PERIODICA POLYTECHNICA SER. CIV. ENG. VOL. 48, NO. 1–2, PP. 157–172 (2004)

LOAD-BEARING GLASS STRUCTURES

Kinga PANKHARDT

Department of Construction Materials and Engineering Geology
Budapest University of Technology and Economics
H–1521 Budapest, Hungary
Tel. +36-1-463 3451
Fax +36-1-463 3450
E-mail: kpankhardt@yahoo.com

Received: June 30, 2004

Abstract

As engineers we are often comfortably and safely directed by ample research and codes of practice to tried and tested solutions. Designing glass structures has been an exciting adventure in uncovering research that is relevant and being forced to make assumptions based more often on good instinct than on scientific evidence.

Nowadays there are many architects, clients and glass fabricant world-wide specifically relating to the structural design of glass assemblies ranging from facades to floor and from framed structures to glass sculptures. This rapid growth suggests that there are many challenges in the design of glass assemblies, which can benefit from the special expertise of the consultant engineer. This paper is focused on the load-bearing glass, which demonstrates the possibilities of creating freestanding structures, where all the principal loads are carried by glass elements.

Keywords: glass, stress concentration, fixing type, tensile testing of glass.

1. Introduction

Glass is an ancient building material and its use, for both environmental and structural purposes, has been governed largely by the technology of making glass and the growing ability to control its properties more precisely. Although the unique properties of glass came to be understood during the 1930s, – 1922 Griffith studies strength of glass fibres – relatively little structural use was made of glass until the war end. Even then, its use was largely based on empirical design methods. In 1930 toughened glass was developed by Saint Gobin, initially for car windscreens.

Prestressing is achieved by cooling quickly the outer surface of hot glass using air jets. As the entire glass section cools, so the outer surface drawn into compression by the inner core acting in tension. Since the early 1960s glass was used more effectively in facades and elsewhere in compression, tension and bending. The quest for the borders of structural use of brittle material glass has resulted in past decade in a new type of frameless glass facades and glass roof, with a range of different primary structures. The next target, which at the moment seems unattainable, is to develop an unbreakable transparent plate material, much more a reliable engineering material than the current material glass.

2. Glass as a Structural Element

In designing a glass element the following issues need to be addressed:

1. The degree and type of loading to which the element will be subjected.
2. The physical properties of the glass.
3. Fixing types according to loading and architectural design.
4. Safety properties, the ways in which the glass could fail.

2.1. Applied Loading

Codes of practice generally describe the range of static loading to be used in the design. Impact loading from falling objects are of special interest in the design of glass structures as severe stresses can build up at the point of contact of projectile causing failure which propagates through the element. A typical test for a stair tread is to drop a 4 kg steel sphere onto the surface from a height of 1 m. Although the glass can crack under this load it should not cause complete failure of the assembly.

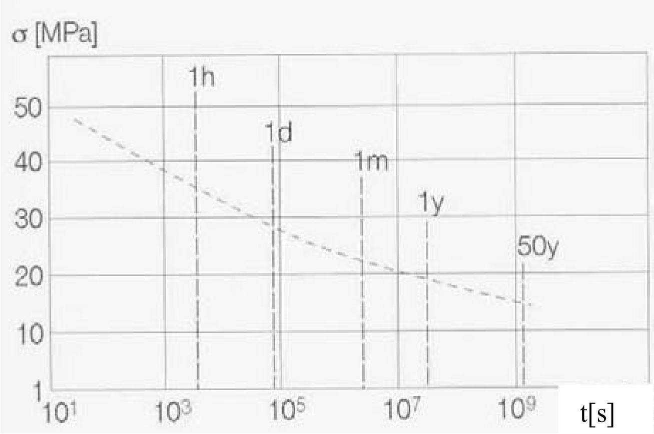


Fig. 1. Relationship between strength of glass and duration of load [1]

2.2. Physical Properties

There are many different glasses produced using chemical compositions appropriate to their application. The mostly used is the soda lime glass. This glass has generally green tint due to the presence of iron tint in the mix. The designer can be confident that the physical properties of the glass are world-wide constant.

