Study of edge strength of load bearing glasses

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A single glass layer can be considered as safety glass if tempered or reinforced with wire mesh. When tempered glass fractures it shatters into tiny pieces with blunt edges. Heat- or chemically strengthened glasses can not be considered as safety glass owing to the fracture pattern (fractures in shards), unless they are laminated. Bending tests were carried out (test arrangement according to standard EN 1288-3:2000) and the bending strength of single layer tempered and float glasses were determined with use of the well-known formulas. The calculated values for surface strength with use of ultimate strain were compared to the bending strength results in the case of float and tempered glasses. The question arise: the strains measured in the centre of the pane and near the edge are equally? Strain measurements of the surface of loaded specimens – at the middle of the pane and near the edge – were also investigated. The failure of glass originates from cracks with microscopic sharp tips. In spite of the careful manufacture and handling of glass panes, impacts by sharp particles or environmental impacts can cause defects on the surface. The glass manufacture e.g. edge finishing techniques influence the glass strength and can cause flaws which can propagate during the lifetime of the glass. Defects of edge surfaces caused by different edge work techniques were shown with scanning electron microscopy. Most of the glass strengthening methods are used to introduce residual compressive stresses into the outer layers by physical or chemical tempering. The compressed resulting layer helps to close cracks initiated on the surface, can stop crack propagation and can also increase the bending strength. Recent studies [6, 14] have shown that surface strengthening can lead to substantial improvements in degradation resistance. Therefore, in outdoor conditions, when the glass surface is exposed to humidity etc., tempered or heat strengthened glass should be used.
Keywords: load bearing glass, edgework, strength, glass, tempered glass

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1. Introduction

Float glass is widely used in the architecture because of the good optical quality of the surface. The float process produces glass sheets with a uniform thickness and perfectly smooth surfaces that need no further polishing. The resulting glass will then be further treated in various ways. Soda lime silicate glass is mainly used for architectural purposes. The advanced treatment technologies are applied to float glass products depending on the end-products and on the application. When float glass is used as load bearing element [1, 2] safety glass is needed. Single glass layer can be considered as safety glass if tempered or reinforced with wire mesh. When tempered glass fractures it shatters into tiny pieces with blunt edges. Heat- or chemically strengthened glasses can not be considered as safety glasses owing to the fracture patterns (fractures in shards) unless they are laminated. Bending strength with the well known formulas was evaluated in case of non heat-treated float and tempered glasses and was compared to the measured surface stresses. The question arise: if strains measured in the centre of the pane and near to the edges are equal. Strain measurements of glass surface of loaded specimens – at the mid of pane (Region 1) and near to the edge (Region 2) – were investigated (Fig. 1.).

The bending strength of a single glass pane is influenced by the following factors [3, 5]:

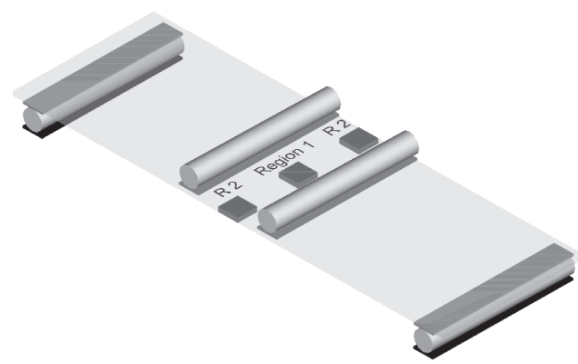


Fig. 1. Region 1 and Region 2 of glass surface strain measurements [3, 4]
1. ábra Üvegfelület alakváltozásainak mérése R1 és R2 jelű tartományokon [3, 4]

a) heat treatment, b) surface condition (e.g. non-slip characteristics), c) rate and duration of loading, d) area of surface stressed in tension, e) relaxation, f) ambient medium, g) age, i.e. time elapsed from the last mechanical surface treatment, h) ambient temperature, i) edgework.

Most of glass strengthening methods are used to introduce residual compressive stresses into the outer layers by physical or chemical tempering (Fig. 2).

Surface stresses are related to the temperature gradient that results from cooling. The produced compressed layer helps to close cracks initiated on the surface (Fig. 3) and can stop crack propagation and can increase also the bending strength.

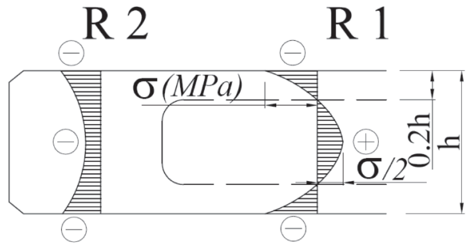
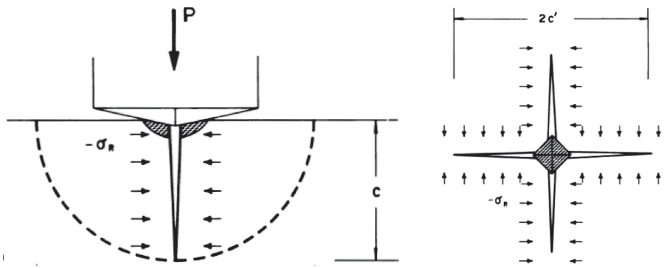


Fig. 2. *Stress distributions over the thickness of tempered glass pane. Residual compressive stresses after tempering near the surface are: 120 to 150 MPa, tensile stress in the middle plane is about half of them [3]*

