ADVANCED DESIGN OF GLASS STRUCTURES

Lecture L1
Historical highlights, production and material characterisation

Viorel Ungureanu

European Erasmus Mundus Master Course
Sustainable Constructions
under Natural Hazards and Catastrophic Events
520121-1-2011-1-CZ-ERA MUNDUS-EMMC

SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

List of lessons

SUSCOS 2013/2015- 2E5 Advanced Design of Glass Structures

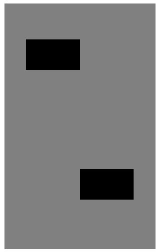
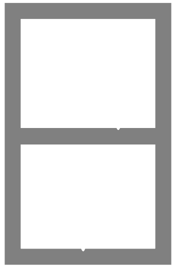
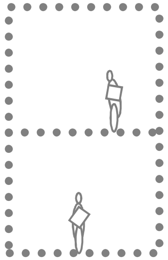
Date	Lectures: 08.30-10.00 2E5	Lectures: 10.30-12.00 2E5	Design Applications: 14.00-16.00 TP	Practice (individual work) 16.00-18.00
21.05	Historical highlights, production and material characterization	Glass strengthening methods (imposed favourable pre-stress field methods)	Design of members in tension. Design of members in compression	
22.05	Laminated glass and interlayers	Insulated glass units	Design of a glass column	
23.05	Fire resistant glass, photovoltaic glass, aesthetic coating	Fracture strength of glass, testing methods	Design of a glass fin	
weekend				
26.05	General design guidelines	Design of compressed glass members	Design of insulated glass units	Preliminary Design of Glass Footbridge
27.05	Design of glass beams	Plate and shear buckling	Design of transparent acoustic barrier	Preliminary Design of Glass Footbridge
28.05	Bolted connection of glass structures	Glued connection	Design of a glass balustrade	
29.05	Hybrid glass components	Curved glass, balustrades, staircases	Design of glued glass T-beam Design of cold bent glass canopy	
30.05	Glass facades	Glass bridges	Design of a hybrid steel – glass beam	
weekend				
02.06			free	
03.06			free	
04.06			TP 2E5 Deadline	
05.06				
06.06.		E X A M I N A T I O N 2E5		
weekend				

Objectives of the lecture

- Introduction to glass structures
- Historical review
- Production - glass products, edge quality
- Material and mechanical properties
- Testing of glass elements

Introduction

Transparency in Design

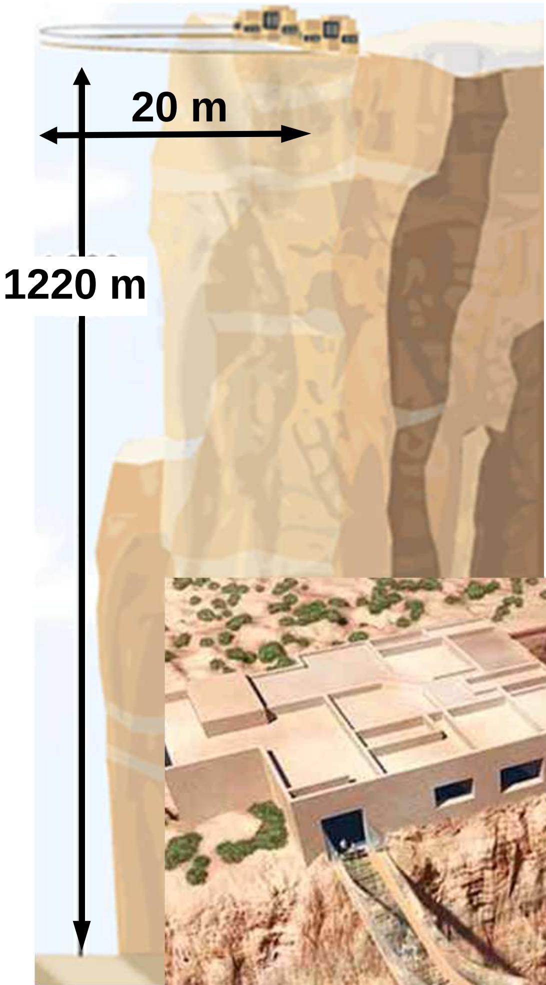




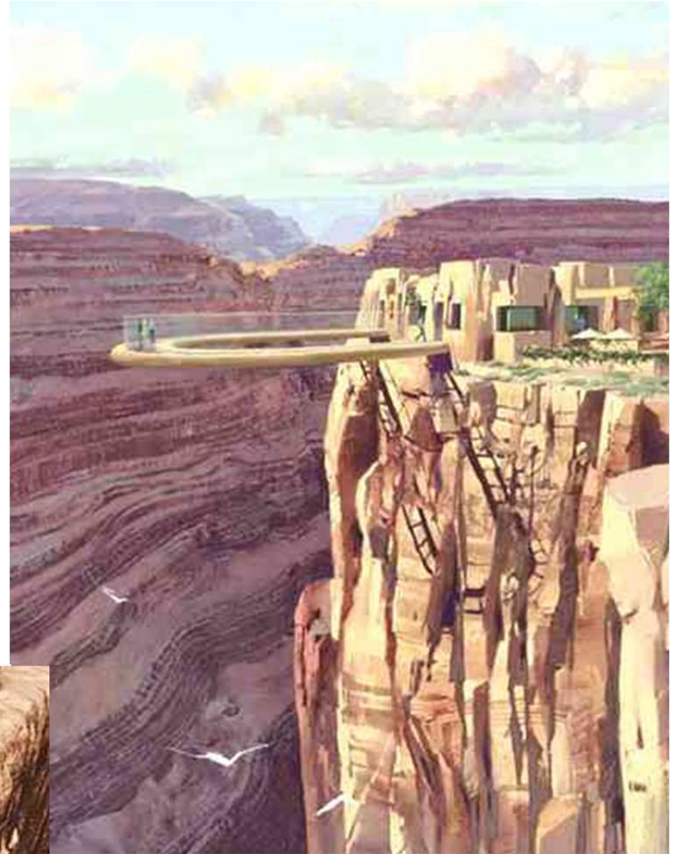
EVOLUTION



Introduction

Intention versus Realisation





Grand Canyon Skywalk USA

- cantilever bridge
- deck width 3,1m
- low iron glass
- glass railing 1,57m tall

Introduction

Grand Canyon Skywalk, USA - assembled on top of the canyon wall in line with its final placement and moved into final position by a jack and roll rig

- 8 box posts 810 x 810mm, 2 bridge box beams 810 x 1800mm

SUSCOS SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

Introduction

Objectives

Introduction

Historical review

Production

Chemical composition

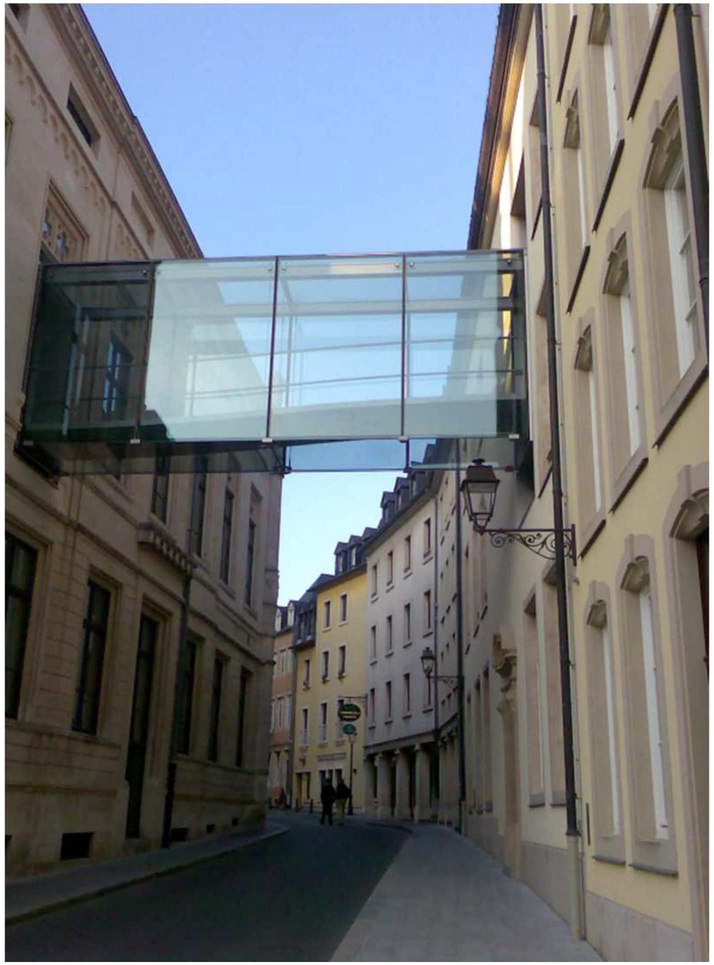
Glass products, edge quality

Material and mechanical properties

Strength of annealed glass

Introduction

- Load bearing elements from glass
- Purpose
- Architectural aspects of new structures
- Design of glass structures



Historical review

- the oldest finds of glass in Egypt – 10 000 BC
- glass recipe, Middle East, 668-626 BC: *”Take 60 parts of sand, 180 parts of ash from marine plants, 5 parts of chalk – and you will obtain glass”*
- **glass blower's pipe** - finding around turn of the era
- glass blowing to the forms – production of the bottles, mugs (hollow objects)