Some properties of this glass are widely published such as [3]:

Young's Modules of elasticity : 70 000 N/mm^2
Poisson's ratio : 0.22-0.23
Coefficient of thermal expansion : 8,5-9$\times 10^{-6}$ 1/$\circ$ C
Mass Density : 2500 kg/m^3
Ultimate tensile stress : 30-100 N/mm^2
Ultimate bending stress : 15 (float) –50(toughened) N/mm^2.

The ultimate tensile and bending stress varies with the duration and the condition of the glass surface or edge.

Toughened glass has exactly the same physical properties as annealed glass except for its ultimate tensile strength which can apparently vary between 150-200 N/mm^2.

The figures for ultimate tensile and compressive stresses are readily published and proved to be the most difficult subject to unravel in the early designs.

Table 1. Strength of different glass types [4]

Glass	Bending strength, *design* N/mm^2	Bending strength, *ultimate* N/mm^2	Normal strength, *ultimate* N/mm^2
ESG, toughened	50	120^1	700-900
TVG, heat strengthened	29	70^2	
Float	12/18^3	45^4	

^{1} characteristic value (at 95%) DIN 1249 T 12;^{2} characteristic value after prEN 1863; ^{3} 12 N/mm^2 by overhead glazing and 18 N/mm^2 by vertical support; ^{4} characteristic value at 95% DIN 1249 T 10

Table 2. Allowed deformation by different type of supports [4]

Glazing	Support	Deformation, design	Definition
1 glass pane	2, 3 or 4 sided	$f \leq l/100$	l: span
Double glazing, upper pane	4 sided	$f \leq 100$ and $f \leq d$	d: thickness of glass
	2 or 3 sided	$f \leq l/200$, $f \leq d$ and $f \leq 8$mm	l: length of free edge d: thickness of glass

3. Fixing of Glass

Frameless glazing is often chosen by architects by virtue of its maximum contrast with closed building parts i.e. concrete, brickwork or metal panels [5].

Tendency is in the architecture to create more transparent buildings, it is necessary to design with small fixings, or more transparent structures also load-bearing structures.

Fig. 2. Glass column with steel joint

By applying point fixing it is necessary to use toughened glass, which is able to carry concentrated loading. By architects mostly used point fixing is applied in glass curtain walls. The sizes of glass panes are nowadays larger, there is also available 'jumbo' size float glass with a measurement of 2.4×6.00 m. The sheet is cut to length of commonly 6000 mm, but can be as long as 8000 mm. The secondary processes of tempering and lamination offer the designer flat glass with enhanced safety, strength and thermal performance. These processes further reduce the available size, with typical sizes of tempering in Europe of 4000 mm long by 2100 mm wide. Maximum dimensions available are up to 5000 mm by 2400 mm. In order to go beyond the production limits of a single sheet of flat glass, for a span over 5000 mm, a joint or connection becomes necessary and this joint is a key element in the design of the glass structure [6].

In spite of the great size, there are some applications of glass, when the glass has to be jointed. Steel joints are widely used with coupling of rubber or plastic elements to damp the stresses in the glass.

Such jointed principal structural elements can be also glass beams or columns with a span larger than 6 m.

There are guide-lines prepared by glass manufacturers by applying glass panes fixed on holes with point fixing.

In our experiments we analysed glass panes subjected to tension force loaded on hole. When the glass is used as principal loadbearing structure it is important to calculate the stresses at the hole. By designing glass structures there are not enough solutions which are comfortably and safely directed by ample research and codes of practice tried and tested. To calculate the ultimate strength in a glass pane cannot be equal and same after the codes. Some recent researches have shown, that the edge stresses are higher, than in the middle of the pane. In this way the codes have to be improved. To calculate the ultimate stresses and the load bearing capacity of a glass pane fixed with point fixing is influenced also by edge stresses.

When a glass element fails it can lose all of its structural strength. Also pieces of glass can break away from the element causing injury or even loss of life [7].

3.1. The Transfer of Load through a Hole in Glass

The presence of a hole in a glass gives rise to high concentrations of stress and further drilling inaccuracies not registered during the fabrication can lead to fracture of the glass.