2. ábra *Jellemző feszültségeloszlás az edzett üveg vastagsága mentén mezőközépen és élek közelében (R2 és R1 tartományoknál). A felületi rétegek hőkezelés után maradó nyomófeszültsége általában: σ=120-150 MPa, az üveg belsejében lévő húzófeszültség: σ/2, [3].*



a) *b)*

Fig. 3. *Vickers diamond pyramid indentation into a tempered glass surface a) section view, b) plane view. Indentation field drives the crack, residual tempering field opposes them [6]*

3. ábra *Vickers gyémánt piramisos behatás vizsgálat edzett üveg felületén a) függőleges metszet, b) felülnézet. A behatás által létrejövő repedéseket, az edzést követő maradó feszültségek összezárják [6]*

There is a peak of tensile stresses at a small distance from the edge (typically 12–25 mm from the edge (Fig. 4.). Tensile stresses are indication of an undesirable edge cooling rate and a potential bending. Therefore, surface strains in Region 1 (at centre of glass panes) and Region 2 (at edge region) were measured in present experiments.

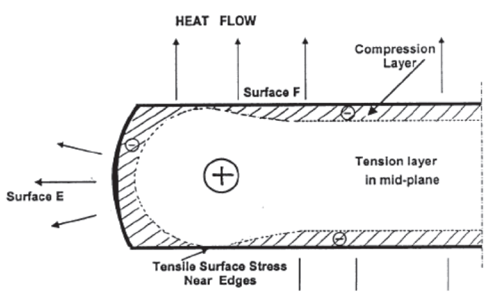


Fig. 4. *Surface and mid-layer stress near to edges [7]*

4. ábra *Élekhez közeli tartományok felület közeli és belső rétegeinek feszültségei [7]*

Failure originates from cracks with atomically sharp tips. In spite of the careful manufacture and transportation of glass panes, impacts with sharp particles or environmental impacts can cause defects on the surface. Research results have shown [8, 9, 10, 11, 12] that aging of newly created flaws should be beneficial, and residual stresses will tend to relax in time (especially in reactive environments). *Mould et al.* (1959) [13] showed that the strength of specimens containing abrasion microcracks can increase with the aging time (i.e., time between abrasion and testing to failure). In case of glasses under such conditions those lifetime design procedures will be difficult which try to make predictions or estimations based on actual glass surface conditions.

Further studies [6, 14] have shown that surface strengthening can lead to substantial improvements in degradation resistance, therefore, in outdoor conditions, when glass surface is exposed to humidity etc. tempered or heat strengthened glass should be used.

2. Materials and experimental procedure

An experimental programme was carried out to analyse the load bearing capacity of single and laminated glass panes. Results of single glasses are discussed in present publication. Specimens were tested in four-point bending. In case of tempered glass, the stress must first exceed the built-in compression stresses before tension develops. The influence of edge strength also influences the strength of glass pane. Therefore, the deformations at mid of pane and at the edge regions were also studied. The results of tempered glass specimens were compared to those of non heat treated float glass specimens.

2.1. Test parameters and test programme

Test parameters of single glass specimens were the following: *Constants:* test arrangement, width and length of specimens, *Variables:* thickness, type of float glass (non heat treated or tempered), rate of loading, temperature of specimens (not discussed here).

Specimens tested in four-point bending were manufactured from soda-lime silicate float glass with polished edges. Any intended changes to the condition of the test specimens like edge working, was completed at least 24 hours before testing [5]. Specimens were stored in laboratory conditions for min. 1 day before being tested. If the glass surface was modified by abrasion, etching, edge working etc., it was necessary to allow the fresh damage to *heal* before the test is done. The continuous surface modification by moisture affects the damage in a way that can reduce any weakening effect [8]. Single glass specimens with nominal thickness of 6 mm and 12 mm as well as 19 mm were investigated. The accuracy of thickness measurements were 0.01 mm. The measured values are the following:

- density of glass, *average* $\boldsymbol{\rho}_{glass}$: 2.50 g/cm^3
- length of specimen, *average* $\boldsymbol{L}$: 1099 mm, (1100 mm ± 5 mm)
- width of specimen, *average* $\boldsymbol{b}$: 358 mm, (360 mm ± 5 mm)
- thickness of specimen, *average* $\boldsymbol{h}_{nom,6\,mm}$: 5.87 mm, (nominal 6 mm)
- thickness of specimen, *average* $\boldsymbol{h}_{nom,12\,mm}$: 11.85 mm, (nominal 12 mm)
- thickness of specimen, *average* $\boldsymbol{h}_{nom,19\,mm}$: 18.99 mm, (nominal 19 mm)

The required pieces of specimens to any combination of parameters were determined according to the standards (at least 3 specimens should be tested). Standard deviation of the tests results was at most 10% of the average of measured values.

2.2. Experimental procedure

2.2.1. Force measurement

All glass specimens with constant span of 1000 mm and supported at width of 360 mm were tested in four-point bending. The load and deflection at mid-span of the glass panes were measured in all tests. The test procedure was a semi-dynamic short-term test. The tests were carried out at specimen temperature of +23 °C. The temperature of the specimens and room temperature was continuously measured during the tests. The specimens were mounted as shown in Fig. 5.