Celtic bracelets

6th century

Phoenician glass

SUSCOS SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

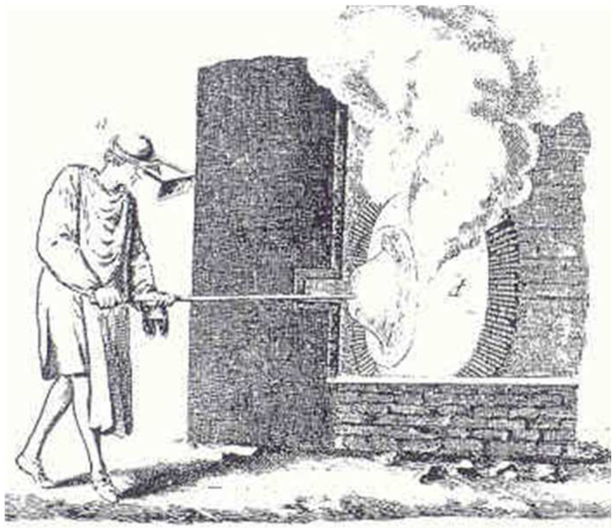
Historical review

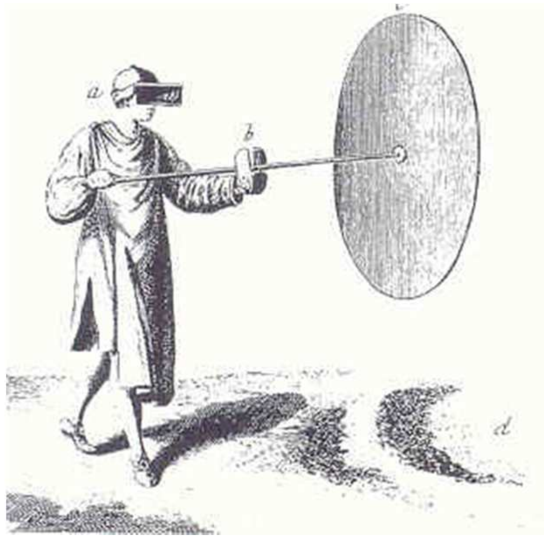
Flat glass

- 10th – 11th century → first panes for windows
- until 19th century: **crown process** –

glassmaker blew a large bubble of glass which he spun rapidly while glass was still soft production of disc in diameter 1.5 – 1.8 m, panes up to 0,5 x 0,75m

thinnest glass at the edge of the disk, thicker glass and more opaque toward the center



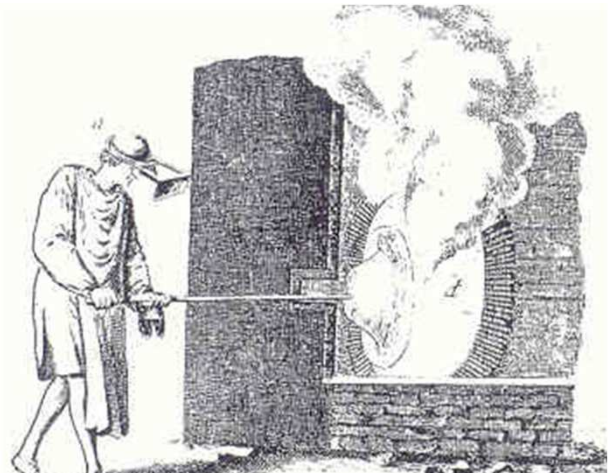


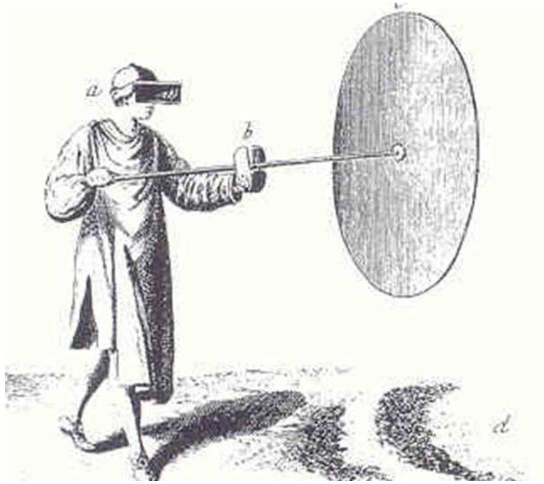
Historical review

Crown glass was an early type of window glass. In this process, glass was blown into a "crown" or hollow globe. This was then transferred from the blowpipe to a punty (iron rod) and then flattened by reheating and spinning out the bowl-shaped piece of glass (bullion) into a flat disk by centrifugal force, up to 1.5 to 1.8 meters in diameter. The glass was then cut to the size required.

The thinnest glass was in a band at the edge of the disk, with the glass becoming thicker and more opaque toward the center.

Due to the distribution of the best glass, in order to fill large window spaces many small diamond shapes would be cut from the edge of the disk and these would be mounted into a lead lattice work and fitted in the window. Known as a **bullseye**, the thicker center area around the punty mark was used for less expensive windows.





Historical review

Crown glass

- for large window small diamond shapes cut from the edge → mounted into a lead lattice work and fitted in the window
- thicker center area used for less expensive windows - **bullseye**

St. Jan Křtitel, Osek – around 1360

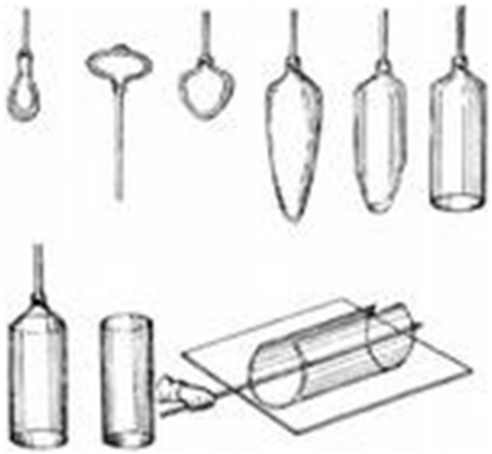
bullseyes

Historical review

Flat glass

cylinder process - broad sheets

- *blowing a bubble of glass, swinging it into a cylindrical shape, the ends of cylinder were cut off, it was slit longitudinally, reheated and opened out into flat sheet $\rightarrow$ panes up to 1,0 x 1,3m, more uniform thickness*

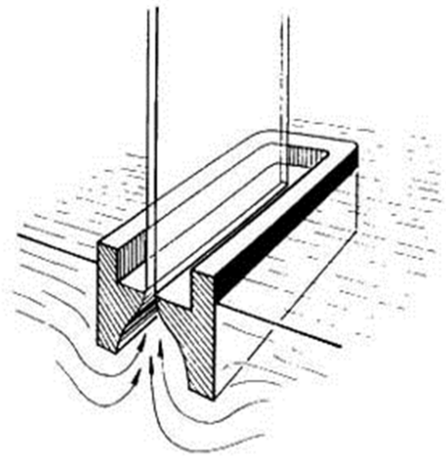


Historical review

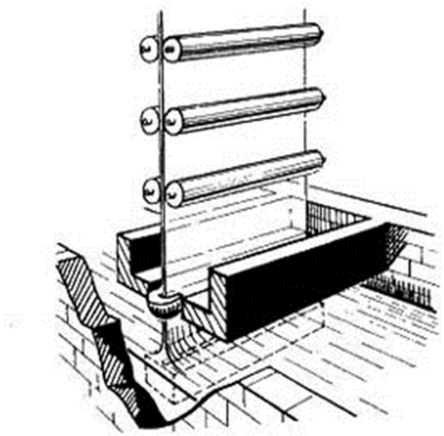
- ½ 19. century: invention of Siemens-Martin firing method – higher temperature → better quality of glass
- 1871 Pilkington – machine for automated production: from discontinuous to flow production
- beginning of the 20th century: development of various **drawn flat sheet processes**

1) *molten glass was drawn from furnace in thin stream, flattened and cooled by pulling between asbestos rollers*

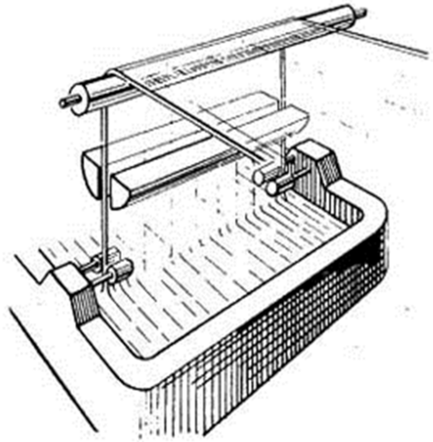
2) *rolling process: manufacture of patterned flat or wired glass – molten glass was poured between water-cooled rollers*



