1E5 Advanced design of glass structures

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List of lessons

1) History, chemical composition, production
2) **Glass as a material for load bearing structures**
3) Design of laminated plates
4) Design of glass beams
5) Design of compressed members
6) Hybrid load-bearing members
7) Curved glass members
8) Design of bolted connection
9) Design of glued connection
10) Glass facades
11) Glass roofs
12) Examples of glass structures

Objectives of the lecture

- Toughened glass, heat-strengthened glass, chemically strengthened glass
- Laminated glass
- Aesthetic coatings
- Conclusions

Toughened glass

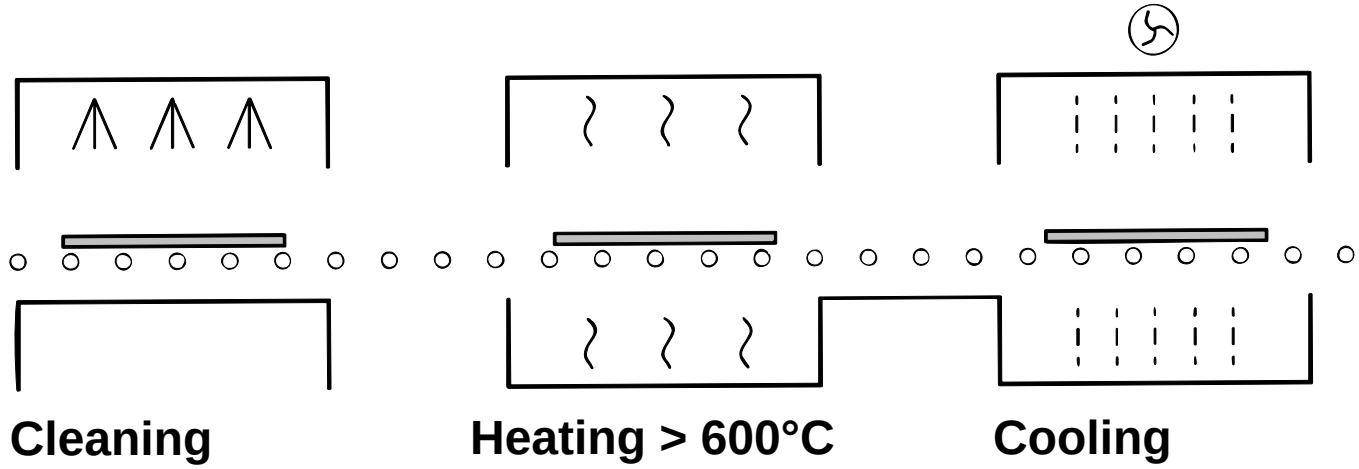
Annealed float glass - insufficient strength in tension

Strength refined glass

- Treatment of glass: greater resistance to mechanical and thermal loads
- Three different basic types with regards to the strength and fracture patterns

Toughened glass

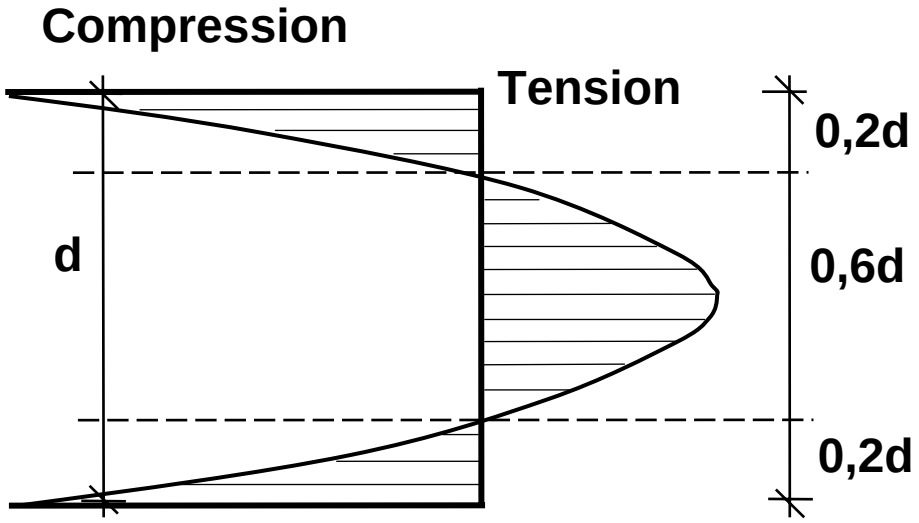
Toughened glass (fully tempered glass)



Manufacturing steps for tempered glass

Toughened glass

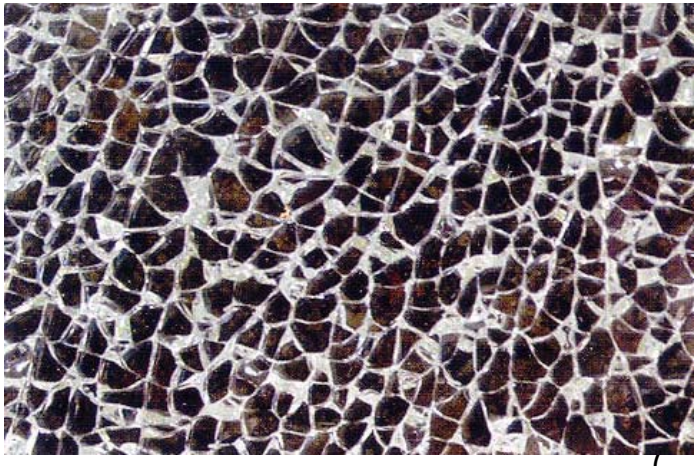
- quenching (fast cooling) with air
- cooling and stiffening first on the surface, delayed cooling and consolidation of the core → internal stress (parabolic distribution)
- surface in compression, core in tension



