive film layer. It should be noted that those plies haven't been considerate in the FE simulation. Thus differences in response can be observed in the bending stiffness. For further studies both adhesive film properties and failure criteria should be implemented in this preliminary study.

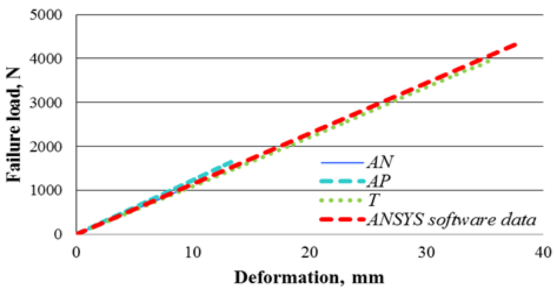


Figure 5. Experimental data compared with *ANSYS* results for single sheet glass samples

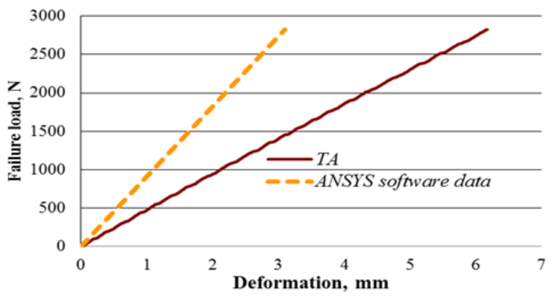


Figure 6. Experimental data compared with *ANSYS* results for two layers samples

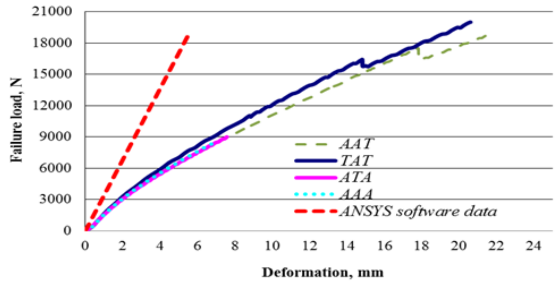


Figure 7. Experimental data compared with *ANSYS* results for three layers samples

Metamodelling approach

Metamodelling is a set of tools, based on design of experiments and approximation of mathematical model of the system. Approximation model should be unsophisticated enough to guarantee short calculation times at the same time keeping sufficient prediction accuracy – for example determined applying cross-validation error estimation. The main steps in design optimization process employing metamodels are: a) defining the design space of the experiments, b) selecting factors (independent variables) and responses (dependent variables), c) setting levels of each factor according prescribed plan of experiments, d) conducting of experiments and recording the system behaviour, e) approximation of system responses, f) minimizing or maximizing responses using approximation model, g) development of recommendations for further product modification.
For creating of efficient design guidelines, three cross-section parameters of the plate have been defined in Table 6.

Table 6

Domain of interest

Parameters	Units	Lower bound	Upper bound
Length *L*	m	0.6	2.4
Width *B*	m	0.22	0.4
Thickness *T1, T2*	m	0.003	0.019

Design of experiments was made employing Latin Hypercube design with Mean Square Error (MSE) space filling criteria in order to uniformly redistribute the points inside domain of interests.
In order to obtain statistically reliable mathematical approximation functions it is necessary to carry out a definite number of numerical experiments. *EdaOpt* (Auzins, 2007) optimisation software was used to create experimental design with 120 and 140 experiments and 3 variables. For approximation purposes freeware software *VariReg* was utilised with ability to approximate experimental data by full or partial polynomials and Kriging. Analysing error estimates was concluded that the smallest

error was conducted by partial polynomial function based on Adaptive Basis Function Construction (ABFC).

This approach allows generating polynomials of arbitrary complexity and degree without the requirement to predefine any functions or to set the maximal degree of the polynomial- all the required basis functions are constructed adaptively specifically for the data at hand. (Jekabsons, 2010)

Verification of the optimisation results

For design of glass material stair landings, the main load need to be considered is load equivalent to human weight. Thus the development of an optimal design practice a load level was assumed at 125 kg and panel is simply supported at both ends of the panel. Summarising the experimental results, one may draw a conclusion that the single glass can take a significant load, but for increased level of safety the stair should be laminated from at least two sheets of glass which bonded together by a polyvinyl butyral (PVB) interlayer. The PVB-material is a rubber like elastomer that keeps the shards of broken glass plates in the frame of the glass unit after the failure. (Hills, 2006)

The graphs show (Figure 8, 9, 10) the optimal step thickness dependence versus span length at a limiting relative deformation level. The step width is assumed constant 0.35 m and 1 kN load is applied. If the glass panel span is longer, than glass thickness is thicker. The optimal configurations found for a single sheet panel of maximum span is set at 2.0 m and glass thickness 19 mm (Figure 8). For two (Figure 9) and three (Figure 10) sheet glass laminate the thickness is smaller but span may be extended.

In order to create a staircase glass landing optimal design guidelines, two most important parameters were assessed. The landing span and width parameters have been evaluated and obtained graphs indicate (Figure11, 12, 13), that thickness decreases if the glass width increases.

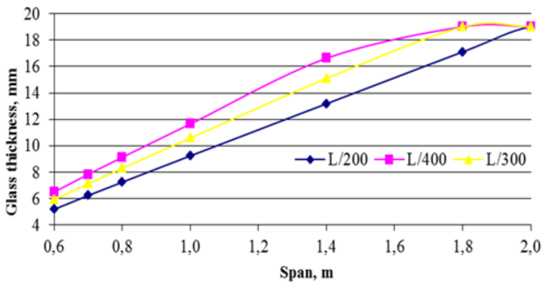


Figure 8. Glass thickness depending on the span of step: for one layer glass

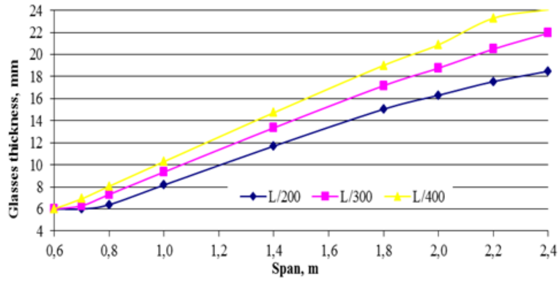


Figure 9. Glass thickness depending on the span of step: for two layers glass

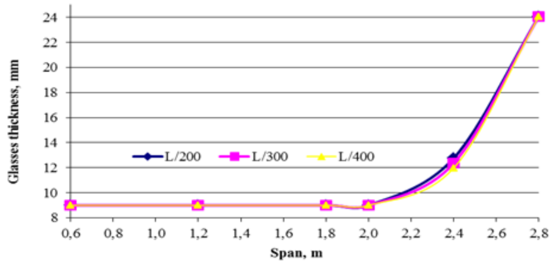


Figure 10. Glass thickness depending on the span of step: for three layers glass

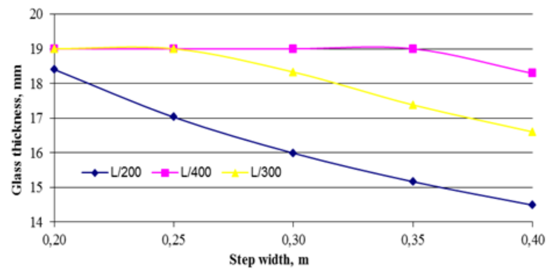


Figure 11. Glass thickness depending on the step width: for one layer glass

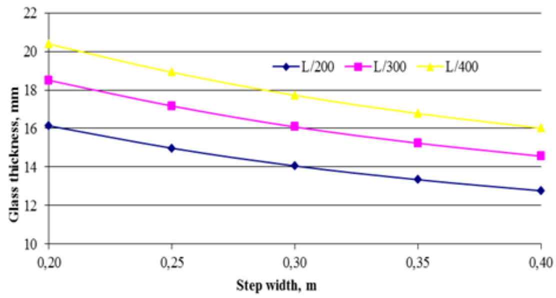


Figure 12. Glass thickness depending on the step width: for two layer glass

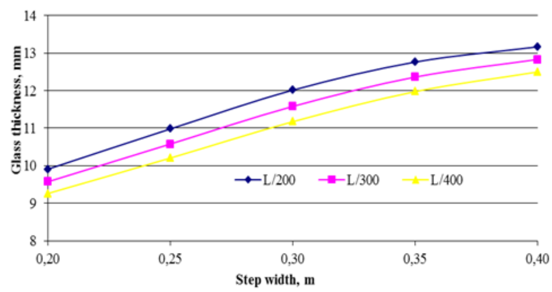


Figure 13. Glass thickness depending on the step width: for three layer glass

CONCLUSIONS

It may be concluded and confirmed that for structural designing one may assume Young's modulus for glass 70 GPa however actual, experimental results confirm a much higher modulus of elasticity reaching 88±5GPa value. Moreover it was confirmed that for tempered and annealed glass, the modulus of elasticity may be assumed equivalent or the difference is insignificant. In order to achieve a high load carrying capacity, annealed glass edges should be polished, then load carrying capacity will increase up to 1.5 times compared to annealed glass without polished edges. Tempered glass is useful for load-bearing constructions because its bending strength, deflection and relative deflection are at least three times higher than for annealed glass.

After experimental data and calculation of the relative deformation of the glass sheet, it can be assumed that annealed glass relative deflection range of annealed glass is from L/300 to L/250, for tempered glass the same configurations, but the design margins may be increased by at least 70%.
For design of laminated stair glass step the highest load - bearing characteristics may be achieved if the tempered glass is placed in the tension zone. Such a design will increase the load carrying capacity, compared with the all annealed glass combination at least 3 times.
Optimizing the glass landing dimensions, it should be noted, that increasing the span length proportionally increases the glass thickness or step's width. Drawing up the triplex design, the lower sheet of the pack should be thicker glass than the other parts, moreover, it should be tempered as well.

REFERENCES

Belis J., Inghelbrecht B., Impe R.V., Callewaert D., *Cold bending of laminate glass panels*. HERON Vol.52, 2007, p. 123- 146.

Davies, G.S. In Proc. N 22- British Ceramic Society. 1973. Edited by D. J. Godfrey. British Ceramic Society, Stoke-on-Trent. Proceeding of the Meeting in Cambridge, July 1972. P 429.

European Standard DRAFT prEN 13474-3, Berlin, June 2008

Froling M., *Strength design methods for laminated glass*. Lund University, 2011.

Haldimann M., *Fracture strength of structural glass elements- analytical and numerical modelling, testing and design*. THESE N^{0}3671, Switzerland, 2006, p.202.

Hills, D.A., "*Analysis, modelling, and optimization of laminated glasses as plane beam."* International Journal of Solids abvnd Structures 43, Bulgaria, 2006, pp.6887-6907.

Kittl, P. Res. Mechanica, 1980, 1,161.

LVS EN 1288-3:2001 "Glass in building-Determination of the bending strength of glass- Part3: Test with specimen supported at two points (four point bending)", Brussels, 2001.

Mangeron D., *Glasses as engineering materials: A review*. Gh. Asachi Technical University of Iasi, Romania, 2010.

Marschall, W.&Rudnick A. *In Fracture mechanics of ceramics*. Vol.1. Plenum Press, New York. P.69.

Migliore A.R. Jnr & Zanotto E.D., *Fracture strength of glass analysed by different testing procedures*. Glass Technology Vol37, No3, Brazil, 1996, p. 95- 98.

Veer F.A., Boss F.P., Zuidema J., Romein T. *Description of the experiment: Strength and fracture behaviour of annealed and tempered float glass*. Delft University of Technology, 2005.

Veer F.A., *The strength of glass, a nontransparent value*. HERON Vol.52, 2007, p. 88- 104.

Button D., at el. *Glass in buildings: a guide to modern architectural glass performance*.- England, 1993,p. 372.

Jekabsons G. *A software tool for regression modelling using various modelling methods*. RTU, 2010

Auziņš J., Januševskis A. (2007) *Eksperimentu plānošana un analīze*. Riga, RTU publishing. p. 208. (in Latvian lang.)

Wurm J. *Glass structures: design and construction of self-supporting skins*. Springer, 2007.p. 255.

Barry J. Toughened glass: *A wonderful material, but with an "Achilles heel"* [online][accessed on 15.01.2013.].