Fourcault

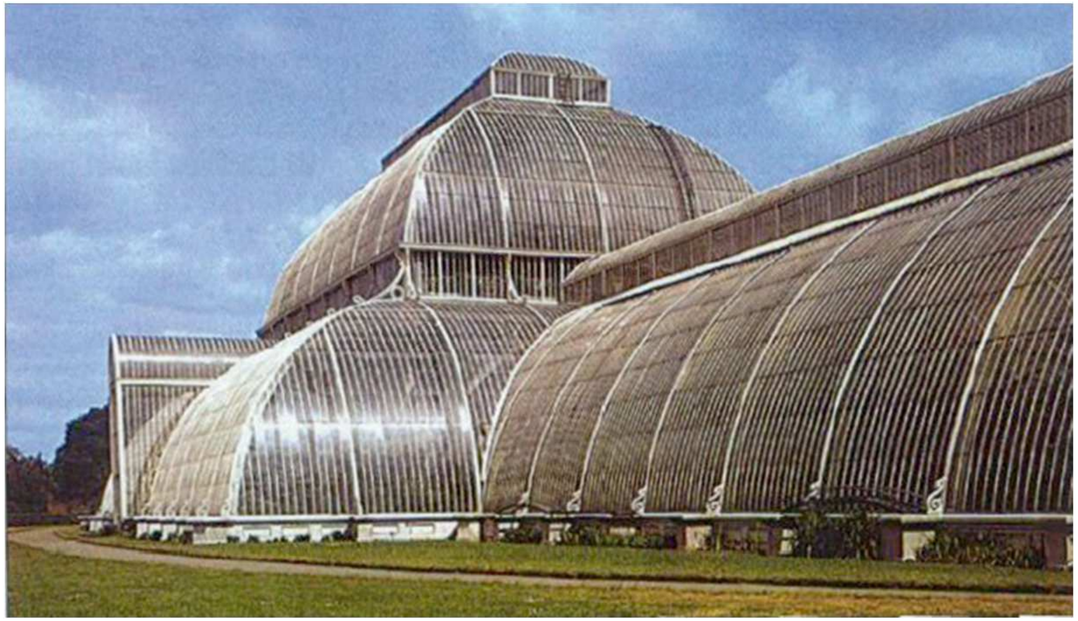


Pittsburgh



Libby-Owens

Historical review

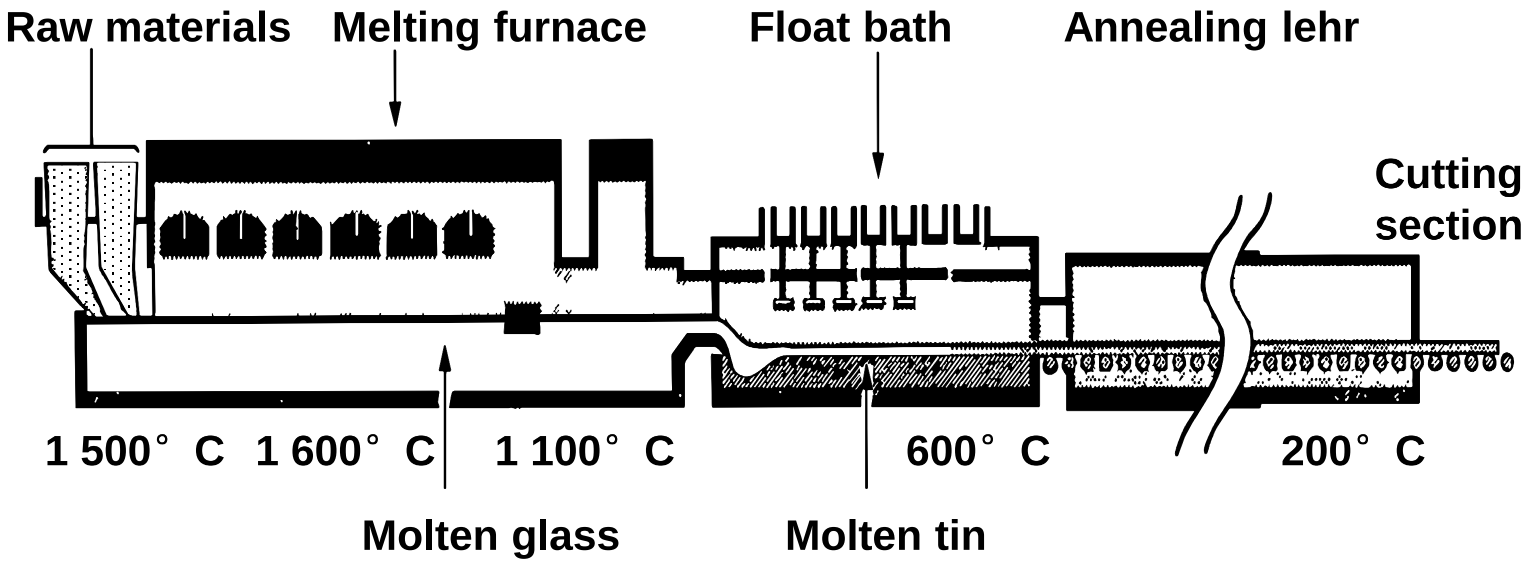


Palm House in Kew Gardens, UK, 1844

Chiselhampton, UK, around 1800

Production

- mid-20th century developed **float glass process** (Pilkington Brothers 1959)

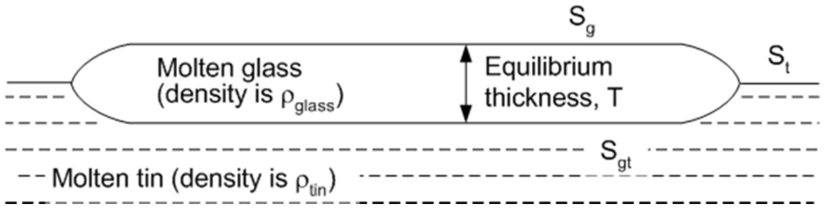


- *silica sand, soda ash, limestone and salt cake with cullet*
- *controlled heating permits glass to flow*
- *flat ribbon of uniform thickness, brilliant and flat parallel surfaces*

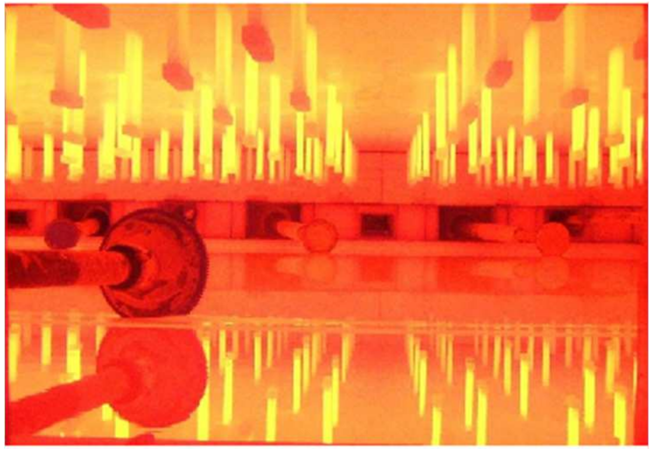
Production

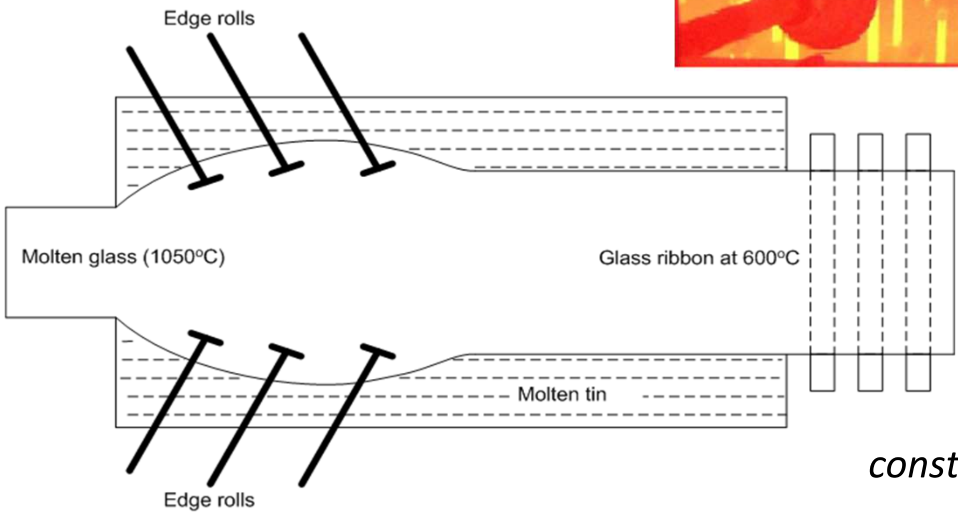
Float glass

- glass: 2500 kg/m³ x Sn: 6500 kg/m³
- tin (Sn) is liquid from 270 ºC to 2270 ºC
- equilibrium t = 7mm
- changing speed 0.4mm < t < 25 mm