Toughened glass

Advantages

- high value of bending strength (compressive surface stress 90 – 150MPa + tensile strength of annealed glass 40MPa)
- compressive stress not influenced by surface defects
- withstand local temperature differences up to 150°C (float glass 40°C)
- overloading or damage – glass breaks into numerous small pieces, not dangerous

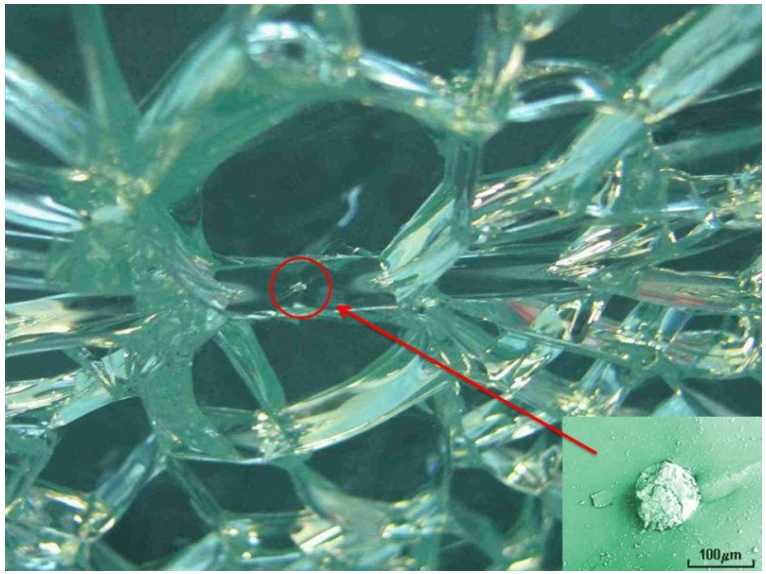


Typical fracture pattern of tempered glass: small fragments or dice

Toughened glass

Disadvantages

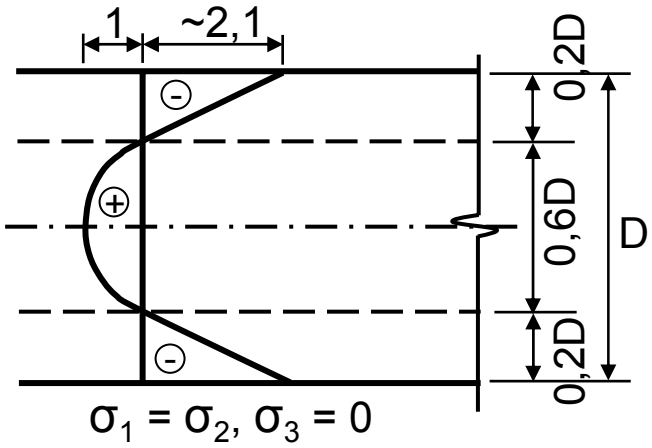
- glass must be at least 4mm thick
- thermal treatment after mechanical work - cutting, drilling
- greater initial deformation – sinusoidal waves from rollers
- spontaneous fracture: invisible nickel sulphide inclusions (NiS), which expand their volume; up to 2 years after production → destructive **Heat-soak test** (DIN 18516):

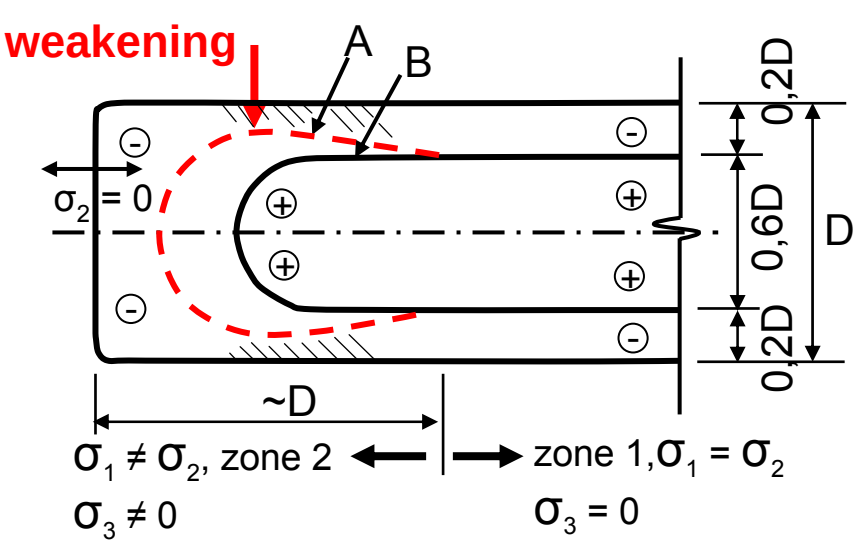


Nickel sulphide inclusions

Toughened glass

Weakened areas of the edge stresses in comparison to the body stresses - toughened glass