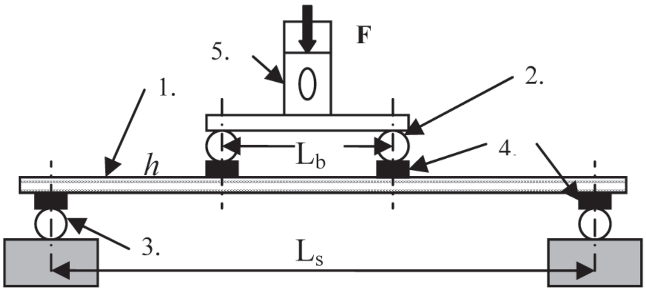


Fig. 5. Test method in four-point bending (EN 1288-3:2000) where, 1.: specimen: 1100×360 mm, 2.: bending roller, 3.: supporting roller, 4.: rubber strips (3 mm thick, according to ISO 48), 5.: custom-made transducer, symbols: L_s: 1000 mm, L_b: 200 mm, h: thickness of the specimen (6 mm, 12 mm, 19 mm) [3, 15].

5. ábra Kísérleti elrendezés két vonal menti hajlítás esetén (EN 1288-3:2000), ahol a számok a következőket jelölik, 1.: próbatest: 1100×360 mm, 2.: terhelőhenger, 3.: alátámasztó henger, 4.: gumiszalag (3 mm vastag, ISO 48:1994 szerint), 5.: saját tervezésű erőmérő, L_s: 1000 mm, L_b: 200 mm, h: próbatest vastagsága (6 mm, 12 mm, 19 mm vagy 2×6, 3×6 mm) [3, 15].

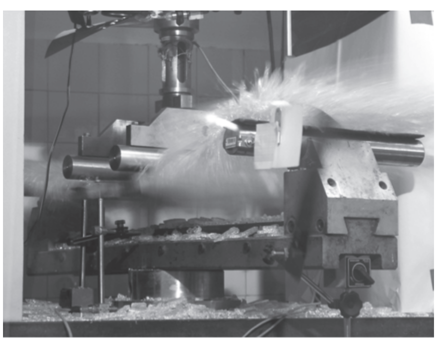


Fig. 6. Fracture of single tempered glass

6. ábra Egyrétegű edzett üveg tönkremenetele

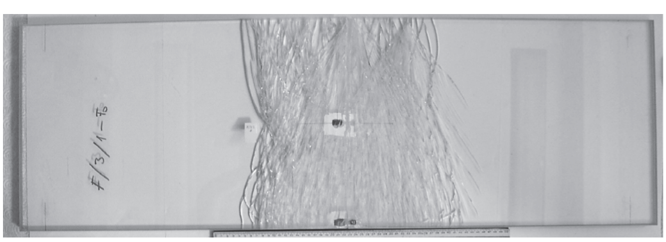


Fig. 7. Fractured laminated glass consisting of three float glass layers (cracks usually started from the edges)

7. ábra Vizsgált laminált három rétegű float üveg (a repedések általában az élektől indulnak)

Rubber strips of 3 mm thickness and hardness of 40 ± 10 IRHD (in accordance with ISO 48) was placed between the specimen and the bending and supporting rollers to avoid hard contacts [16]. The bending tests were carried out at (23 ± 5) °C room temperature with relative humidity between 55% and 65%. During the test the temperature was kept constant with ± 1 °C in order to avoid the development of thermal stresses.

Load was measured with a self-made force transducer, developed by the authors [17] for *Instron Type of 1197* testing instrument and calibrated with *Hottinger Baldwin Messtechnik's 200 kN* force transducer (No. 76411). The self-made transducer was fixed to the upper plate of the *Instron type 1197* testing equipment. The authors developed a steel construction with hinge connections at defined places was constructed to transfer the loads from the test equipment Instron to the specimens with four-point bending. Displacements were measured with a *Hottinger Baldwin Messtechnik type W50* displacement transducer. Signs of the instruments were transformed with software *Catman* to the measured values in *μm/m*. Measured values during the tests were recorded by computer. The fracture process and crack pattern of glass specimens were recorded with digital optical methods *(CMOS SONY Camera)*. The applied loading rates of glass specimens with thickness of 6 mm were: 50 mm/min, 20 mm/min and 5 mm/min as well as 1 mm/min (by *Instron Type 1197* available). The applied loading rate of glass specimens with thickness of 12 and 19 mm was: 20 mm/min. The specimens were tested until their fracture (Figs. 6., 7.).

2.2.2. Strain measurement

Strains at selected points on the surface (in R 1 and R 2 Region) of the glass panes with strain gauges Type *HBM LY11-10/120* were measured (Fig. 1).

For temperature compensation another glass specimen with strain gauges on its surface was applied and stored at the same condition with the tested specimens. The change of resistance in *mV/V* of the gauges was measured and transferred to the digital channels of *HBM Spider8* instrument. The software *Catman* after calibration was able to transform the measured *mV/V* data in *μm/m*. Stresses at glass surface may be calculated with *Hooke's* law for linear elastic materials.

2.2.3. Scanning electron microscopic analysis (SEM)

To study morphologically the edge regions of single glasses four different types of edges were prepared: a) manually arrised edge, b) machine ground edge, c) machine ground + acid etched edge, d) machine polished edge. Type of used scanning electron microscope was: *JEOL JSM-5500LV*. The edge samples were covered with Au-Pd vapour for electron microscopy. The parameters of electron microscopy were the following: high vacuum mode, using of secondary electron *(SE)* detector, acceleration voltage 25 kV. Digitally photos were taken with magnification of ×50, ×100, ×300, ×1000. In the photos the scaling line is also printed.