tin bath





constant width

Production

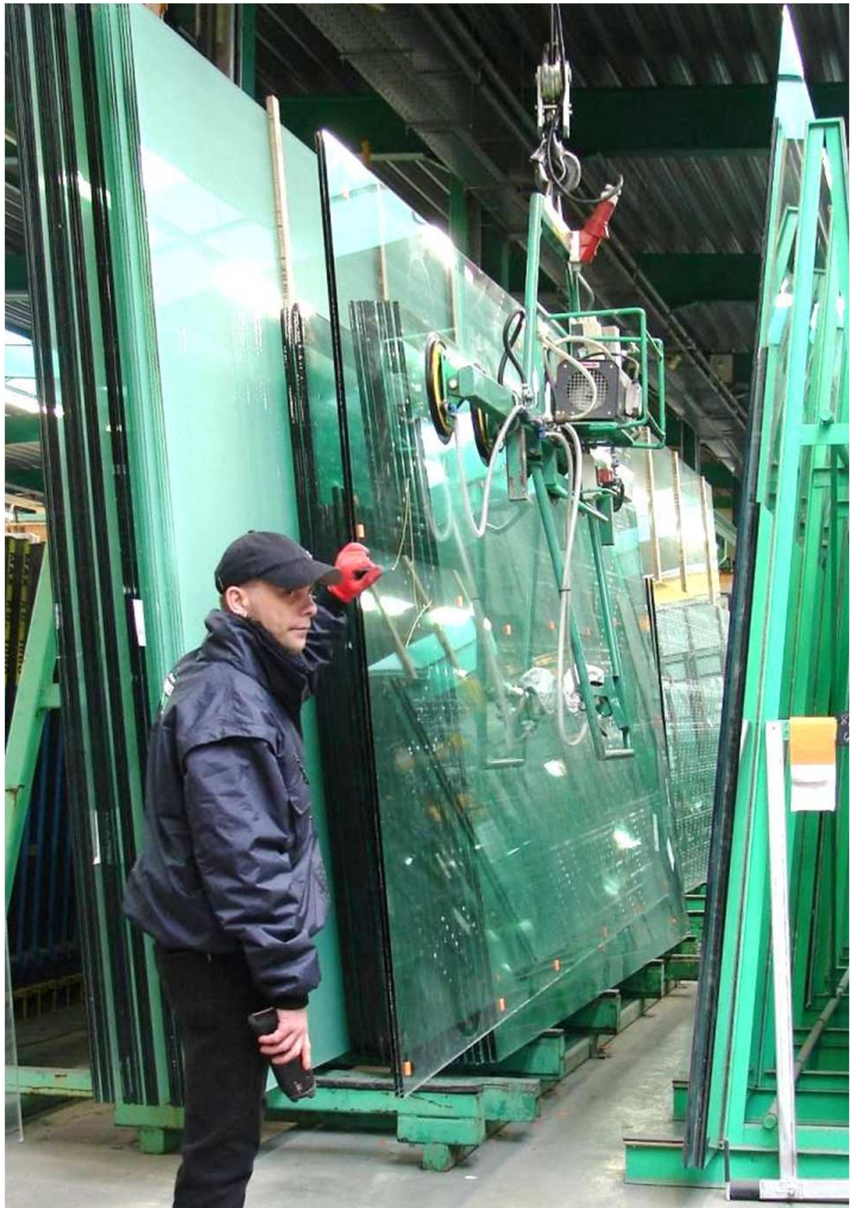
Float glass plant

Float glass ribbon cut to panel size

Production

Production of one float line

- 900 m float glass (4mm) per hour
- 700 tons per day
- 70 000 m² float glass (4mm) per day
- 35 full trucks per day



Chemical composition

Objectives

Introduction

Historical review

Production

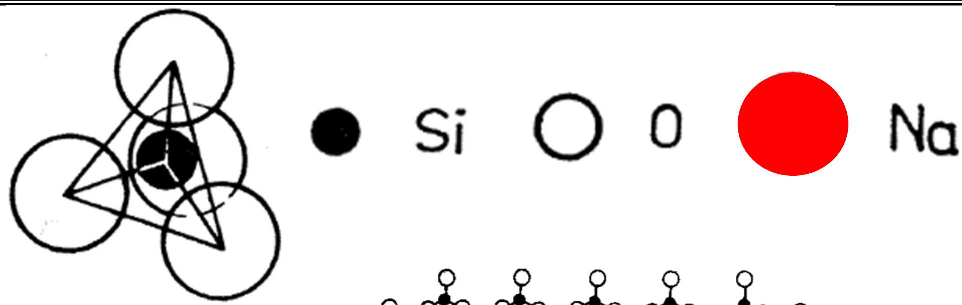
Chemical composition

Glass products, edge quality

Material and mechanical properties

Strength of annealed glass

What is glass ?



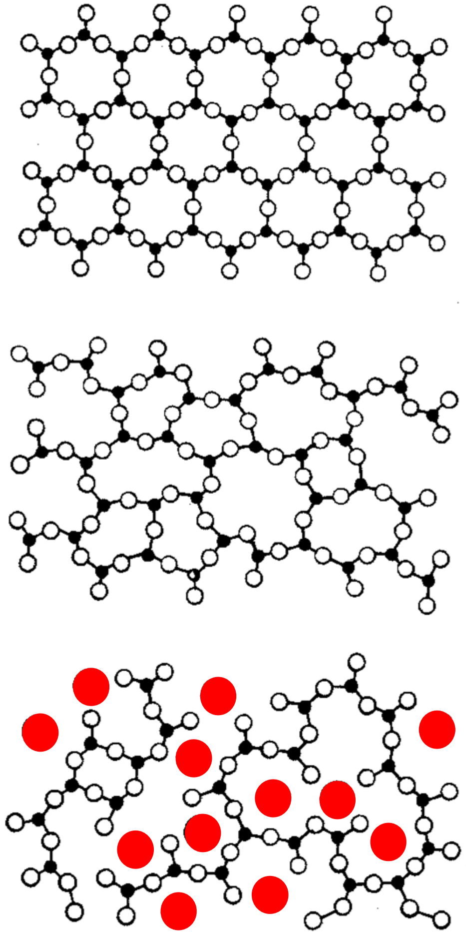
- **Quartz SiO_2 (Crystalline)**

  Silicon dioxide SiO_2

- **Silica Glass (Amorphous)**

- **Soda Lime Silica glass (Amorphous)**

  Sodium (Na) used to reduce the melting temperature



Chemical composition

Glass is isotropic, inorganic, visco-elastic material without lattice structure, solid at room temperature, liquid above transition zone ~580° C.

Typical composition:

- Silica SiO_2 70 – 74%
- Lime CaO 5 – 12%
- soda Na_2O 12 – 16%
- other chemical elements with influence to: spectral transmittance, thermal properties, tensile strength, fracture toughness, colour, etc.

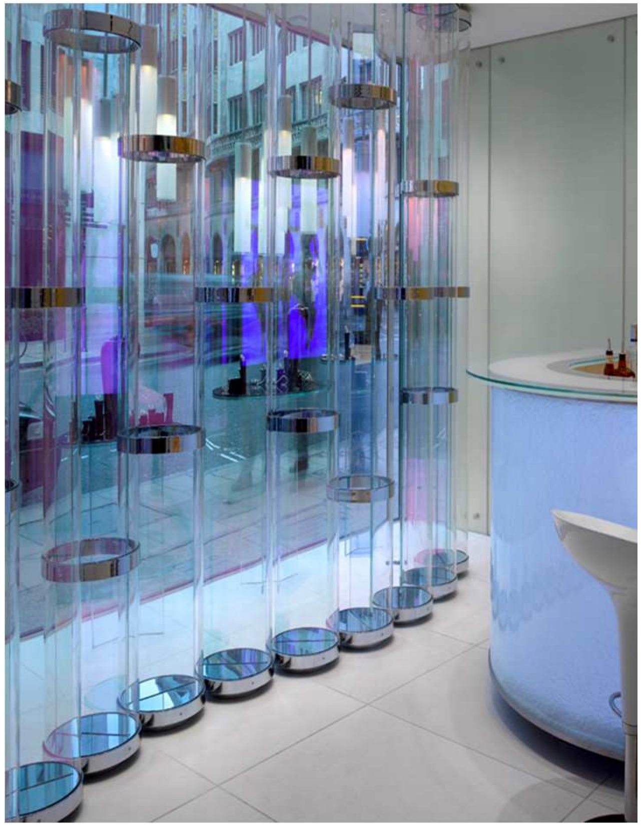
Glass colours produced by the addition of metal oxides

- **green – iron or chromium oxide**
- **red – copper oxide or gold oxide**
- **blue – cobalt oxide**

Chemical composition

		Soda Lime Silica Glass	Borosilicate Glass
Silica sand	SiO_2	69 – 74 %	70 – 87 %
Lime	CaO	5 – 14 %	–
Soda	Na_2O	10 – 16 %	0 – 8 %
Boron-oxide	B_2O_3	–	7 – 15 %
Magnesia	MgO	0 – 6 %	–
Alumina	Al_2O_3	0 – 3 %	0 – 8 %
Others	-	0 – 5 %	0 – 8 %

Indicatory values (mass %) according to EN 572-1&2



Borosilicate glass:

- *better resistance against thermal shock*
- *more expensive than Soda Lime Silica Glass*
- *exceptional in construction - e.g. glass tubes,…*

Glass products, edge quality

Size and tolerances

- **Nominal** thickness:

  2, 3, 4, 5, 6, 8, 10, 12, 15, 19 (and 25*) mm

- Standard sheet size: 6 m x 3.21 m

- Oversized sheets: *possible, though rather exceptional*

- Annealed glass:
  no (significant) residual stresses

Exceptionally large glass pane, made in China (25 m)

Glass products, edge quality

Manufacturing tolerances

Dimensional accuracy

- *length* *± 2 – 4 mm*
- *squareness (difference in length between diagonals of a rectangle)* *± 2 – 4 mm*
- *thickness of the float glass – in the table*
- *diameter of drilled holes* *± 0,5 mm*
- *distance of the hole's centres* *± 0,5 – 2 mm*

nominal thickness [mm]	tolerances [mm]
2 - 6 mm	*± 0,2 mm*
8 - 12 mm	*± 0,3 mm*
15 mm	*± 0,5 mm*
19 - 25 mm	*± 1,0 mm*

- **annealed flat glass – low initial deformation < L/2500 (negligible)**

Glass products, edge quality

- flat glass
  t = 3, 4, 5, 6, 7, 8, 10, 12, 15, 19, 25 mm,
  max. size 6,0 x 3,2 m

- channel glass C, U
  length up to 6,0 m

- circular tube
  thickness from 0,7 to 10,0 mm,
  diameters d = 3 to 325 mm

low iron channel glass profile

- glass block
  hollow - (115 x 115 x 80 mm - 300 x 300 x 95 mm)
  solid - (120 x 120 x 40 mm - 200 x 200 x 50 mm)