Zone 1: central area

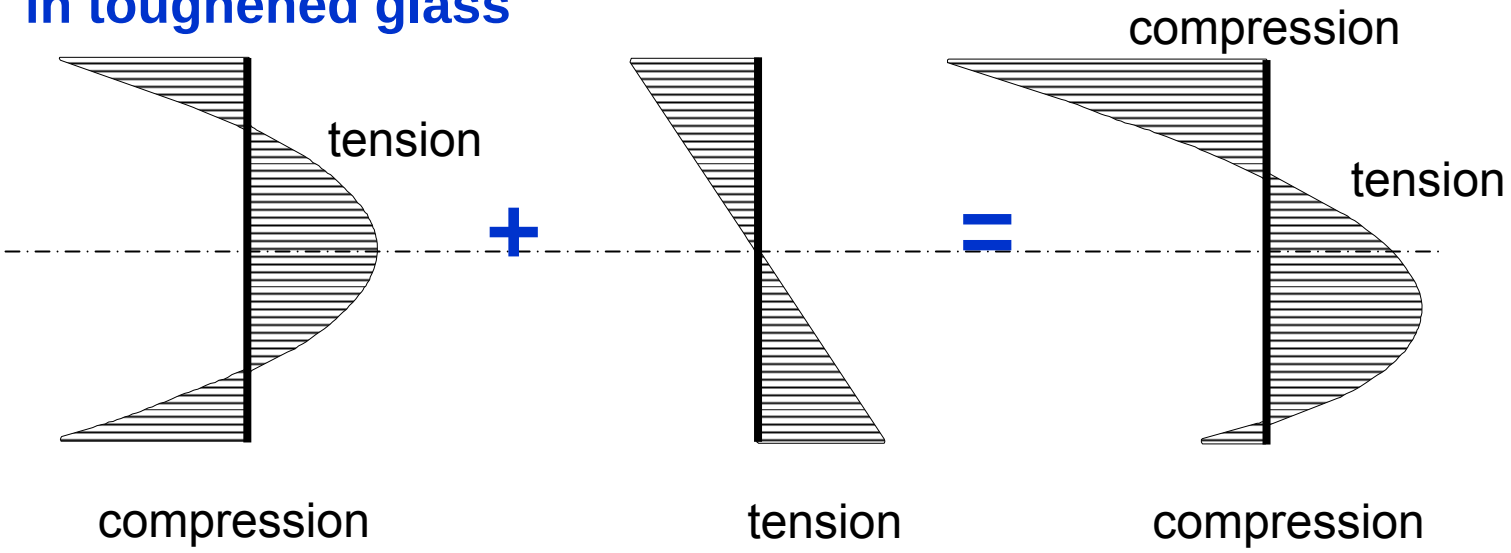
Zone 2: edge

Toughened glass

Toughened glass upon loading

Stress distribution in toughened glass

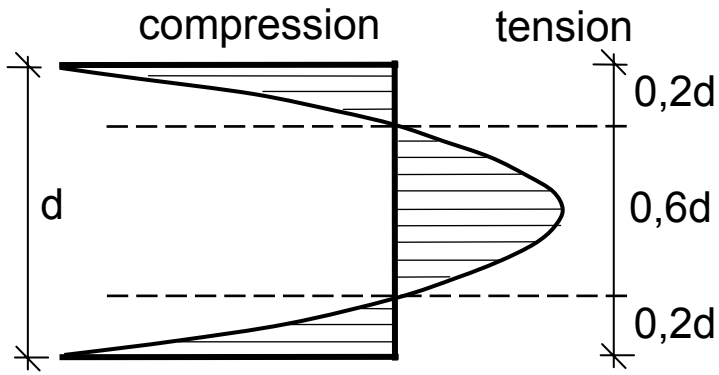
Bending stress



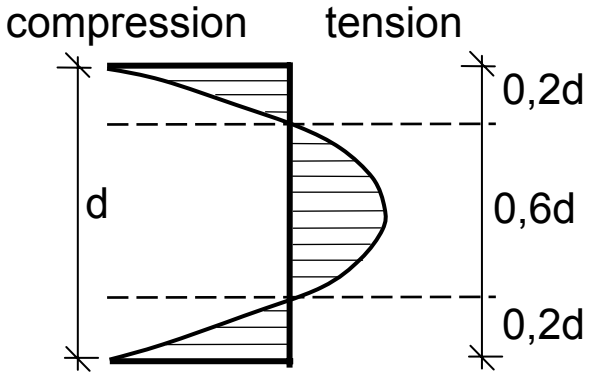
Heat strengthened glass

Heat strengthened glass (partially tempered glass)

- similar production – from same initial temperature slower cooling
- reduction of the surface pre-stress level (35 – 55 MPa)
- withstand local temperature differences up to 100°C
- greater initial deformation in comparison with float glass