3. Results and discussion

3.1. The effectiveness of tempering

In most of the references [18, 19] can be found that the load bearing capacity in case of tempered single glasses is 3 to 4 times higher than in case of float glasses. The question arise: is the load bearing capacity of tempered glass always 3 to 4 times higher in case of different glass thicknesses or in case of different applied loading rates?

The authors suggest to introduce the definition *effectiveness of tempering* (heat treatment). The effectiveness of tempering shows the proportion of load bearing properties (e.g. maximal force) of tempered glasses to non heat treated float glasses with the same thickness. The authors have experimentally shown that the effectiveness of tempering depends on the glass thickness and the loading rate. Based on the laboratory four-point bending tests the authors have shown that the effectiveness of tempering decreases with the increase of glass thickness by loading rate of 20 mm/min. The relationship between effectiveness of tempering and glass thickness is linear (Fig. 8.).

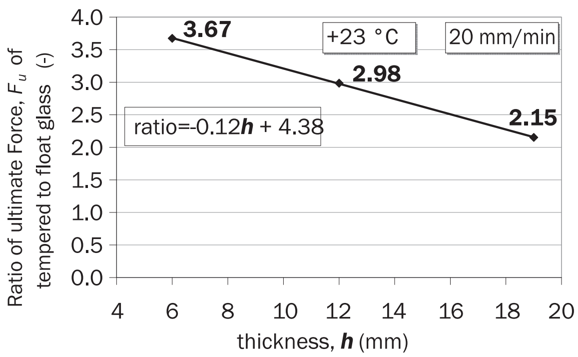


Fig. 8. Effectiveness of tempering vs. glass thickness in case of loading rate of 20 mm/min
8. ábra Edzés hatékonysága az üvegvastagság függvényében 20 mm/min terhelési sebesség esetén

The authors have experimentally shown in case of nominal glass thickness of 6 mm that the *effectiveness of tempering* decreases with decrease of loading rate from 20 mm/min to 1 mm/min (Fig. 9.) and no significant changes with increase of loading rate from 20 mm/min to 50 mm/min. Explanation for that is: the development of cracks starting from surface scratches needs time which is rather available in case of loading rates of 5 or 1 mm/min than in case of loading rates of 50 or 20 mm/min.

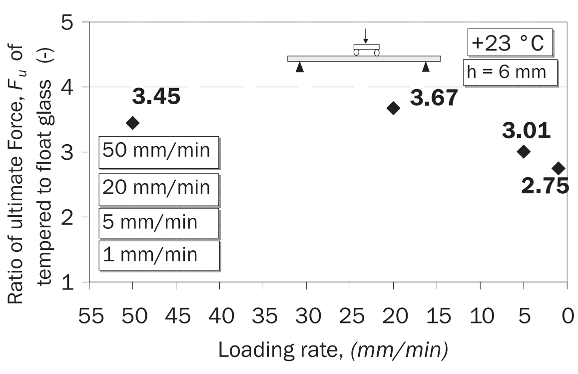


Fig. 9. Effectiveness of tempering vs. rate of loading by 6 mm glass thickness
9. ábra Edzés hatékonysága és a terhelési sebesség összefüggése 6 mm vastagságú üvegeknél

With the effectiveness of tempering (heat treatment) it is possible to choose the appropriate and economic glass thicknesses in the field of glasses which were heat treated (tempered or heat strengthened).

3.2. Deformations of glass surface at mid of pane (Region 1) and edge region (Region 2)

Strains were measured at the bottom (tensioned) surface of specimens. In case of tempered specimens the stress must first exceed the built-in compression stresses before tension develops, therefore, the so called *prestressed* layers of tempered specimens help to reduce the strains caused by deflection at same force level. Results of strain measurements indicated that the measured strains are higher in Region 2 than in Region 1, both in case of float non heat treated glasses and tempered glasses with thicknesses of 6, 12, 19 mm (Fig. 10.).

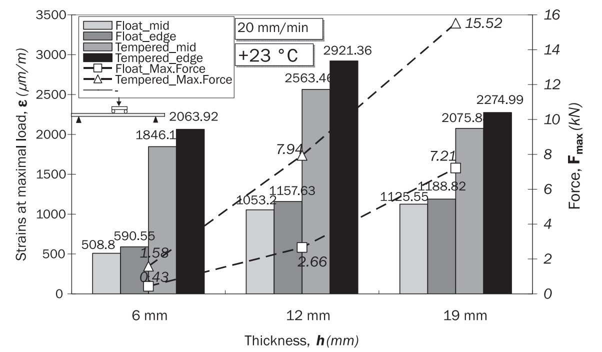


Fig. 10. Maximal force vs. strain at bottom surface in Region 1 (mid) and Region 2 (edge) of single tempered and float glass specimens thicknesses of 6, 12 or 19 mm, with loading rate of 20 mm/min
10. ábra Törőerő és törési alakváltozások az R1 és R2 tartományoknál, 6, 12 és 19 mm vastagságú float és edzett üvegek esetében, 20 mm/perc terhelési sebességnél

The ratio of maximal strain and ultimate force is illustrated as a function of glass thickness in Fig. 11.