- curved glass
  radius R = 300 mm - ∞
  depend on the thickness, bends in one or two planes

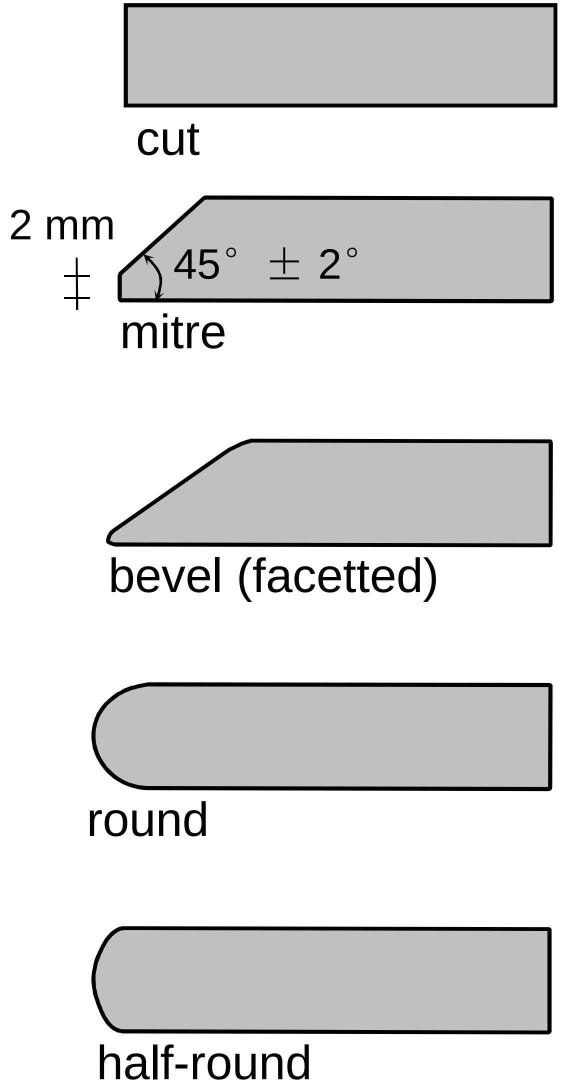
SUSCOS SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

Glass products, edge quality

Edge quality

- **CUT** – unfinished sides of glass with sharp edges;
- **ARRISED** – the sharp cut edges have been broken off or bevelled with a grinding tool
- **GROUND** – to required dimensions, with blank spots
- **FINE GROUND** – edge is fully ground over its full surfaces, without blank spots
- **POLISHED** – the fine ground edges are finely polished

Edge shape

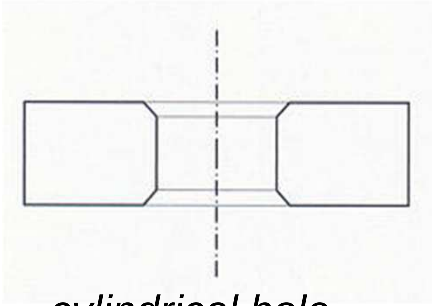


Edge Finishing

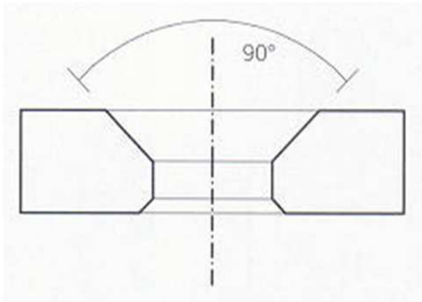
computer controlled machine

SUSCOS
SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

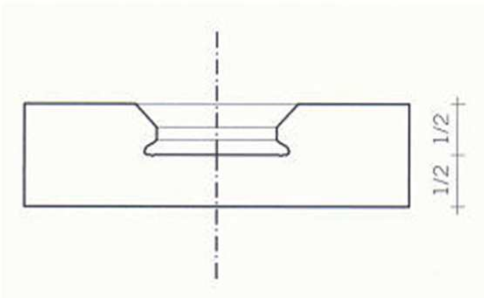
Hole Drilling / Water Jet Cutting



cylindrical hole



conical hole



undercut hole

water cutting

Edge Finishing

Material and mechanical properties

High durability

Resistance to:

- water percolation
- corrosion
- salt water
- carbonated water
- strong acids
- organic solvents
- ultra-violet radiation

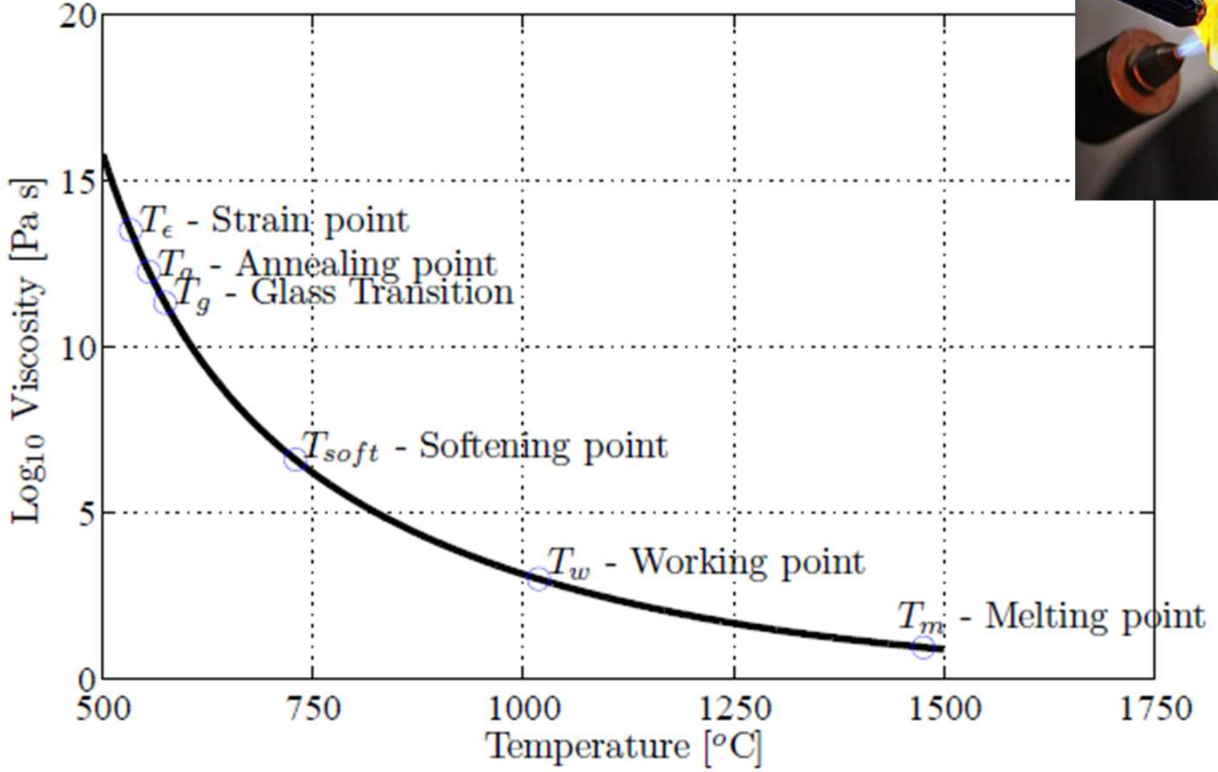
Material and mechanical properties

Glass property	Value	Unit
Density ρ	2500	kg/m^3
Young's modulus of elasticity E	**70 000**	**MPa**
Shear modulus G	30 000	MPa
Poisson's ratio ν	0,23	-
Coefficient of thermal expansion α_T	7,7 - 8,8 x 10^{-6}	1/K
Thermal conductivity λ	1,0	W/(mK)
Emissivity ε	0,89	-
Compressive strength	**up to 1 000**	**MPa**
Tensile strength	**10 - 100**	**MPa**

Effect of Temperature on the Viscosity of Glass

Name of reference temperature	*Symbol*	*Temp.* [°C]	*Viscosity* [Pa s]
Practical melting temperature[a]	T_m	1475	5
Working point	T_w	1020	1×10^3
Softening point	T_{soft}	730	$1 \times 10^{6.6}$
Glass transition temperature	T_g	575	$1 \times 10^{11.3}$
Annealing point[b]	T_a	550	$1 \times 10^{12.4}$
Strain point	T_ϵ	530	$1 \times 10^{13.5}$

[a] Values ranging from 1 Pa s to 10 Pa s.
[b] Sometimes the value of 1×10^{12} Pa s is used.



Effect of Temperature on the Viscosity of Glass

The chemical composition has an important influence on the viscosity, the melting temperature T_s and the thermal expansion coefficient α_T of glass.

While the melting temperature is about 1710° C for pure silica oxide, it drops to 1300 - 1600° C through the addition of alkali.