The design and detailing of the bearing connection thus become a primary factor of the overall capacity of the structural system. Given the brittle nature of glass, failure due to local high stresses can be avoided by ensuring that the structural transfer of load to the local glass is fully understood and predicted to lie within acceptable strength parameters for any loading configuration. Reference must be made to the elastic analysis of glass, as the material cannot yield, to offer a true understanding of performance.

The local stress concentrations around holes in plate material under various loading conditions have been documented by many authors on classical plate theory. General discussion and studies on stress concentration for holes can be found in (Timoshenko and Woinowsky-Krieger, 1959); (Timoshenko and Goodier, 1970); (Peterson, 1974). Here is important to differentiate between stress concentrations which arise when load is applied to a plate with a hole and when load applied to a pin in a hole. The case of a circular hole in an infinite plate with load applied to the plate in direct tension was solved by Kirsch in 1898, with a stress concentration factor of 3.

Fig. 3. Stress measurement with photoelastic method

Example:

$a = b = 1$ cm
$c = 30$ cm
$d = 30 - 2 = 28$ cm
$\sigma_{max} = \sigma_0$fixings
$\sigma_{max} = \sigma_0 \frac{90}{28} = \sigma_0 \times 3{,}2$
The stress is 3.2 time higher at the hole.

The effect of the hole is local. The result has been well confirmed by strain measurements and the photoelastic method.

Of more relevance to common connections is the case where two overlapping plates are connected by a transverse pin and the load is applied to a pin in the hole.

Fig. 4. Stainless steel spider intermediate support

3.2. The Type of Fixings

Frameless glazed structures consist of a system of interrelated components that rely on one another to transfer loads and movements. There are various types of systems on the market, 4 main elements are [8]:

- the main support structure,
- the intermediate support,
- the mechanical fixing,
- and the glass.

3.2.1. Intermediate Support

The intermediate support fixing provides a point of attachment for mechanical fixing and transfer loads to the support structure. In some glazing installation assembly and installation tolerances may be taken out here. Oversized and slotted holes in spiders and brackets or the use of pins make allowance for thermal and in plane movements. Examples: angle brackets, spiders (cast and machined), pin brackets and clamping plates.

3.2.2. Mechanical Fixing

The mechanical fixing provides support to the glass and transfers the glass selfweight and lateral loads to the intermediate support.

Cantilevered bolt (shear) fixings transfer both out of the plane and in the plane loads directly through the bolt and glass interface. Movement is placed outside of the glass and the bolt is rigidly fixed in to the glass, by clamps either side of the glass or by countersunk fixing into the body of the glass.

Articulated bolt fixing transfers both out of plane and in-plane loads directly through the bolt and glass interface. In this system an articulation (spherical bearing) is included in the plane of the glass. Thereby shifting the moment generated outside of the glass. The fixing is attached to the glass by clamping either side of the glass or via countersunk hole.

The type of fixing has a pronounced effect on the ultimate capacity of the connection.

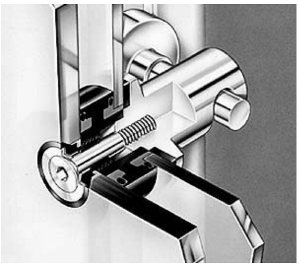


Fig. 5. Cantilevered bolt fixing

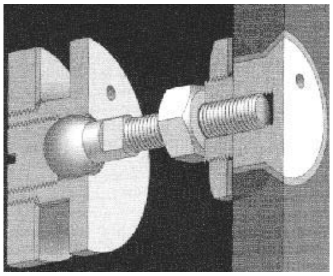


Fig. 6. Articulated bolt fixing

3.3. Glazing

The glazing transfers loads to mechanical fixings, in some instances the glazing is used to stabilize the main support structure. The composition of glazing may consist of either

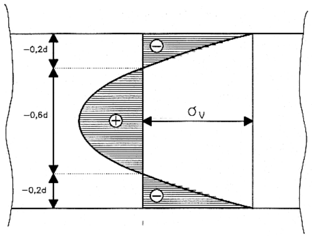
- monolithic,
- laminated,
- double glazed units.