internal stress: 90 – 150 MPa

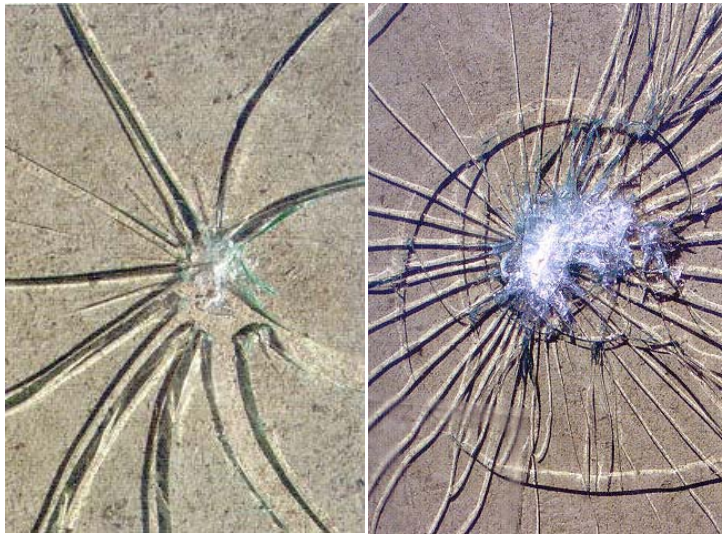


internal stress: 35 – 55 MPa

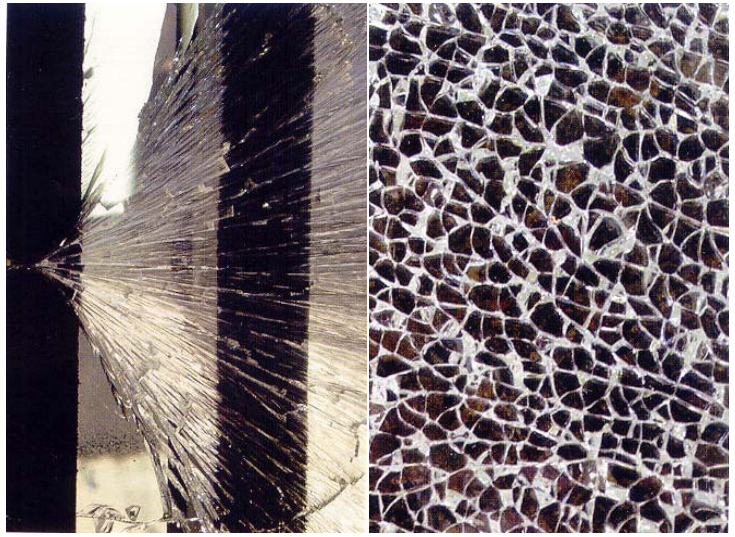
Heat strengthened glass

Advantages

- without spontaneous failures due to nickel sulphide inclusions
- fragmentation similar to annealed glass = keep glass panes in position after cracking when they are framed or laminated



Comparison of fracture pattern:
float x heat-strengthened glass



Comparison of fracture pattern:
heat-strengthened x tempered glass

Heat strengthened glass

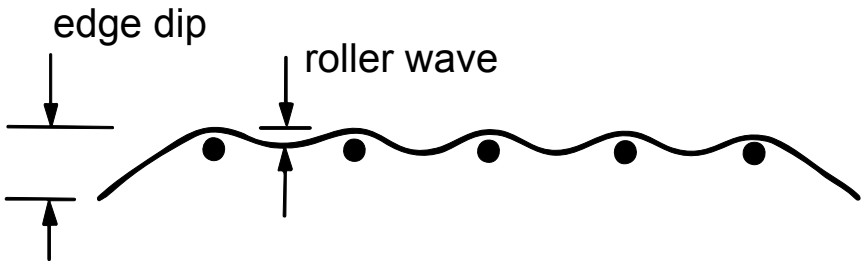
Determination of the surface stress

- destructive tests: fragmentation test – BS 6206, pr EN 12150
  - struck in a controlled manner
  - number of glass fragments in a standard area
  - surface compression can be deduced from the number of fragments (higher number of fragments = increasing surface stress in given area)
- non-destructive tests: optical instrument – differential surface refractometr

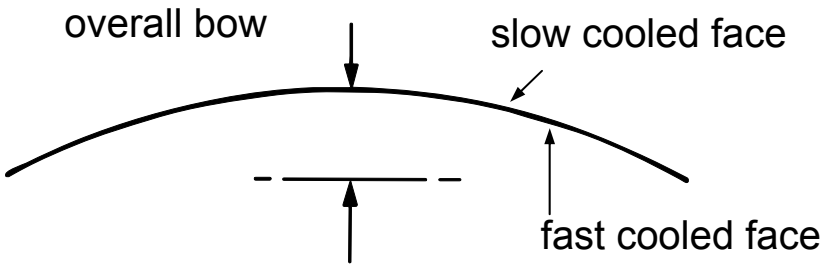
Heat strengthened glass

Initial deformation

- float glass – less than < L/2500
- thermally strength refined glass – the shape of sinusoidal waves ~ L/300



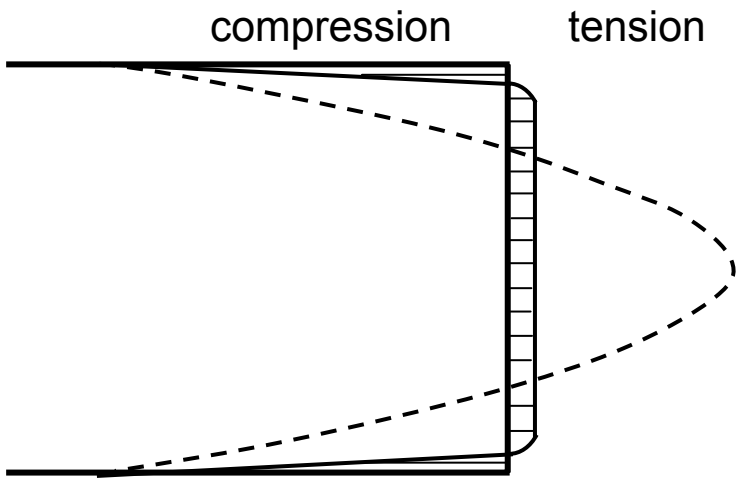
roller wave and edge dip caused by sagging in semi-molten state



overall bow caused by differential cooling of the two sides of the plate

Chemically strengthened glass

- chemical pre-stressing is realized by ionic exchange
- glass pane is immersed in a hot molten salt (hot potassium chloride bath)
- smaller sodium ions in the glass surface are exchanged for the larger potassium ions
- fracture behaviour corresponds to float glass



Stress cross-sectional diagram of chemically strengthened glass

Chemically strengthened glass

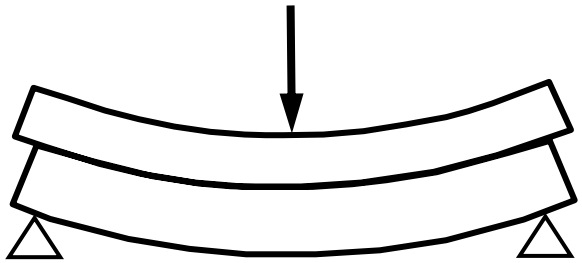
Advantages

- without thermal deformation ⇒ suitable for very thin glass panes
- chemically strengthened glass can be cut, edge has strength of normal glass

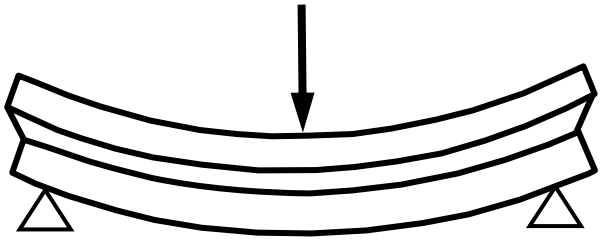
Disadvantages

- small depth of penetration ⇒ highly susceptibility to surface defects because strengthened zone is not very deep

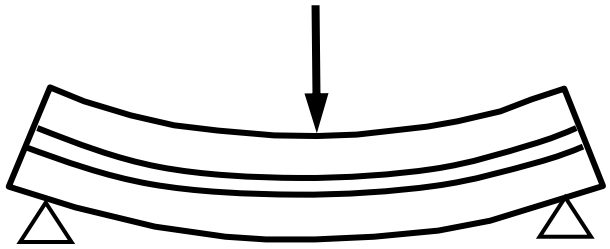
Laminated glass



with no interlayer / loose



with flexible interlayer bond



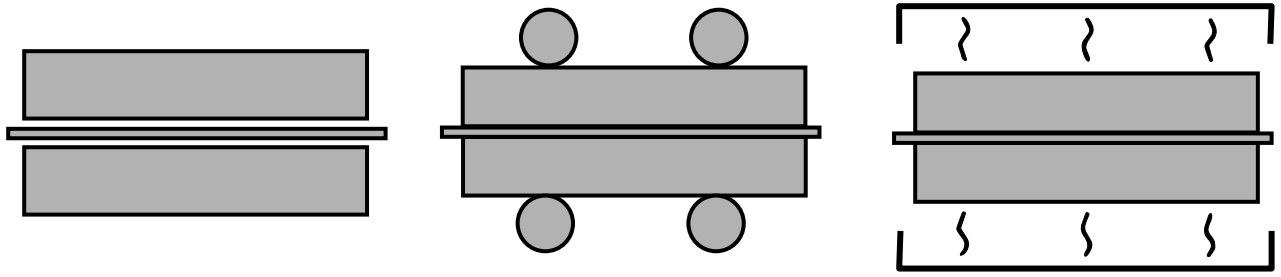
with stiff interlayer bond

- modification of the mechanical, optical properties through the selection of the component layers, their sequence and thickness
- overhead glass, wind screens, bullet proof glass, glass beams and columns, glass in automotive industry

Laminated glass

Laminated glass with foil

- two or more glass panes bonded by a transparent interlayer of plastic (up to 25 layers, thickness over 100 mm); float glass, tempered glass, polycarbonate, bent glass
- glass panes are washed, foils are layered and the assembly is heated (70°C) and pressed (*prelamination*) by roller process to squeeze out the air, in autoclave is heated to 140°C under a pressure about 0,8 MPa; largest size of pane 6,0 x 3,21m



positioning and layering | **prelamination by calender** | **autoclave**

Laminated glass

Intermediate layer:

- PVB foil (poly-vinyl-butyral) – basic thickness 0,38 mm, maximal thickness of the interlayer = 6 mm
- EVA (ethylene vinyl-acetate)
- PU (polyurethane)
- Ionoplast → SenryGlass

- influence of temperature
- influence of load duration

Enter to the autoclave

Laminated glass

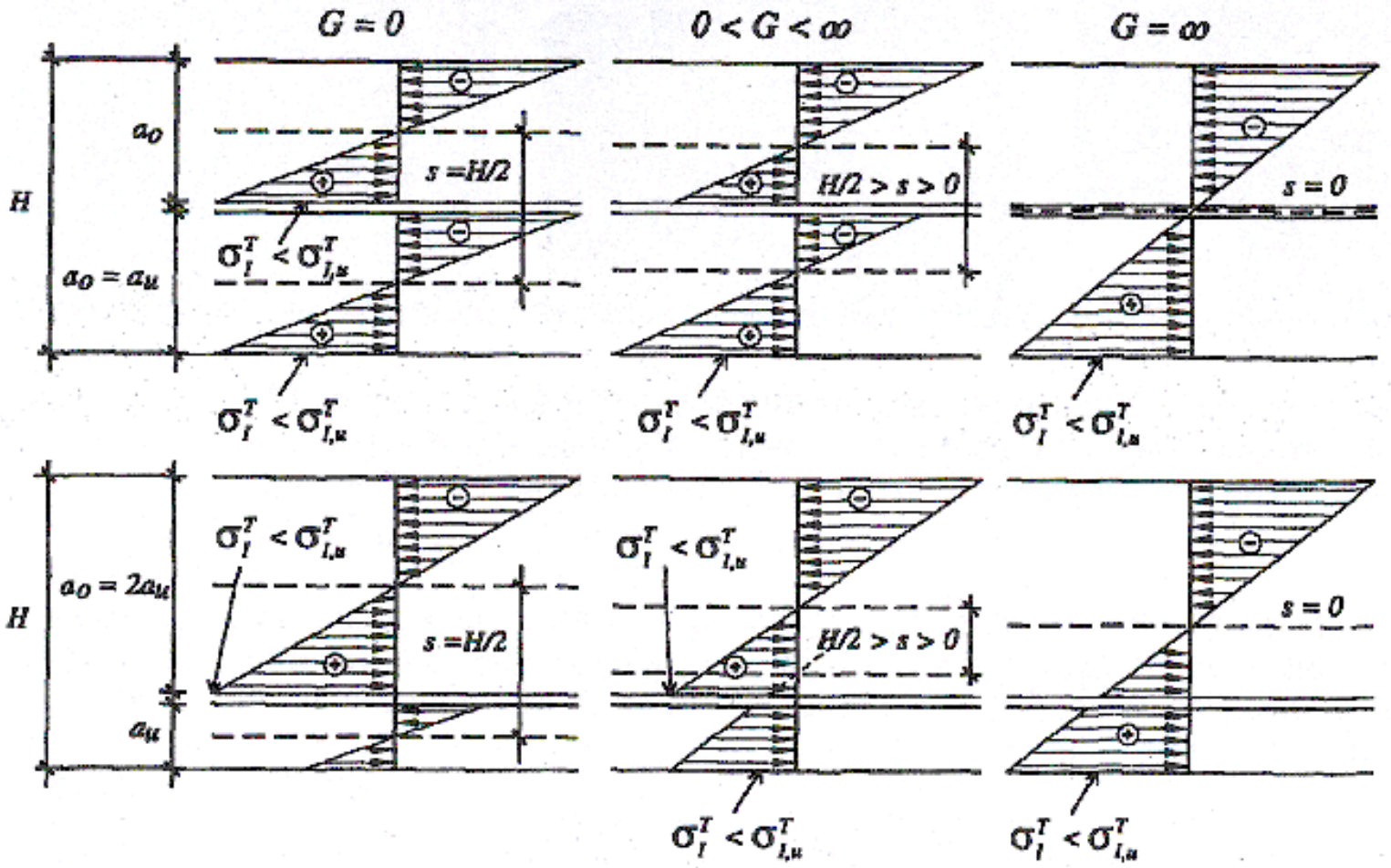
Advantages

- laminated glass incorporates many thicknesses and combination of glass types ⇒ many products with required mechanical and optical properties
- "safety glass" – after failure broken glass pieces remain bonded to the foil = **residual load-bearing capacity**, interlayer can prevent penetration ⇒ impact test

Disadvantages

- thicker foils are used with heat treated glass to accommodate undulations = sinusoidal waves
- offset of adjacent glass edges due to the lamination process = misalignment up to 2 mm

Laminated glass



Bending stress distribution of laminated glass depending on shear modulus G of PVB interlayer

Laminated glass

Laminated glass with resin interlayer

- liquid cast resin (epoxy, acrylic, polyester)
- glass panels vertically positioned with defined gap (about 1 – 2mm), edges sealed with transparent double-sided adhesive tape, resin poured between two panels
- resin curing by chemical reaction or UV light

Advantages

- no additional autoclave ⇒ large panel size
- better acoustic insulation,
- suitable for thermally strengthened glass

Disadvantages

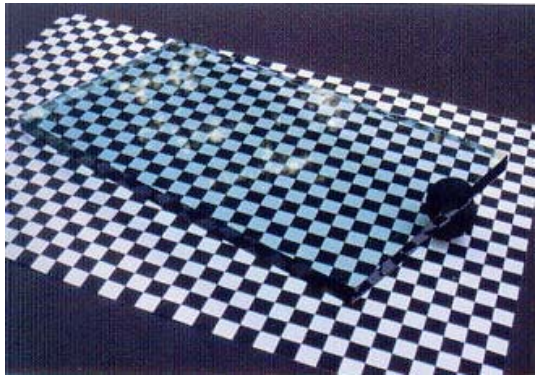
- less residual load-bearing capacity ⇒ post-fracture integrity

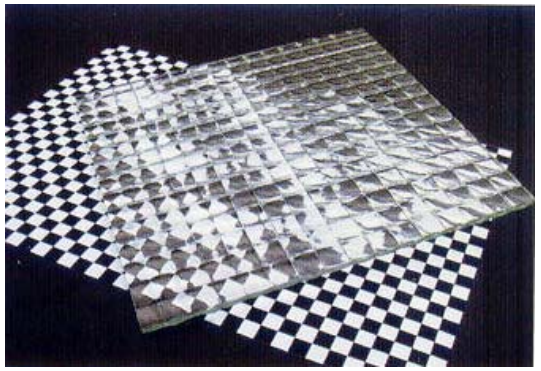
Appearance, coatings

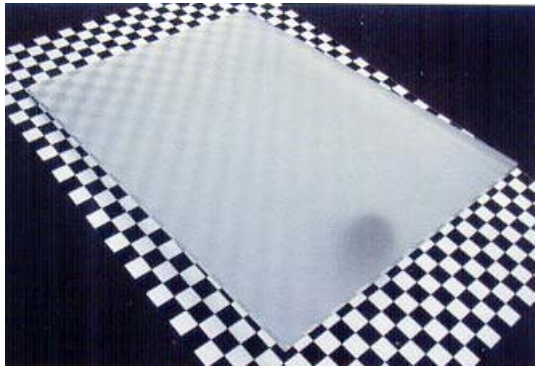
Glass appearance

Influence of the surface type to transmission and reflection

- perfectly smooth surface
- textured surface
- rough surface



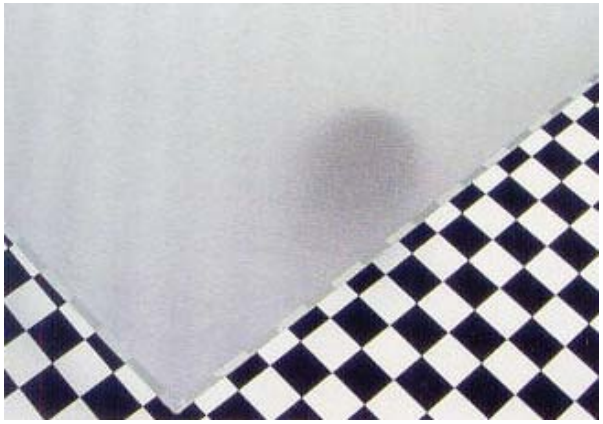




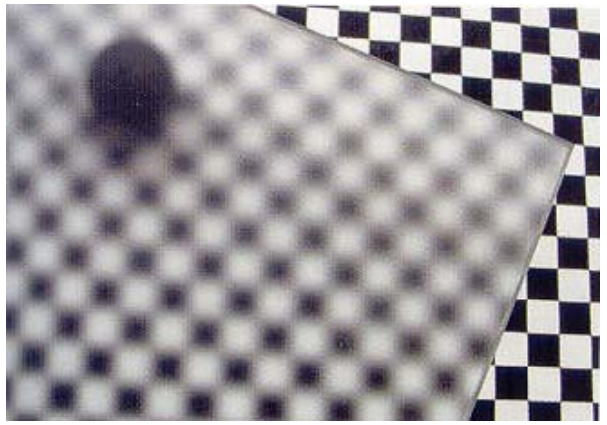
Appearance, coatings

Rough surfaces of glass

- Sandblasting: abrasive is blasted under pressure onto the glass surface ⇒ glazing surface is roughened and translucent pattern is created, reduction of the strength up to 50%
- Acid etching: liquid acid bath or acid pastes / screens, very durable patterns



sand-blasted glass surface – less optical quality

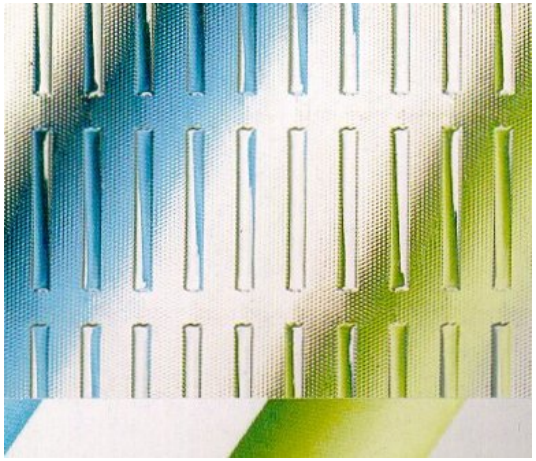


etched glass surface

Appearance, coatings

Texture rolled glass

- patterned glass is formed by reversal of pattern on the roller and cooled down, variety of architectural appearance
- the deeper the pattern, the greater the degree of obscuration and diffusion



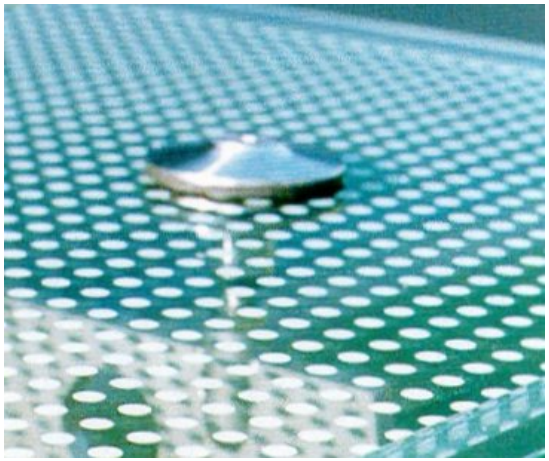
ornamented glass

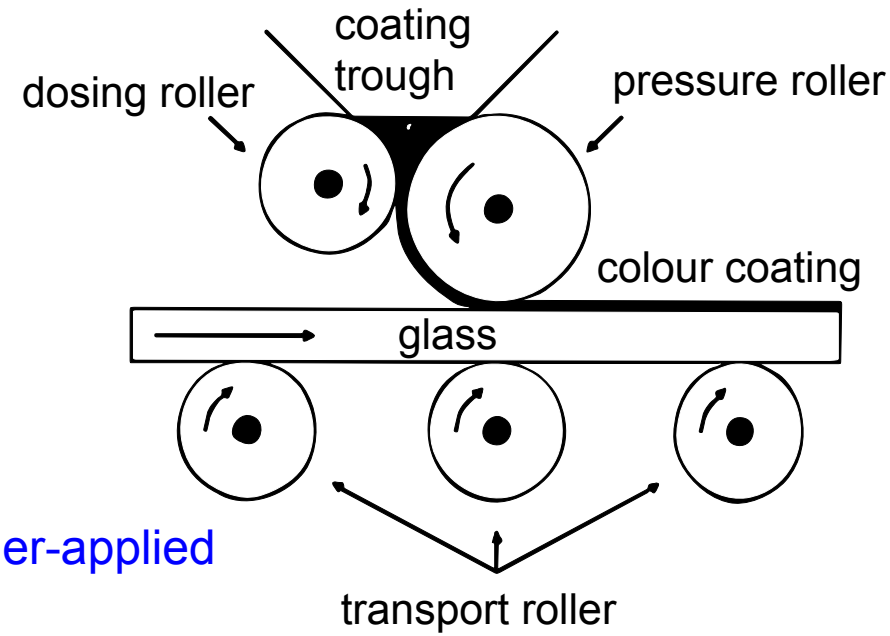
textured rolled glass surface with wire mesh

Appearance, coatings

Enamelled glass

- ceramic pigments or frits are rolled, poured or screen-printed over one side of glass and are baked onto the glass during heat treatment = permanent bonded
- enamelling reduces the bending strength of tempered or heat- strengthened glass about 40%



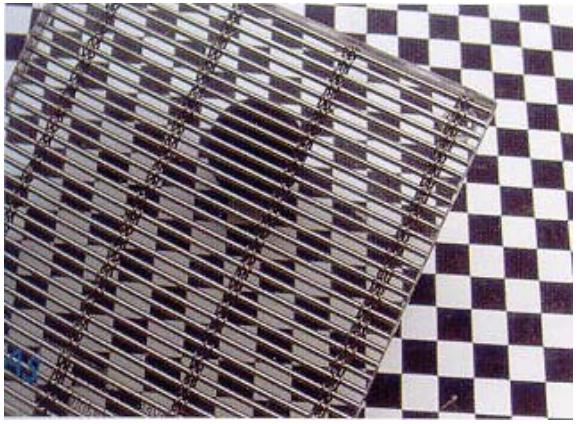


principle of roller-applied colour coating

Appearance, coatings

laminated safety glass with coloured PVB films

laminated safety glass with printed film interlayer



laminated glass with decorative interlayer = metal sheet

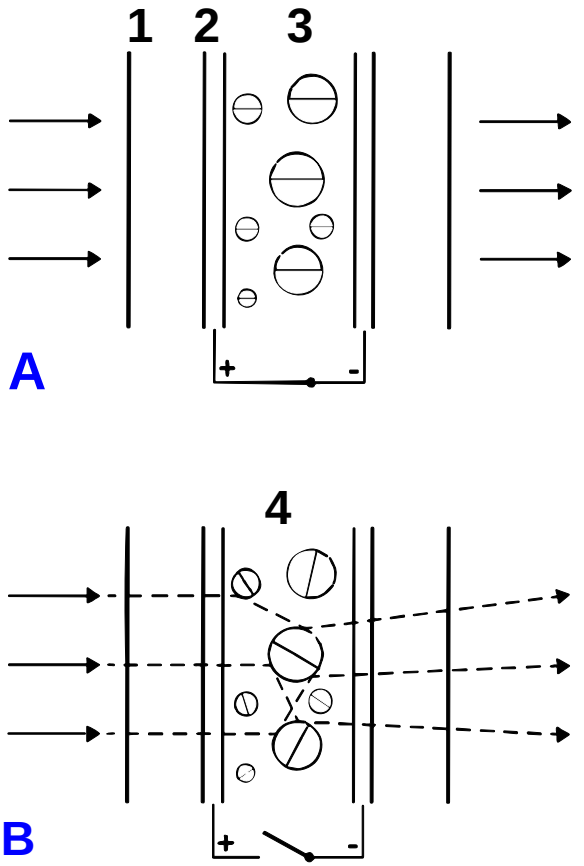
solar modules integrated into the glass skin

Appearance, coatings

Electro-optic glass

translucent glazing (B) unit becomes transparent (A) when an electric field is applied

1. glass
2. transparent electrode layer
3. polymer layer with aligned liquid crystals
4. polymer layer with randomly oriented liquid crystals



Appearance, coatings

Coatings techniques

impact on transmittance, absorption, reflection – solar control glass

hard coatings

- fired into the glass surface under very high temperature 600 – 650°C, metallic oxides
- advantages: hardness ⇒ can be glazed also to exterior sides, good economics in fabrication
- disadvantages: have to be integrated into the float process ⇒not flexible, maximum number of layers = 2

Appearance, coatings

soft coating

- chemical or physical vapour deposition, most common technique = DC-magnetron sputtering process
- up to 15 different materials = big variety of the coating composition, typical coating material tin oxide, silver,
- total coating thickness about 0,01 – 0,1µm
- advantages: very precise, flexible with constant quality, possible to reproduce the same coating with the same technical properties after many years
- disadvantages: susceptibility to aggressive air pollution and mechanical damage, necessity of the protection by protective layer, placing onto the inner side of insulating units

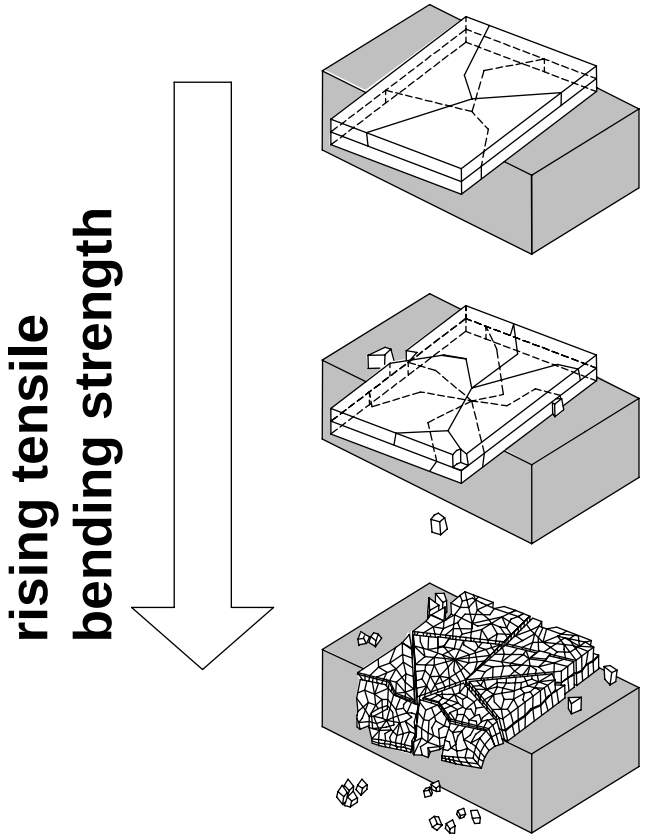
Appearance, coatings

Fire resistant glazing

- special transparent gels or intumescent (swelling) interlayer which are transparent at room temperature, but foaming above higher temperature
- glazing might break but stay in position without falling down
- special glazing products allow fire protection up to 120 minutes

Conclusions

Summary



Conclusions

Tension strength of glass

Glass type	Use	f_k [MPa]	f_d [MPa]	γ_M
Tempered float glass		120	50	120/50 = 2,4
Tempered rolled glass		90	37	90/37 = 2,4
Enamelled tempered float glass		70	30	70/30 = 2,4
Annealed glass	overhead	45	12	45/12 = 3,8
	vertical	45	18	45/18 = 2,5
Rolled glass	overhead	25	8	25/8 = 3,1
	vertical	25	10	25/10 = 2,5
Laminated glass from annealed glass	overhead	45	15	45/15 = 3,0
	vertical	45	22,5	45/22,5 = 2,0
Heat-strengthened float glass		70	29	70/29 = 2,4
Enamelled heat-strengthened float glass		48	18	45/18 = 2,5

Thank you
for your kind attention