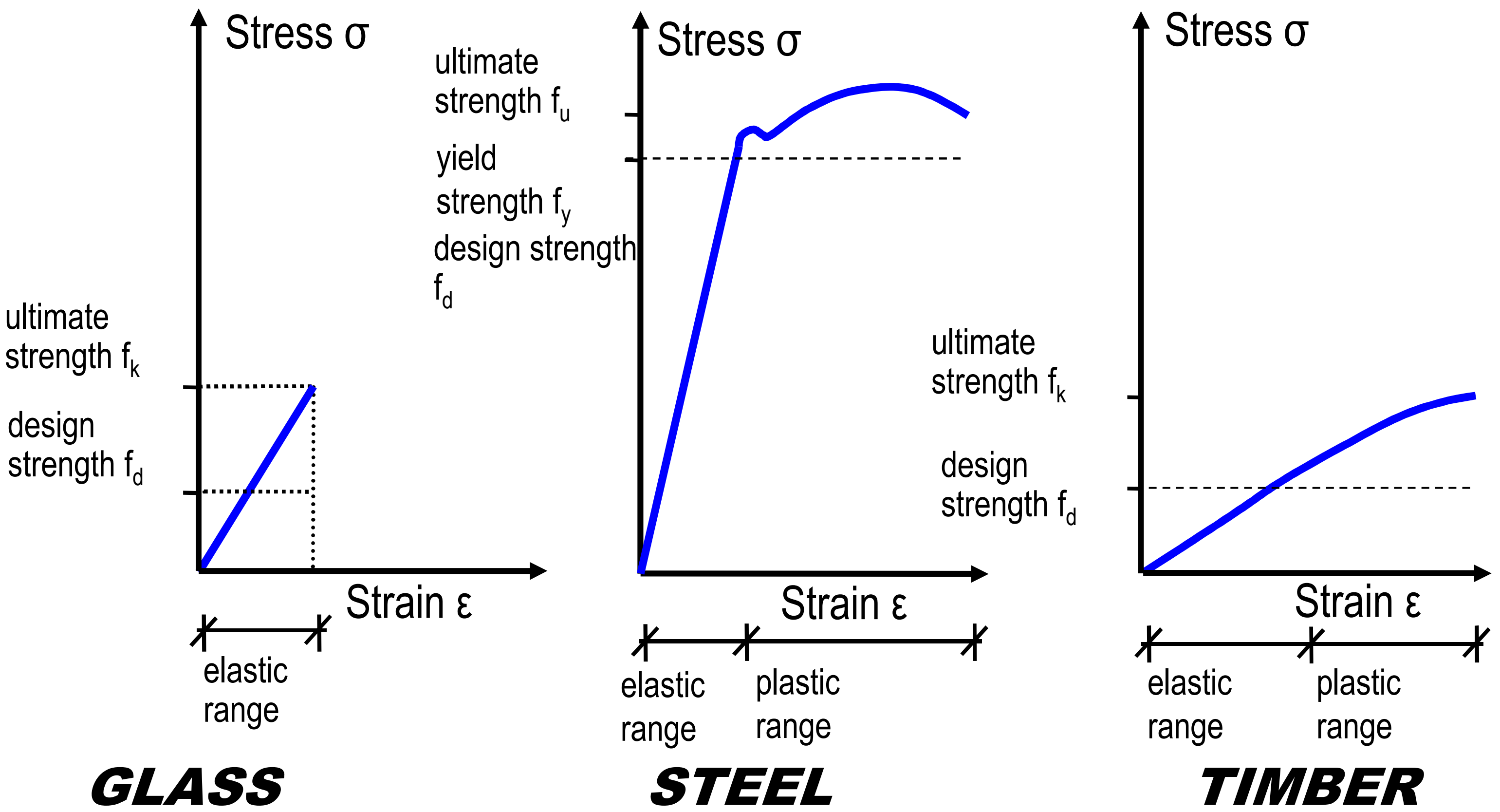
The thermal expansion coefficient is about $0{,}5 \cdot 10^{-6} K^{-1}$ for pure silica glass and $9 \cdot 10^{-6} K^{-1}$ for soda lime silica glass.

During the cooling of the liquid glass, its viscosity increases constantly until solidification at about 10^{14} Pa s. The temperature at solidification is called transition temperature T_g and is about 530 ° C for soda lime silica glass.

Melting gradual (Melted glass is like Honey).

Material and mechanical properties

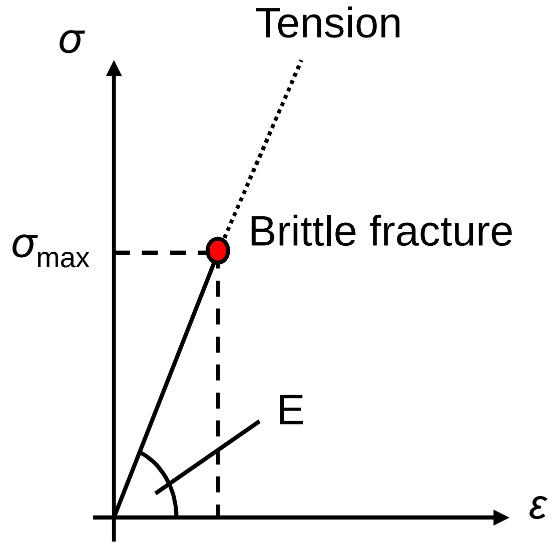
Objectives
Introduction
Historical review
Production
Chemical composition
Glass products, edge quality
Material and mechanical properties
Strength of annealed glass



- *annealed glass behaves perfectly elastically until the moment it fractures –* ***without warning***
- *dangerous shards*
- *no creep, no fatigue in the metallurgical sense*
- ***slow growth of cracks under sustained or cyclical loading***

Mechanical Behaviour

Linear elastic behaviour; no plasticity



BRITTLE BEHAVIOUR

- *Glass breaks suddenly*
- *Glass breaks completely*

As such, glass is NOT safe as a building material

Strength of annealed glass

Strength of glass depends on:

- surface condition and edge quality
- load duration
- environmental condition, especially humidity
- stress distribution on the surface
- size of the stressed area
- damage of glass surface – flaws and cracks

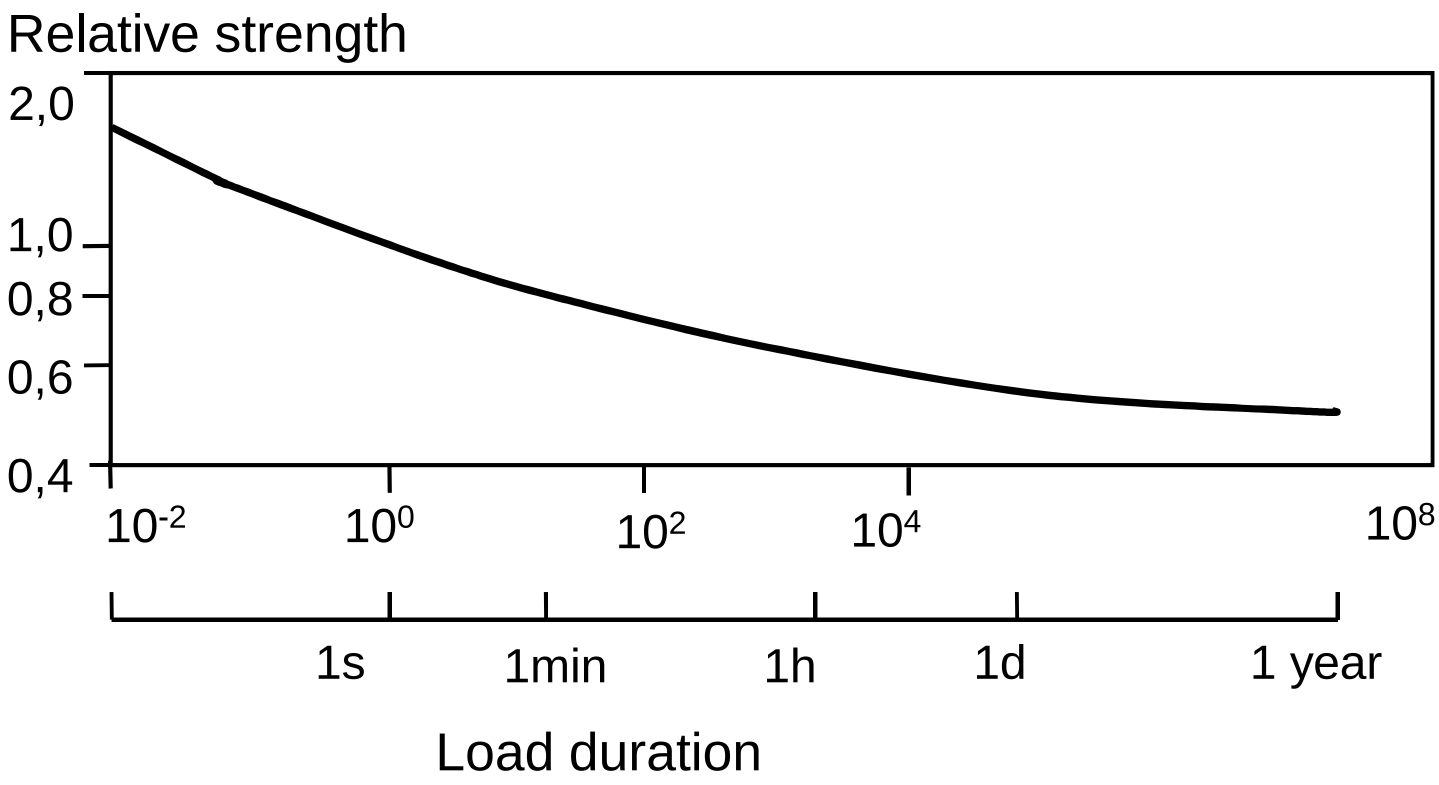
Strength of annealed glass

Irregularities and defects in glass

- manufacturing – in material (vents, sulphate scab, inclusions)
- mechanical processing – sawing, cutting, drilling, edge and surface grinding
- environment – cleaning (new micro cracks and scratches are generated)
- glass has ability to reverse damage in unstressed state (i.e. heal the micro cracks)