Load bearing glazing will invariably consist of toughened glass [4].

Toughened glass, stresses after toughening process:

Stresses in the glass are dependent on a number factors including:

- shape and size of *glass*,
- type (concentrated or distributed), rate, time and velocity of loading, *fixing type*,
- number and position of *fixings*,
- size, type and quality of the *hole* and
- *bearing material*.



- surface stress 140-170 Mpa
- stress in the middle = surface stress/2

Fig. 7. Stress distribution in toughened glass pane

The point support causes high stress concentrations, which tend to be greater than mid pane or mid edge stress. In many instances the stress at the hole or deflection of the glass will dominate the selection of the glass thickness.

4. Experiments

Tensile tests were carried out to assess the strength of 1 ply and laminated tempered glass panels. The test enabled a measurement of the failure tensile stress of glass with the stress concentrations.

Local stress fields around bearing connection are the result of a complex interaction between the local and global stress fields in the element. The design process should begin with an elastic analysis to define stress concentration states, however, confirmation by testing is also required.

4.1. Method of Testing

Tensile force is applied to the glass specimens by bolts through the drilled holes of the specimens. Tensile force is measured with a custom-made force transducer, calibrated with Hottinger Baldwin Messtechnik's 200 kN force transducer (No. 76411). The transducer is fixed to the lower plate of the INSTRON type 1197 testing equipment. The upper crosshead is fixed to the upper plate of the testing equipment. Displacement between the lower plate and the upper crosshead is measured with a Hottinger Baldwin Messtechnik type W50 displacement transducer. Time is also measured by the data acquisition computer, therefore actual displacement/time ratios can be calculated offline.

Measured data is displayed on the data-acquisitioning computer's screen in real time.

Printed output of force-displacement curves are also available.

Two versions of test methods were carried out:

TEST A) Simple test with constant displacement: 0.2 mm/min till fracture.

3 specimen of 4 ply laminated toughened glass were tested by this case.

TEST B) Combined test (with cyclic loading)

The testing instrument was controlled by force. Force was varied between 55 and 110 kn. Applied displacement: 0.5 mm/min.
Every 3 specimens were undamaged after the cyclic loading.

After cyclic loading each specimen was tested after test A) to fracture. (Force applied from 0 kn till fracture). Number of cycles: Nr.1.: 600, Nr.2: 1000, Nr.3. 2000.

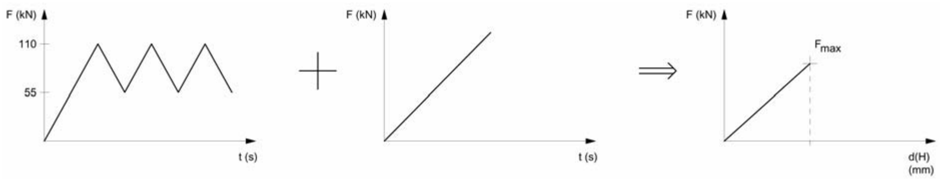


Fig. 8. Combined test method B)

Cyclic load can happen by variable loads. The durability of glass depends on cyclic loading.

4.2. Testing of Toughened Tensile Glass Specimens with Hole

Specification of Specimens:

Tested specimens:

- 6 pieces of 12 mm toughened glass,
- 6 pieces of 4×12 mm laminated toughened glass, lamination with resin,
- 2 pieces of 4×12 mm toughened glass, without lamination only with using of spacer,
- 3 pieces of 2×12 mm toughened glass, without lamination only with using of spacer.