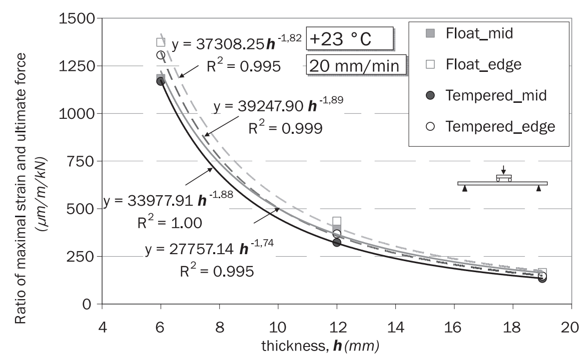


Fig. 11. Ratio of maximal strain and ultimate force at bottom surface in Region 1 (mid) and Region 2 (edge) of single tempered and float glass specimens vs. thicknesses of 6, 12 or 19 mm
11. ábra Törési alakváltozás és törőerő aránya R1 és R2 tartományoknál 6, 12 és 19 mm vastagságú float és edzett üvegek esetében, 20 mm/perc terhelési sebességnél

Fig. 11. indicates that the ratio of maximal strain and ultimate force decreases with increase of thickness for both float and tempered specimens calculated at Region 1 and Region 2, respectively. This ratio also indicates the effectiveness of tempering in case of single glass specimens.

To determine bending strength in four-point bending the following formula can be applied:

$$\sigma_{bB} = k\left[F_{\max}\frac{3(L_s - L_b)}{2bh^2} + \sigma_{bG}\right] \quad (1)$$

where, b-width of specimen; h-thickness of specimen; L_s-distance between the centre lines of the supporting rollers; L_b-distance between the centre lines of the bending rollers; y-central deflection of the specimen; $k=k_e$-dimensionless factor as function of y/h to determine the stress at the mid of span k=1; σ_{bB}-bending strength; σ_{bG}-bending stress imposed by the self-weight of the specimen.

The bending stresses should be calculated by applying a factor k to take into account non-uniformity of the stress filed, (see factor k in *Eq. (1)*) and the calculated bending stress is called *effective bending stress*. Factor k is used when it is required to determine the bending strength of glass where the effects of the edge conditions are important. For calculating the overall bending strength or equivalent bending strength of the surface area, including the edges the value k=1 shall be used. For calculating the bending strength or equivalent bending strength of the free edges of the glass pane $k=k_e$ shall be used. The appropriate value of k_e for use in *Eq. (1)* shall be obtained from Fig. 12., which gives the value of $k=k_e$ as a function of the value of y/h.

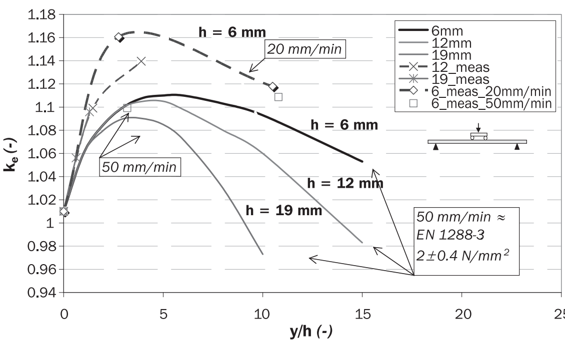


Fig. 12. Dimensionless factor k_e as a function of y/h of 6, 12, 19 mm thickness of glass, continuous lines as given in EN 1288-3:2000, dashed lines are measured values with loading rate of 20 mm/min, rectangles indicate measured values for 6 mm glass with loading rate of 50 mm/min

12. ábra Szorzótényező, k_e 6, 12, 19 mm vastagságú egyrétegű üvegekhez a lehajlás/vastagság (y/h) függvényében 50 és 20 mm/min terhelési sebességeknél. A folytonos vonalak az EN 1288-3:2000 szabványban megadott görbéket jelzik. A szaggatott vonalak a 20 mm/perc terhelési sebességhez javasolt értékeket jelzik

Based on the laboratory results the authors have shown that the value of factor k_e is influenced by the loading rate. The authors determined the values to factor k_e with applied loading rate of 20 mm/min in case of single glasses thickness of 6 mm, 12 mm and 19 mm. Fig. 12. indicated that in case of reduced testing speed from 50 mm/min to 20 mm/min k_e increases. Defects caused by edgework are initiations location of cracks and the nucleation of cracks needs. With increase of loading time more cracks can develop, therefore the stresses in Region 2 increase. Further investigations on the effect of glass strength in Region 2 with different type of edge works and testing speed should be done.

Stresses at selected points on a glass surface can be determined from strain measurements. Surface stresses have been calculated based on Hooke's law using the theoretical Young's modulus of glass $E=70\ 000\ N/mm^2$. The average of calculated surface strength, σ of individual single glass specimens and the bending strength, σ_{bB} calculated with *Eq. (1)* are indicated in Table 1.

Mid pane strength, σ_{bB} (in Region 1) and edge strength, $\sigma_{bB,edge}$ (in Region 2) have been calculated with *Eq. (1)* on the bottom surface of single non heat treated float (F) and tempered (E) glass specimens. Table 1. gives the surface stresses at maximal force which are different from the calculated bending strengths of single glass specimen with thicknesses of 6, 12 and 19 mm, respectively. The calculated surface stresses at maximal force are lower in case of single glass specimens with thickness of 6 mm than the bending strength. The maximal surface stress should be considered in case of glass panes thinner than 6 mm for both tempered or float glasses [4]. In case of specimens with large deformation (no appropriate shear resistance) the calculated strengths (both surface and bending) are overestimated for thin (6 mm) specimens with use of *Eq. (1)*, see also [4, 20]. In case of single glass specimens thicker than 12 mm or with appropriate shear resistance *Eq. (1)* can be applied.

The surface stresses are more influenced by the surface condition of glass element than the bending strength. Impacts on glass surface by hard, sharp particles e.g. scratching are the initial locations of cracks, which can develop and quickly propagate. When the surface stresses will reach the surface strength of the pane, fracture occurs. The probability of glass failure starting from the edge region is higher than of mid region. Edges of panes or bore holes contain more defects.

Specimens	h	Measured values (avg.)				Theoretical surface strength, σ		Calculated bending strength				
		$F_{max,m}$	$y_{max,m}$	$\varepsilon_{max,m}$ Mid (Region 1)	$\varepsilon_{max,m}$ Edge (Region 2)	Mid (Region 1)	Edge (Region 2)	σ_{bG}	σ_{bB} (Region 1)	y/h	k_e	$\sigma_{bB\ edge}$ (Region 2)
	mm	kN	mm	μm/m		N/mm²	N/mm²	N/mm²	N/mm²	-	-	N/mm²
	6	1.58	61.63	1846.14	2063.92	129.20	144.50	3.80	157.50	10.50	1.12	176.40
	12	7.94	46.15	2563.46	2921.36	179.40	204.50	1.90	191.40	3.81	1.14	218.20
E	19	15.52	24.73	2075.88	2274.99	145.30	159.20	1.20	145.40	1.29	1.10	159.90
	6	0.43	16.20	508.80	590.55	35.62	41.34	3.80	45.60	2.76	1.16	52.90
	12	2.66	17.41	1053.20	1157.63	73.70	81.00	1.90	65.40	1.42	1.10	71.90
F	19	7.21	11.87	1125.55	1188.82	78.80	83.20	1.20	68.20	0.62	1.06	72.30

Table 1. Bending strength and surface strength of tested single glass specimens, where symbols are: E - tempered glass, F - non heat treated glass (average values are avarages of four measurements)

1. táblázat Egyrétegű üvegek számított hajlító szilárdsága és alakváltozásmérések eredményeiből számított felületi szilárdságok (rövidítések: E - edzett üveget, F - float üveget jelölnek)

In case of float glass specimens the edge strength is more influenced by thickness and edge condition than in case of tempered specimens. Reaching the ultimate strain in edge region, fracture occurred. Therefore, the effect of the edge quality is important on load bearing capacity and durability of glass. Load bearing capacity of a glass pane with same thickness decreases with decrease of edge strength. Although the tested specimens were manufactured with machine polished edges, further glasses with different edgeworks were investigated for scanning electron-microscopic observation. Fig. 13. indicates that manually arrised edges contain defects in macroscopic scale.

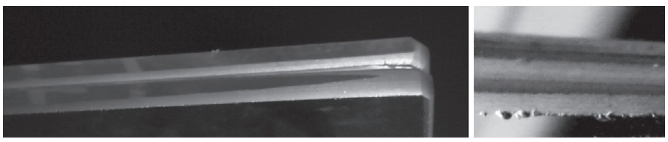


Fig. 13. Macroscopic defects as initiators of cracks at "manually arrised" edge of a glass pane
13. ábra Makroszkopikus zámolt élmegmunkálási hibák, mint a repedések kiindulási helyei

Fig. 13. indicates that the edge region of glass was the most damaged by manually arrised edgework which can be initiator of cracks. The roughness of edge surface decreases with use of finer abrasives or with acid etching. Edgework reduces the initiation of cracks caused by cutting of glass pane, see *as cut* edge in Fig. 14.

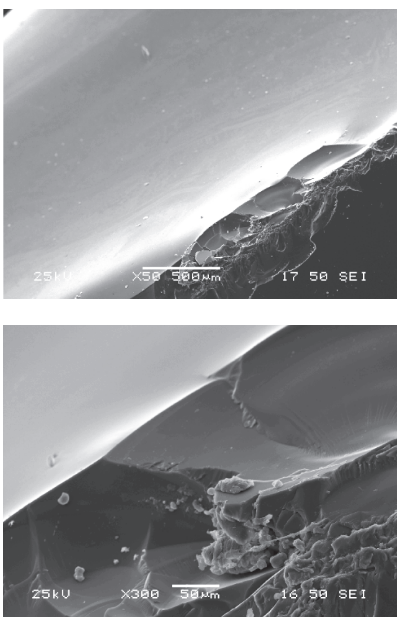
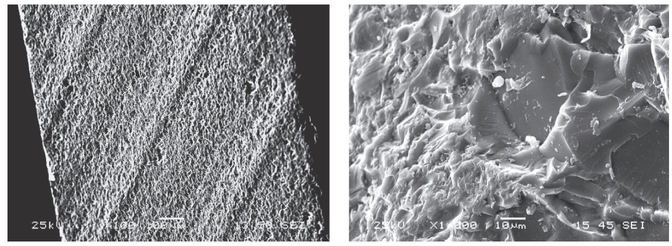
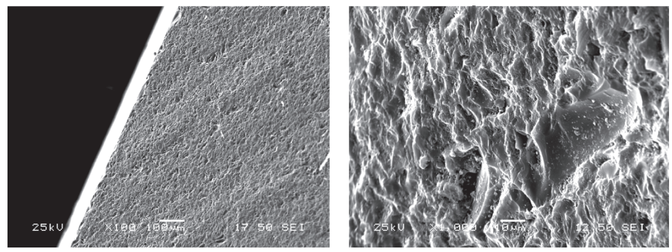