Strength of annealed glass

Relationship between time to failure and applied stress



Strength of annealed glass is time-depended

Strength of annealed glass

Relationship between time to failure and applied stress

$$\sigma^n T = constant$$

σ - stress

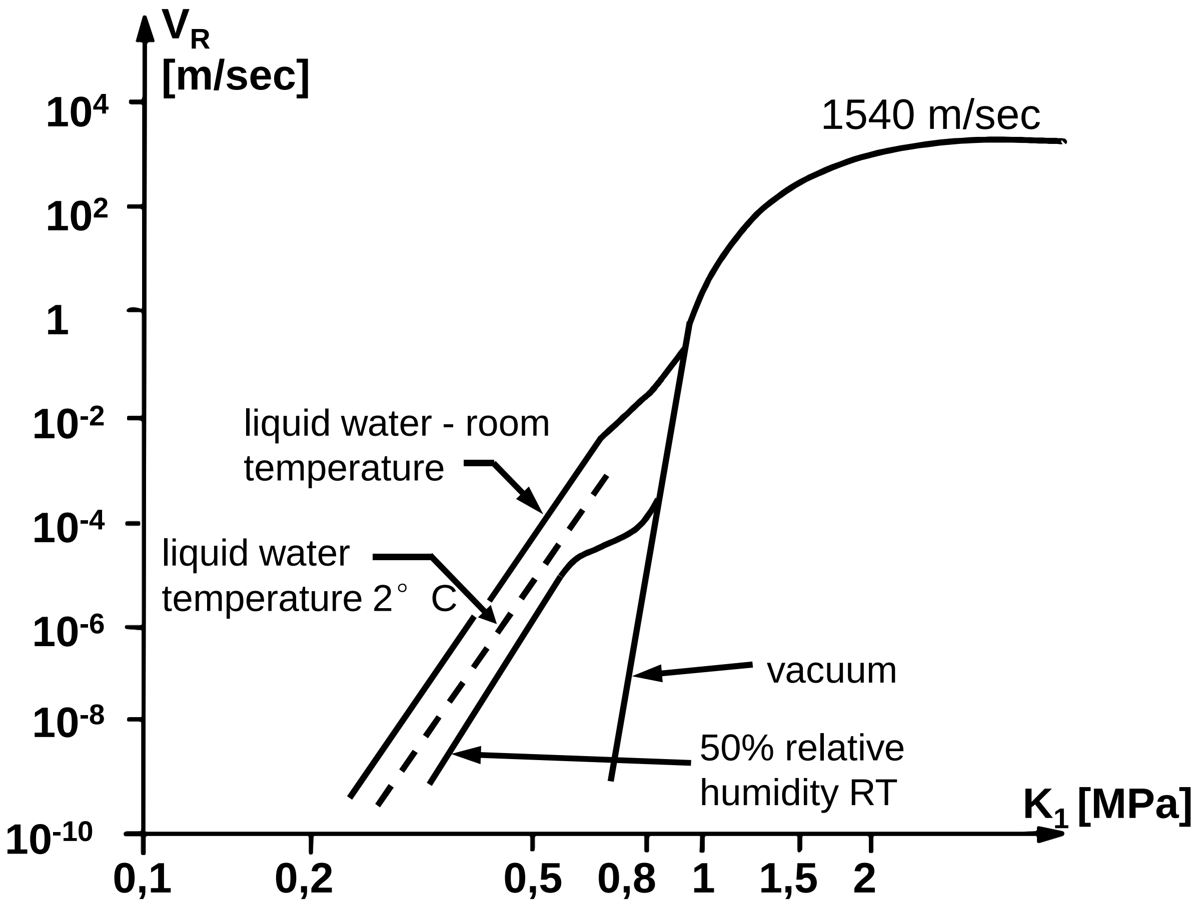
T - duration of stress

n - constant

environment	**constant *n***
water at 25°C – recommended for design purposes	16,0
air with 50% relative humidity at 25° C	18,1
air with 10% relative humidity at 25° C	27,0
vacuum	70,0
melting snow at 2°C	16,0

Strength of annealed glass

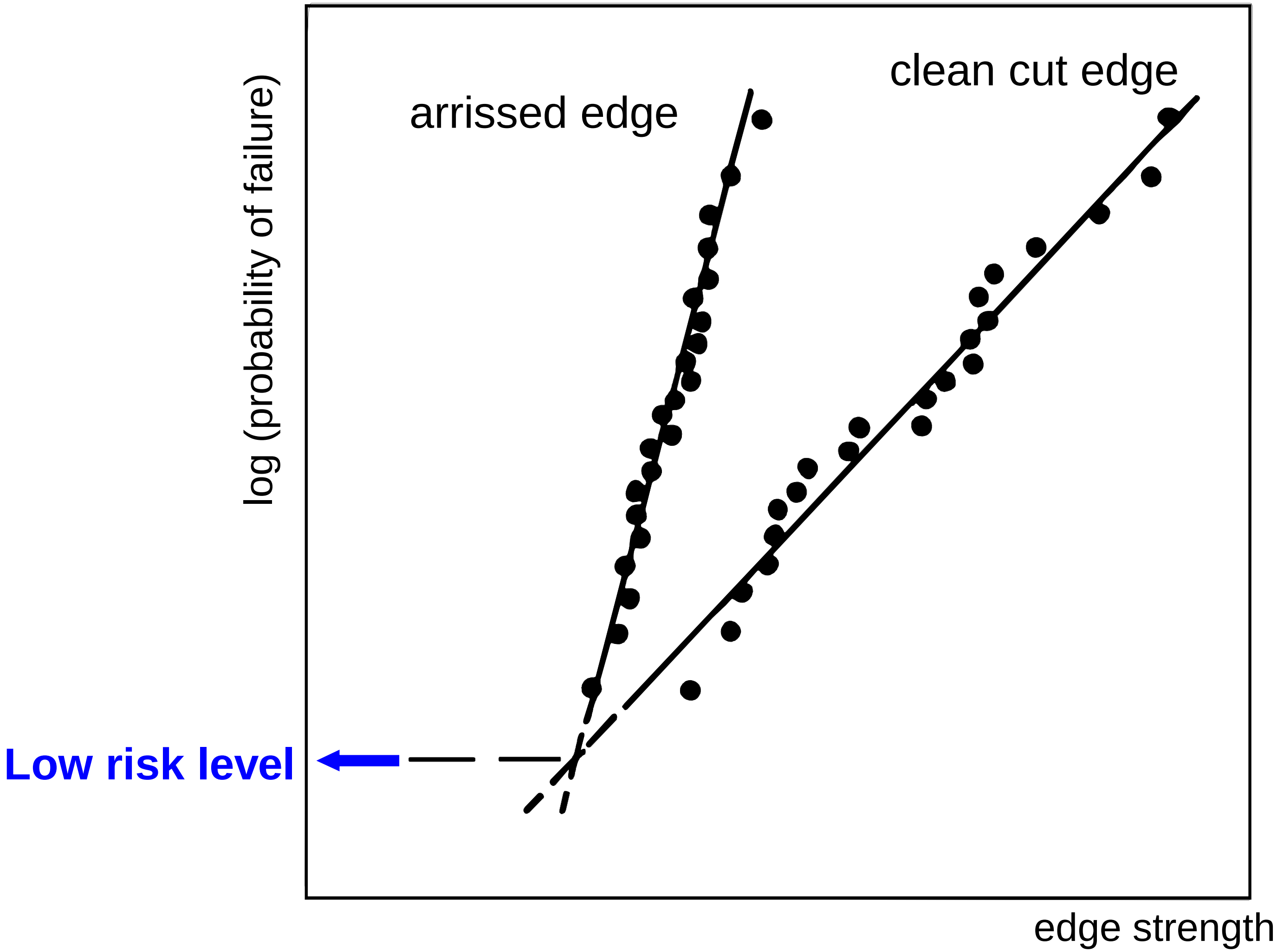
Graph of crack growth speed versus stress intensity for different humidities