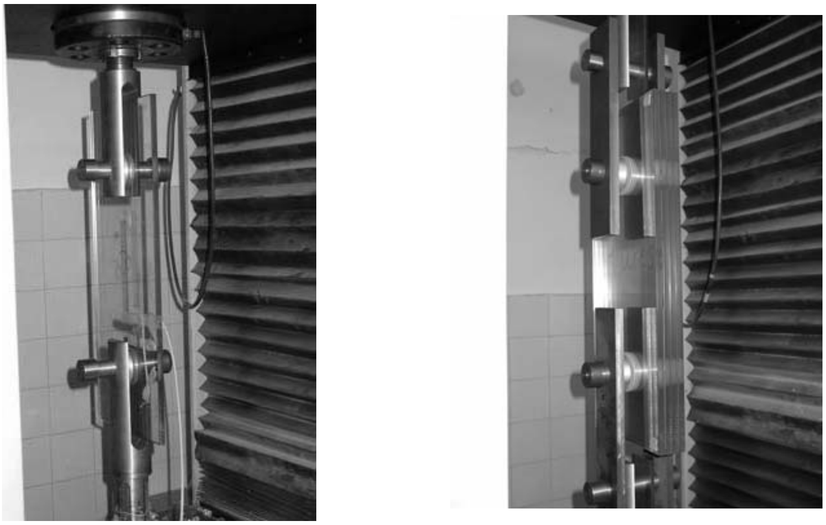
Measurements of specimens: L= 595 mm, B=244 mm, diameter of holes D=46 mm, distance of holecentre from edges d=122 mm. Each hole was filled with ARALDIT epoxy width= 3 mm, to have a smooth hole surface to even the offset differences after the lamination.

The specimen size was determined after a beam connection prototype of a glass beam with 9 m span.

The problem was to determine the load bearing capacity of a glass beam, jointed together from two parts of glass beams with a steel joint, which transfers load through glassholes.

For this case, we developed a special testing method for tension, which was able to use our instruments.

Each toughened glass was tested to fracture.



Figs. 9-10 Toughened glass specimens, 1 ply and 4 ply laminated glass

Result of the experiment

The load bearing capacity of laminated 2 glass pane is 1,55 time higher then that of 1glass pane.

The load bearing capacity of only with spacer laminated two pieces of glass pane is 46,5 % lower then of four pieces of glass pane laminated only with spacer.

The test results of 4 ply laminated glass have shown difference between test type A) and type B). After cyclic loading the load bearing capacity decreased 77%. See *Fig. 1*: Time dependent durability of glass.

On *Fig. 13* we can see that the behaviour of glass is linear till fracture.

The rigidity of the glass increased after lamination or using more pane of glass.

The deformation characterizes the whole construction with the fixing type and buildup of support, not only the glass as material.

We measured the deformation of the glass at two places at the surface of the glass pane. One stamp was placed on the middle of the glass pane, the other near to the hole.

Figs. 11-12 Toughened glass specimens, 1 ply and 4 ply laminated glass pane after testing

Table 3. Table of testing results

Specimen	Ultimate Force of 1 pane kN	Ultimate Force of laminated 4 pane with resin kN	Ultimate Force laminated 4 pane with resin (cyclic loading) kN	Ultimate Force laminated 2 pane only with spacer kN	Ultimate Force laminated 4 pane only with spacer kN
1	62.37		123.26	88	176.18
2	64.79		133.47	81.45	218.77
3	52.57		123.47	105.91	
4	54.99	186.1			
5	64.84	160.4			
6	63.74	186.7			
f_{min}	52.57	160.4	123.26	81.45	176.18
average f_m	60.55	177.73	126.73	91.79	197.48

The measured elongation was in the middle 3 time smaller than near to hole. Ultimate strain of the material glass is 0.06-0.17%.

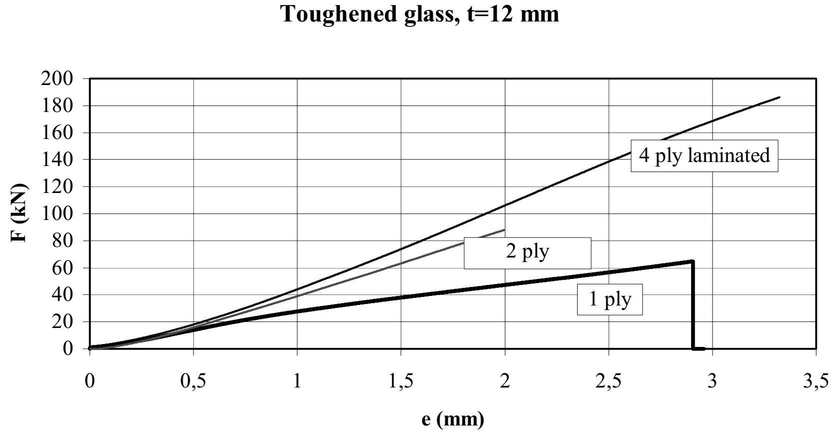


Fig. 13. Tension tested glass panes, average of force and extension of tested specimens

4.3. *Testing of Toughened Adhesive Bonded Tensile Glass Specimens with Hole*

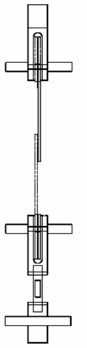


Fig. 14. Testing scheme of chemical jointed toughened glass panes

The problem was to determine the load bearing capacity of a glass construction, jointed together from two parts of glass pane with a chemical joint, which transfers loads, and the support of glass were steel bar through glasshole.

Specification of specimens:

Two pieces of laminated toughened glass, width: B=300 mm, length: L= 850 mm, thickness: t=10 mm, length of lamination: $L_{\text{lamination}}$ = 100 mm, distance of hole from edges d=50 mm, hole diameter D=20 mm, lamination area A= 300 cm$^{2.}$

Two types of lamination material were tested:

1. Type: UNILAM 1418 RESIN
2. Type: Araldit

Two type for chemical joint were tested, each on 3 specimens.

FEM Model:

For good calibration of the testing instrument,it was important to recognize the ultimate strength of the material.

After linear FEM model calculations the available maximal load: $F_{\max} =$ 30 kN.

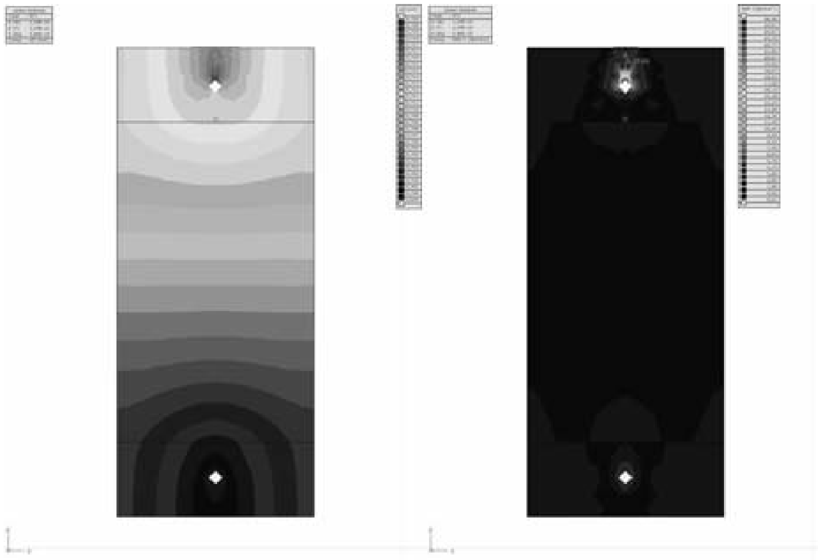


Fig. 15. FEM calculation to determine the strength

Result of the experiment

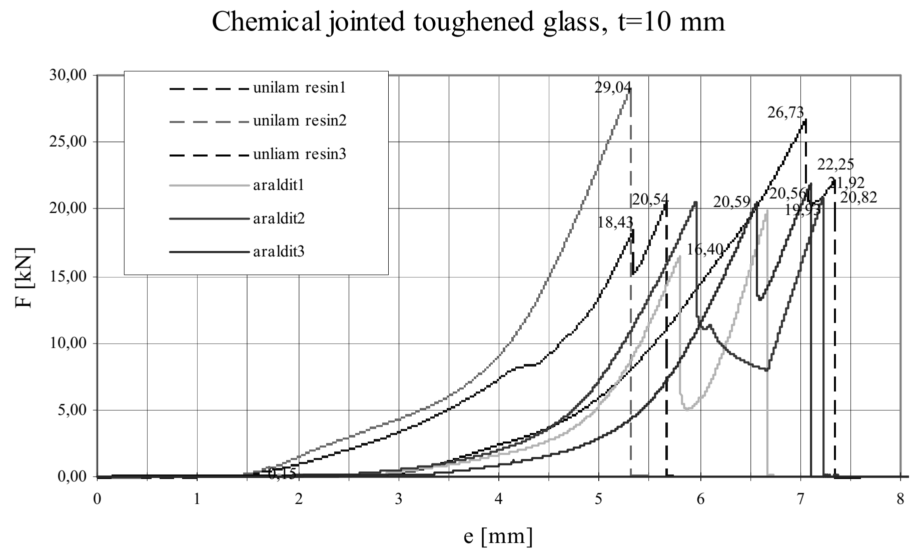


Fig. 16. Tested chemical bonded glass specimens, force and elongation curves

The UNILAM 1418 RESIN showed better behaviour: higher load-carrying capacity, quicker finishing and better transparency.

On *Fig. 16* we can see, that after the fracture of first glass pane (first top of the curve) the resin transfers the load to the second pane (between the two tops of the curve).

By using of UNILAM RESIN, after fracture of first pane, the measured minimum force was F=18.43 kn.

The deformation characterizes the whole construction with the fixing type and buildup of support. Maximal elongations were after fracture about 7.3 mm.

Relationship between FEM and experiment results

The measured maximal force was: $F_{\mathrm{MAX,m}} = 29.04$ kN.
The calculated maximal force was: $F_{\mathrm{MAX,calc}}= 30$ kN.

5. Conclusions, Future Work

The type of fixing has a great influence on how the glass responds and the fixing type is in turn influenced by support structure.

The tensile test has shown, that the glass is also able to carry high loads, and its load-bearing capacity is more influenced not only by the support, but by the load-transfer intermediate material too.

After cyclic loading the load-bearing capacity decreased to 77%. See *Fig. 1* : Time dependent durability of glass.

The behaviour of the glass construction manual, under tensile force is linear till fracture, in this case we can calculate glass as a linear elastic brittle material in the FEM.

The measured elongation was in the middle of the pane 3 time smaller then near to hole.

The deformation characterized the whole construction with the fixing type and buildup of support, not only the glass as material.

It is important that both the designers and fabricants understand all the implications associated with interactions of the materials and components.

There are, however, many areas where research and design development will still be required, for example:

- A statistical approach to applying factors of safety in multi-ply construction.
- An approach to designing glass edge bearings and guidance on pull out and shear values for fixings through glass holes.
- A guide to the use of adhesives and laminating inter-layers.

In our future work we want to analyse the stress in glass by varying the laminating type and hole diameter, to calculate the stress distribution in the whole glass pane.

Acknowledgement

I would like to thank Salem G. NEHME from TUB Dept. of Construction Materials and Engineering Geology for his intellectual and practical help and Pál DOBRÓCZKY from Orosházaglas for his intellectual support.

References

[1] SCHITTICH, Glass Construction Manual, Birkhauser Verlag, 2000

[2] Strengthening of Flat Glass, International Glass Review, Issue 2, 1998 p. 97.

[3] Strengthening of Flat Glass, International Glass Review, Issue 2, 1998 p. 97.

[4] Gestalten mit Glas (in German) Interpane Glas Industrie, 6. Auflage, Lauenförde, 2002, S. 310, 314.

[5] PANKHARDT, K., Development of Glass Constructions (in Hungarian) Az üveg tartórendszerek fejlődése, Alaprajz 5/2000.

[6] PANKHARDT, K. – GORDON, P., Load Bearing Glass Slabs in Hungary, (in Hungarian) Járható üvegfödémek Magyarországon, *Interglass* 2002 II./1. S. 8.

[7] LOUGHRAN, P.: Falling Glass, Birkhauser-Publishers for Architecture, Basel-Berlin-Boston, S. 126.

[8] PANKHARDT, K., Special Glass Bearing Structures in Hungarian Civil Engineer Practice (in Hungarian) Különleges üveg tartószerkezetek a magyar építőiparban, Alaprajz 2003.