Fig. 14. Typical edge in "as cut" samples a) surface defects ×50, b) ×300 as potential initiator of cracks (photos taken by B. Koczka, Department of Inorganic and Analytical Chemistry, BME)
14. ábra Jellemző vágott él a) felületi hibák ×50, b) ×300 repedések potenciális kiindulási helyei

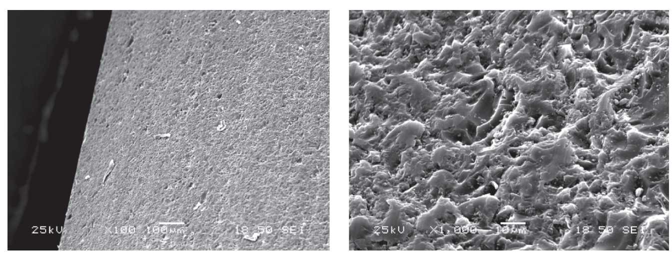
The traditional edge work process requires a steady stream of water and an abrasive compound. Abrasives are available in many different sizes (called *grits*), ranging from around mesh size 60 (= 250 micron, which is a very rough grit used for initial grinding) to around mesh size 600 (= 30 micron, an extremely fine grit). Generally, achieving a highly polished finish involves using a series of finer and finer abrasives (diamond discs or pad, SiC silica carbide slurry, Cerium dioxide etc.). A finished ground surface will appear whitish and dull (Figs. 15. b, c), but polished surface will shine with no visible scratches (Fig. 15. d).



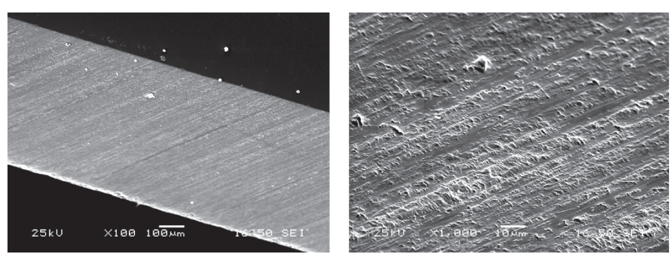
a) manually arrised edge, left: ×100; right: ×1000
very coarse abrasive size around 420 to 250 micron,
(diamond wheel speed in rpm's 1600-2400)
a) zámolt él, bal: ×100; jobb: ×1000



b) machine ground edge, left: ×100; right: ×1000
to remove large rough areas of glass the process begins with abrasive about 105 micron and require further processing down to medium size around 53 to 48 micron,
(speed of feed from 0.5 up to 4 m/min)
b) gépi csiszolt él, bal: ×100; jobb: ×1000



c) machine ground + acid etched edge, left: ×100; right: ×1000,
medium abrasive size around 53 to 48 micron, acid type of hydrogen-fluoride
c) gépi csiszolt + savmaratott él, bal: ×100; jobb: ×1000

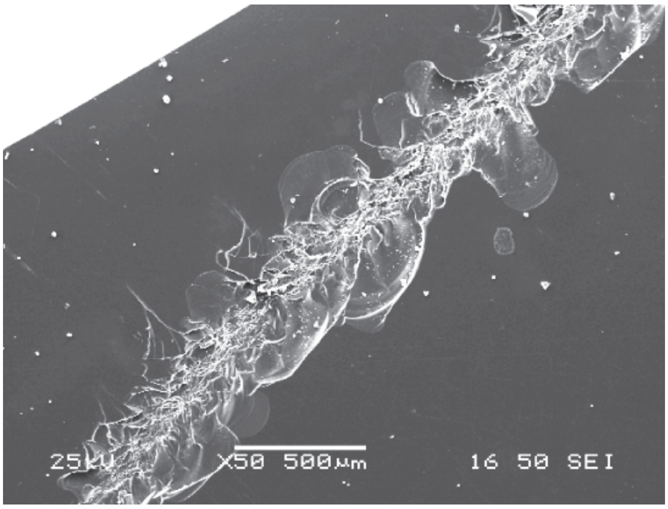


d) machine polished edge, left: ×100; right: ×1000
very fine Cerium dioxide (CeO_2) abrasive, size around 37 to 29 micron
d) polírozott él, bal: ×100; jobb: ×1000

Fig. 15. Typical edge finishing of a) manually arrised, b) machine ground, c) machine ground+ acid etched d) machine polished samples (photos taken by B. Koczka, Department of Inorganic and Analytical Chemistry, BME)
15. ábra Jellegzetes élmegmunkálások a) zámolt él, b) gépi csizsolt él, c) gépi csizsolt + savmaratott él, d) polírozott él (a fotókat a BME Szervetlen kémia és analítikai tanszékén Koczka B. készítette)

Fig. 15. indicates that the manually arrised edge has the roughest surfaces and will contain the most defects. By cutting

process initiated sharp crack tips can be eliminated or the size of initiated cracks can be reduced with use of edge finishing techniques. Transportation of glass can also cause flaws on the surface (Fig. 16.), which can propagate during the lifetime of glass. The results [14] have shown that the nature of flaws is an important factor in fatigue characterization. A flaw of given size may respond in different ways, depending on whether there are residual stresses present or cracks have been formed. This is also important in the context of lifetime design.



Surface scratch ×50, caused by steel razor, F=0,4 kN

Fig. 16. Typical surface of float glass surface scratch with "shell-like" fracture ×50, (photo taken by B. Koczka, BME Department of Inorganic and Analytical Chemistry)
16. ábra Üveg felületi karcolás jellegzetes „kagylós törési" képe 50×szeres nagyításban

4. Conclusions

1. The conclusions for **the effectiveness of tempering** can be summarized as follows:
   It is suggested herein to introduce the definition *effectiveness of tempering* (heat treatment). The effectiveness of tempering shows the proportion of load bearing properties (e.g. maximal force) of tempered glasses to non heat treated float glasses with the same thickness. **The higher the thickness the lower is the effectiveness of tempering.** The tempering is more effective in case of single layer glass specimens with thicknesses lower than 12 mm. The results indicated that **the effectiveness of tempering decreases with decrease of loading rate from 20 mm/min to 5 mm/min and 1 mm/min.**
2. The conclusions for the maximal strain at various regions and the influence of edgework **on the edge strength** can be summarized as follows:
   Strength of a glass pane should be investigated at least at 2 different regions. Region 1 at mid of pane and Region 2 at edge region. The effect of edge work should be also studied. The maximal strain of edge region (Region 2) is higher than of mid of pane (Region 1). In case of float glass specimens the edge strength is more influenced by thickness and edge condition than in case of tempered specimens. Reaching the ultimate strain in edge region fracture occurred, therefore, the effect of the edge quality is important on load bearing capacity and durability of glass. **The edge region of glass contains more defects caused by edgework. When glass fractures, it fails practically at the edges first and the crack propagates in the direction of mid of pane.** In case of reduce the testing speed from 50 mm/min to 20 mm/min k_e increases. **Defects caused by edgework are initiations location of cracks and the nucleation of cracks needs time. With increase of loading time more cracks can develop, therefore the stresses in Region 2 increase.**
3. The conclusions **for the relationship of bending strength and surface strength** can be summarized as follows:
   The surface strength (calculated by Hooke's law) is more influenced by the surface condition of glass element than the bending strength (calculated from the maximal moment). Surface strength results earlier failure than bending strength, especially in the case of thin float ($h < 10$ mm) glass panes. In case of float non heat treated and relatively thick ($h > 10$ mm) specimens the strength is considerably influenced by the size effect.
4. The conclusions for **different types of edgework** can be summarized as follows:
   By cutting process initiated sharp crack tips can be eliminated or the size of initiated cracks can be reduced with use of edge finishing techniques. The size (roughness) of the edge defects decreases with use of finer abrasives in the edge finishing process. The roughness of the edge surface decreases with use of acid etching.

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Teherhordó üvegek éleinek szilárdsága

Az egyrétegű üvegeket akkor hívhatjuk biztonsági üvegeknek, ha edzettek (hőkezelési eljárással) vagy dróthálóval erősítettek. Ha az edzett üveg eltörik, apró tompa szilánkokra esik szét. A hőkezelt vagy kémiailag edzett üvegek törésképeik miatt nem tartoznak a biztonsági üvegek közé, csak akkor, ha laminált formában alkalmazzák őket. Hajlító vizsgálatokat végeztünk (EN 1288-3:2000 szabvány szerinti elrendezéssel), és meghatároztuk az egyrétegű edzett és float üvegek hajlító szilárdságát az ismert összefüggésekkel. Továbbá a számított értékeket összehasonlítottuk az üveg felületén mért törési alakváltozásokból számított szilárdsági értékekkel nem hőkezelt float valamint edzett egyrétegű üvegeknél. Felmerült a kérdés: vajon az alakváltozások egyenlők lesznek-e az üvegtábla síkjának középpontjában vagy a tábla élekhez közeli helyen mérve? Alakváltozási méréseket végeztünk az üvegtábla közepén és a tábla élhez közeli tartományokban.

Az üveg tönkremenetele a mikroszkopikusan kicsiny repedéscsúcsokból indul ki. Az üvegtáblák felületén az elővigyázatos gyártásuk és szállításuk ellenére az éles tárgyakkal való érintkezésükkor és a környezeti hatások következtében karcolások keletkezhetnek. Az üvegfeldolgozás (pl. vágás, élmegmunkálás) által számos további olyan behatás éri az üveget, melyek repedéseket eredményezhetnek. Pásztázó elektronmikroszkópos vizsgálatokkal kimutattuk különböző élmegmunkálási eljárásokkal kialakított élek felületének hibáit. A legtöbb üveg erősítési módszer célja, hogy maradó nyomófeszültségeket vezessen az üvegtábla felületéhez közeli rétegeibe fizikai vagy kémiai úton. A keletkezett, nyomott réteg segíti a felületi repedések (karcolások) összezárását, ezáltal gátolja a repedések továbbterjedését, és növeli a hajlítószilárdságot. Tanulmányok [6, 14] kimutatták, hogy az üvegfelület erősítése jelentősen javítja a degradációval szembeni ellenállását, így különösen, teherhordó üvegek kültéri alkalmazásánál, edzett vagy hőkezelt üvegek alkalmazása javasolt.

Kulcsszavak: teherhordó üveg, élmegmunkálás, szilárdság, üveg, edzett üveg