Humidity encourage crack growth

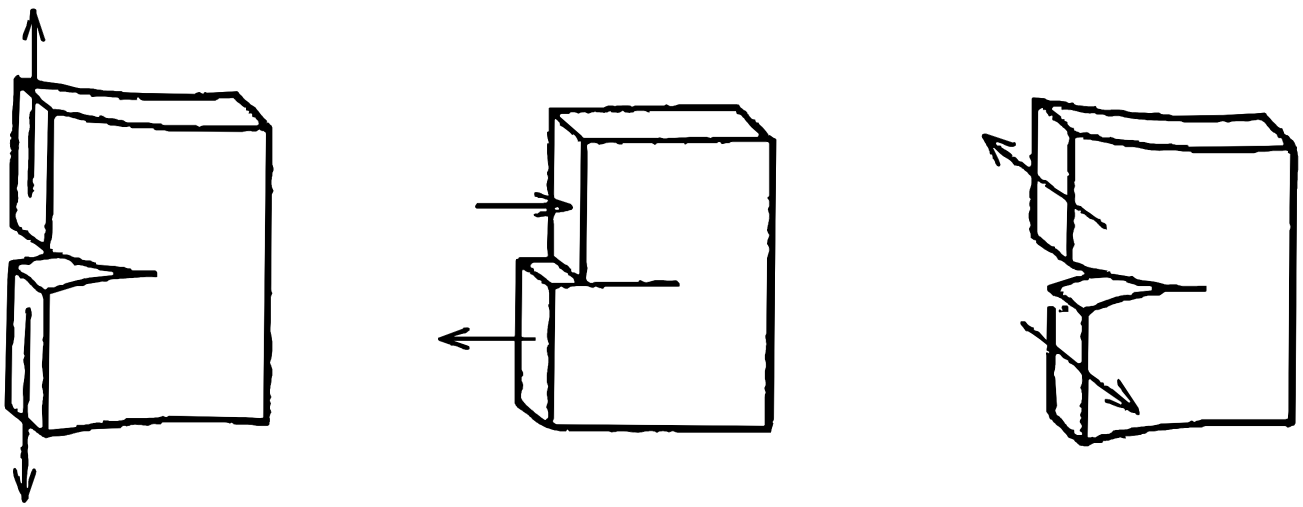
Strength of annealed glass

Edge finishing



Strength of annealed glass

Different type of flaw opening → type of loading



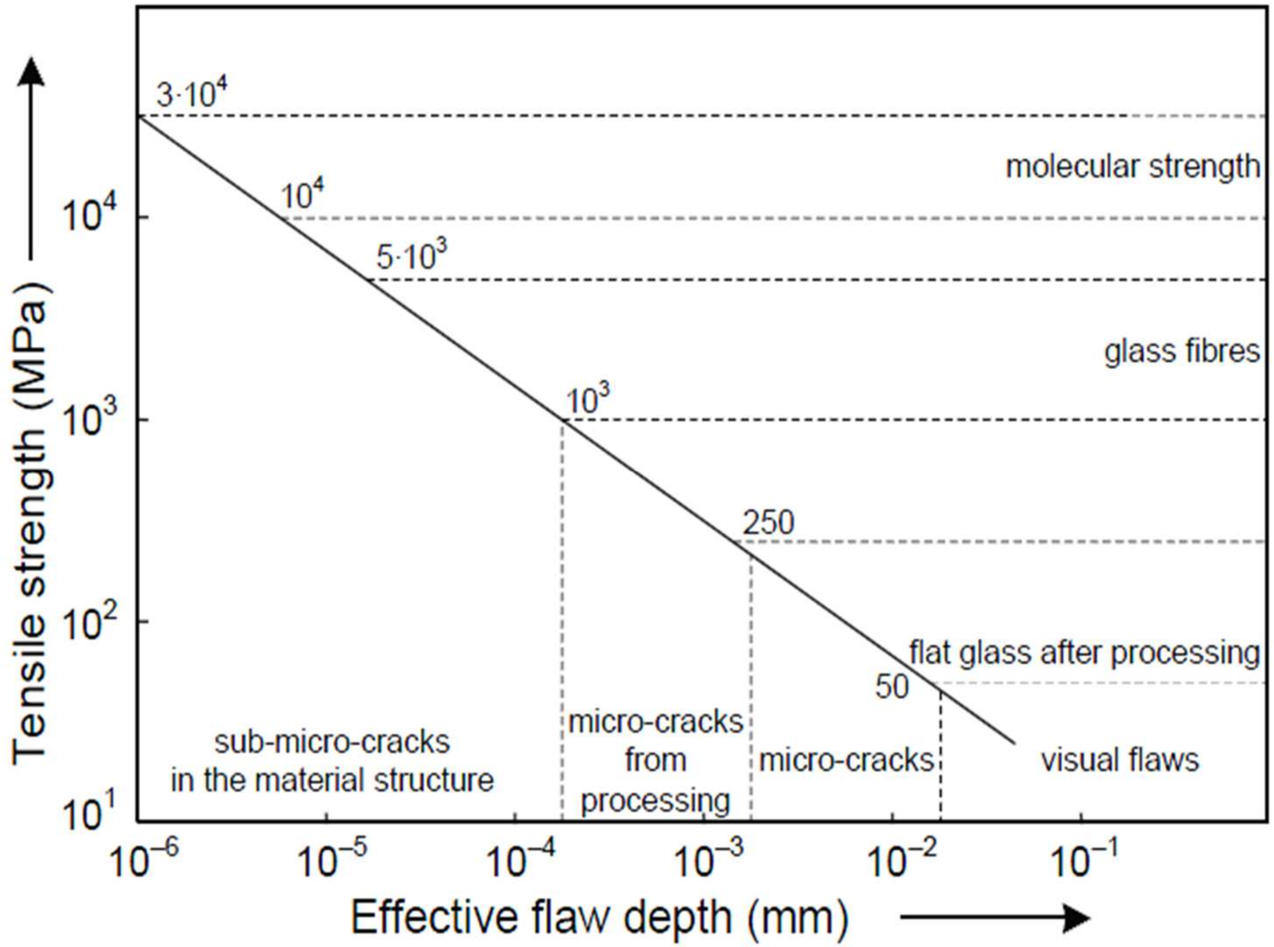
a) tensile stress perpendicular to the plane of crack

b) shear stress parallel to the plane of crack and perpendicular to its edge

c) shear stress parallel to the plane of crack and of its edge

SUSCOS SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

Influence of surface flaws

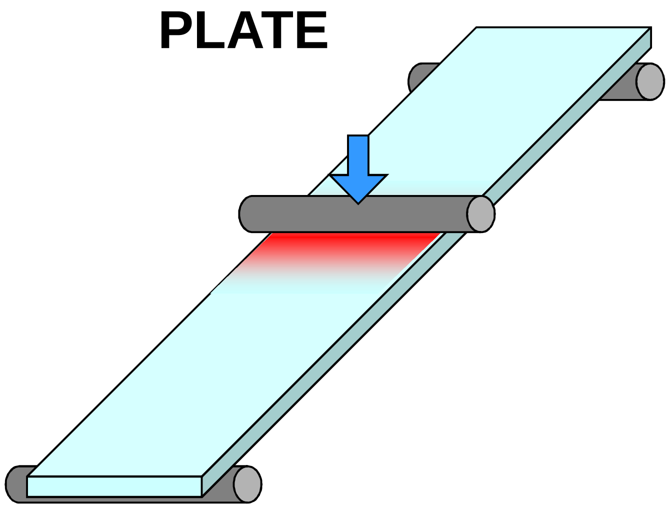


Typical short-term strengths as a function of the flaw depth

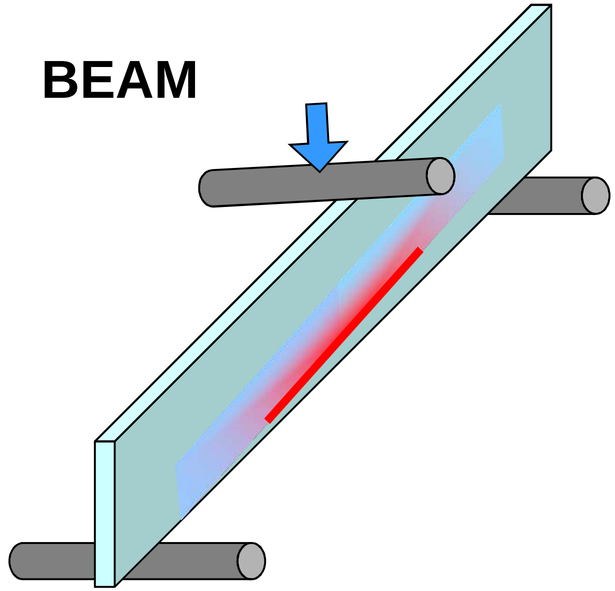
SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

Strength of glass

Glass used as Plate or Beam…



- *planar surface loading*
- *codes available*



- *edge loading*
- *edge = damage*
- *no codes*
- *need of experiments*

Edges of annealed glass weaker than its flat surface → annealed glass beams designed to lower stresses in comparison with glass plates

References

Educational pack of COSTActin TU0905 „Structural Glass - Novel design methods and next generation products“

HALDIMANN, Matthias; LUIBLE, Andreas; OVEREND, Mauro.
Structural Use of Glass. Structural Engineering Documents 10 , IABSE, Zürich:2008. ISBN 978-3-85748-119-2

RICE, Peter; DUTTON, Hugh.
Structural Glass, E & FN SPON, 1995.

WIGGINGTON, Michael.
Glass in Architecture, Phaidon Press, 1996.

KNAACK, Ulrich.
Konstruktiver Glasbau, Rudolf Müller, 1998.

SCHITTICH, Christian; STAIB, Gerald; BALKOW, Dieter; SCHULER, Matthias; SOBEK, Werner.
Glass Construction Manual, Basel: Birkhäuser Edition Detail, 1999.

NIJSSE, Rob.
Glass in Structures, Birkhäuser, 2003.

KALTENBACH, Frank.
Transluzente Materialien, Detail Praxis Edition Detail, 2004.

WURM, Jan.
Glass Structures – Design and construction of self-supporting skins, Basel-Boston-Berlin: Birkhäuser, 2007.

THE INSTITUTION OF STRUCTURAL ENGINEERS
Structural use of glass in buildings, London: The institution of Structural Engineers, 1999.

This lecture was prepared for the 1st Edition of SUSCOS (2012/14) by Prof. Sandra Jordão (UC).

Adaptations brought by Prof. Viorel Ungureanu (UPT) for 2nd Edition of SUSCOS

Thank you
for your kind attention

viorel.ungureanu@upt.ro

http://steel.fsv.cvut.cz/suscos

European Commission
ERASMUS
MUNDUS

SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS