ADVANCED DESIGN OF GLASS STRUCTURES

Lecture L2
Glass strengthening methods

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European Erasmus Mundus Master Course
Sustainable Constructions
under Natural Hazards and Catastrophic Events
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SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

List of lessons

1) History, chemical composition, production
2) **Glass strengthening methods**
3) Laminated glass and interlayer's
4) Fracture strength and testing methods
5) Glass plates under uniformly distributed load
6) Aesthetic coatings, insulated glass units
7) General design guidelines
8) Design of compressed members
9) Design of glass beams
10) Hybrid load-bearing members
11) Curved glass members
12) Design of bolted connection
13) Design of glued connection
14) Glass roofs
15) Structural glass facades
16) Examples of glass structures

SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

Objectives of the lecture

- Introduction
- Strength of annealed glass
- Fully tempered glass
- Heat strengthened glass
- Chemically strengthened glass
- Glass failure modes

Introduction

Why temper (strengthen) glass?

- Increase apparent tensile strength due to compressive residual stresses on the surfaces of the glass;
- Principally similar to “prestressing” - methods in structural engineering;
- Improve breakage performance due to small, blunt pieces/ splinters – so called safety glass (a tempered glass);
- Improve apparent tensile strength but still keep breakage performance in laminated glass after fracture similar to laminated annealed glass (heat strengthened glass).

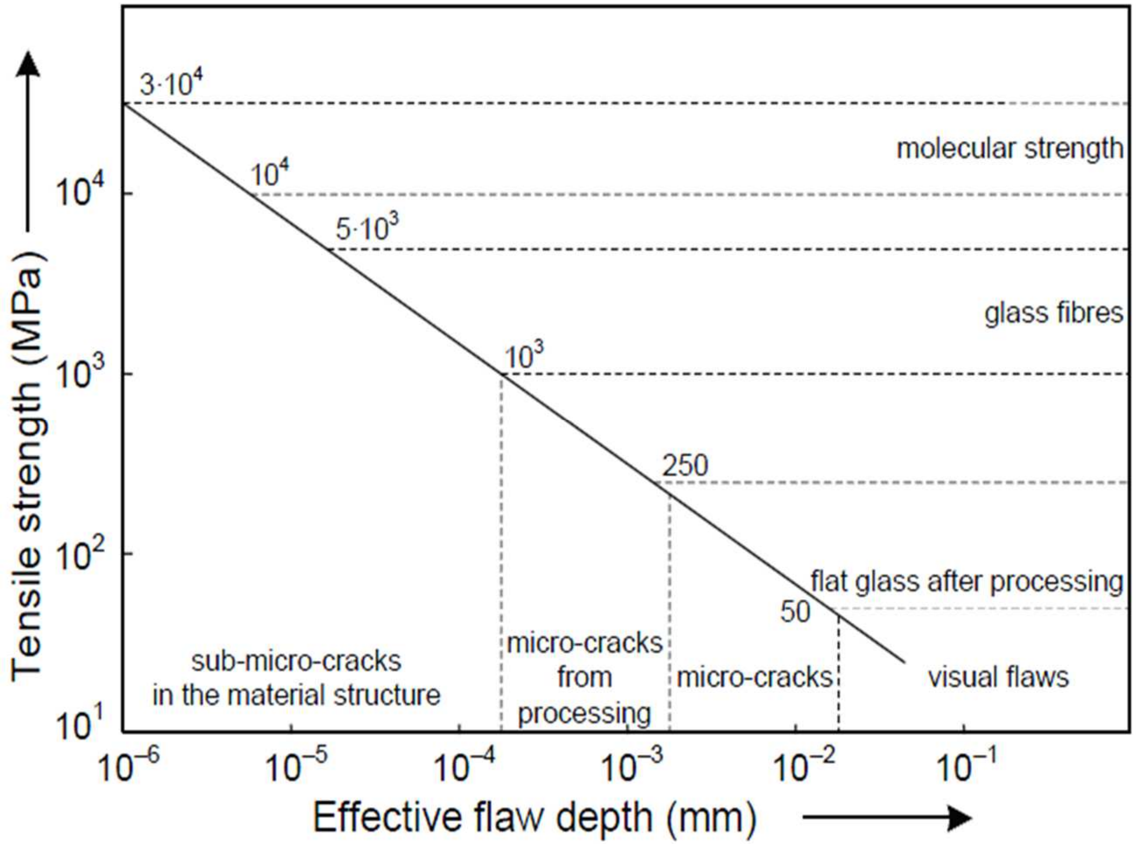
Introduction

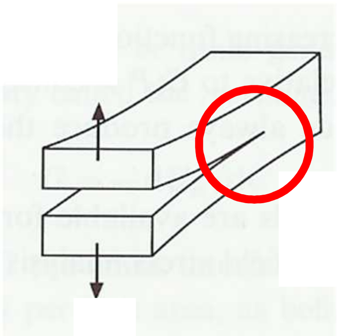
Strength of glass depends on:

- 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

Influence of surface flaws

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





Strength of annealed glass

Annealed float glass - insufficient tensile strength due to surface flaws → heat treatment – tempering

- *unavoidable flaws on the surface can grow under effective tensile stress*
- *tensile strength of annealed glass 45 MPa*

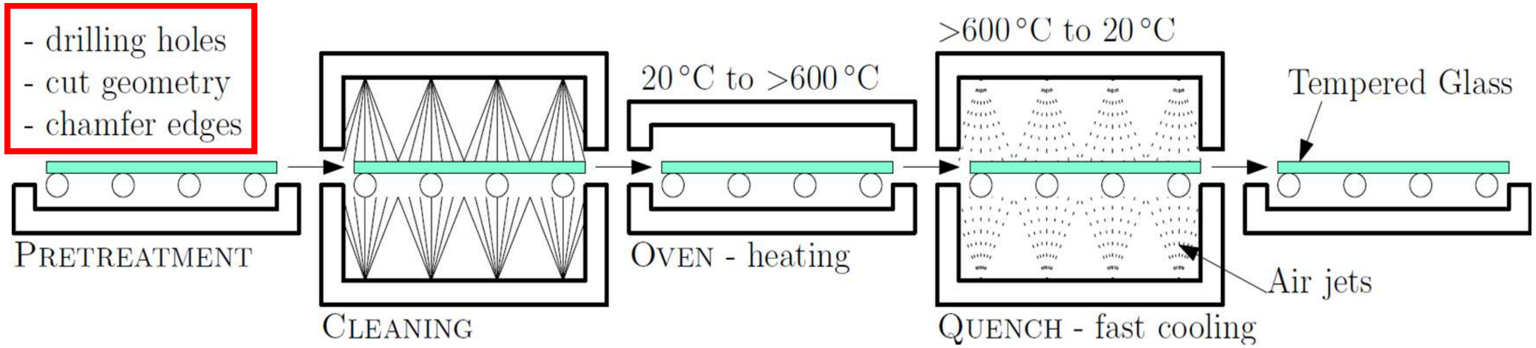
⬇

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

Fully tempered glass

1. FULLY TEMPERED GLASS (TOUGHENED GLASS)

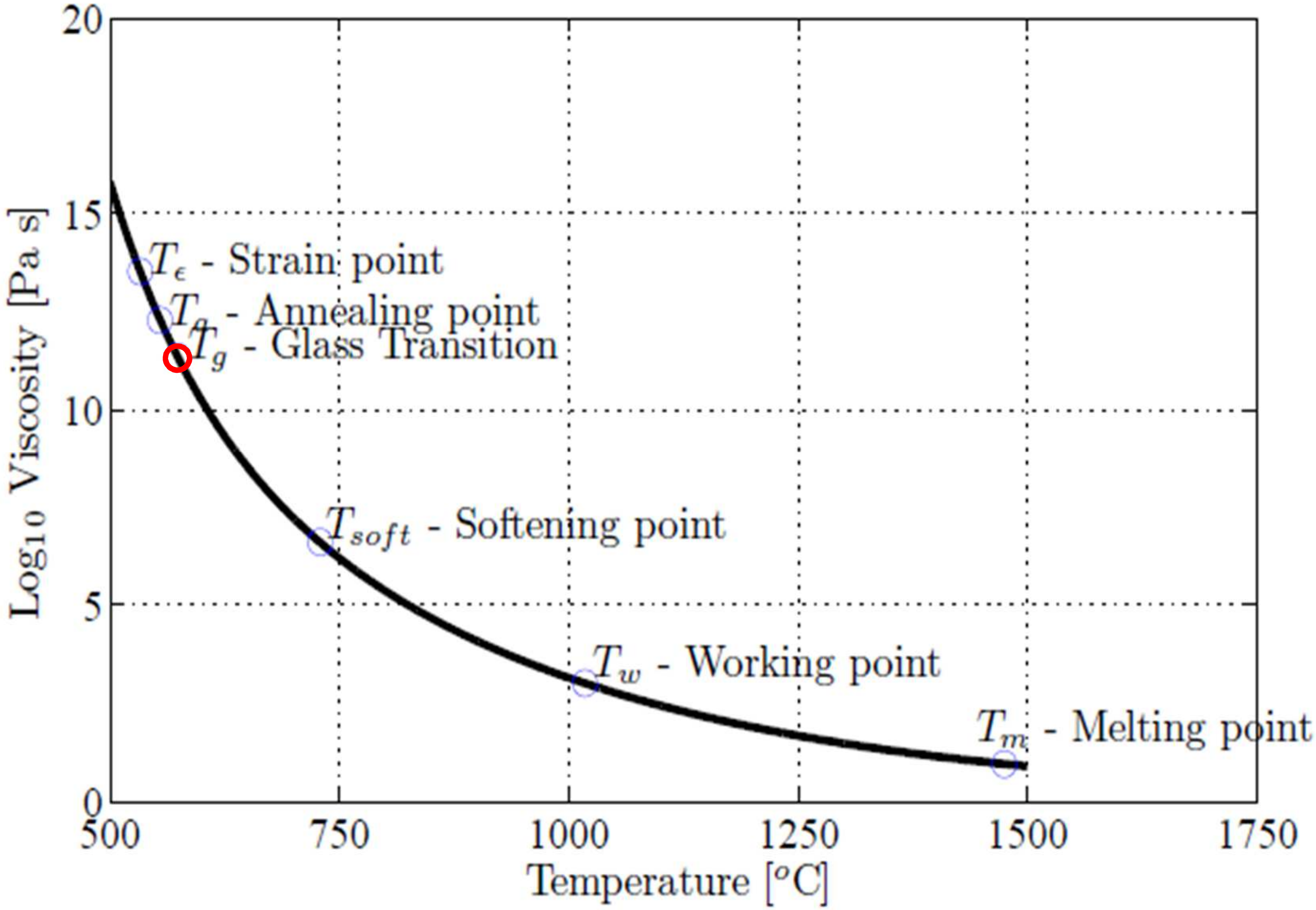
Principle of the thermal tempering process



- *Idea: Heating the glass well above the glass transformation temperature T_g and rapid quenching of the surfaces to ambient temperature*

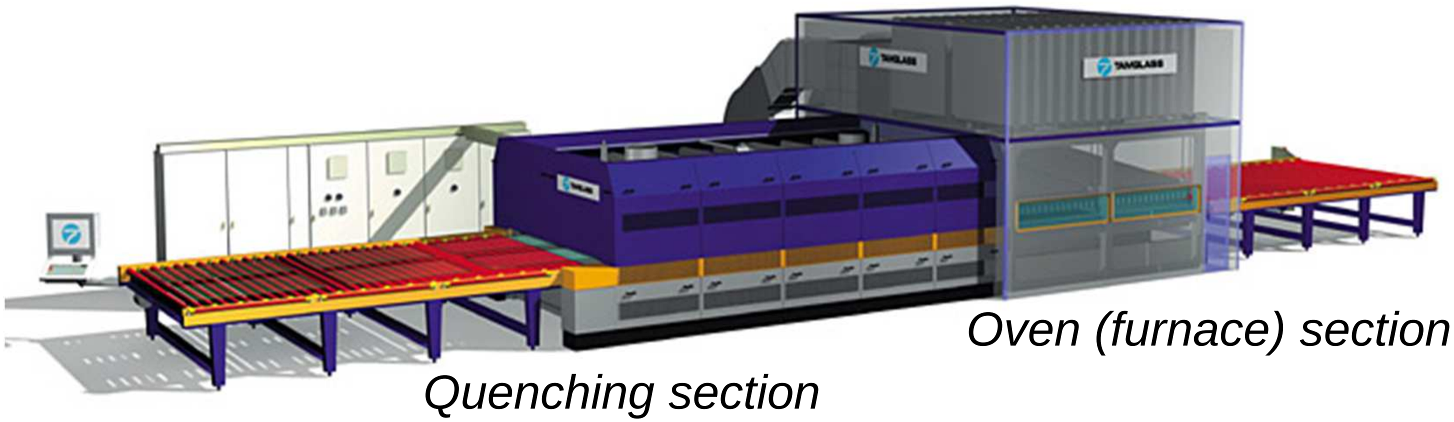
Fully tempered glass

Viscosity of soda-lime glass at elevated temperatures



Fully tempered glass

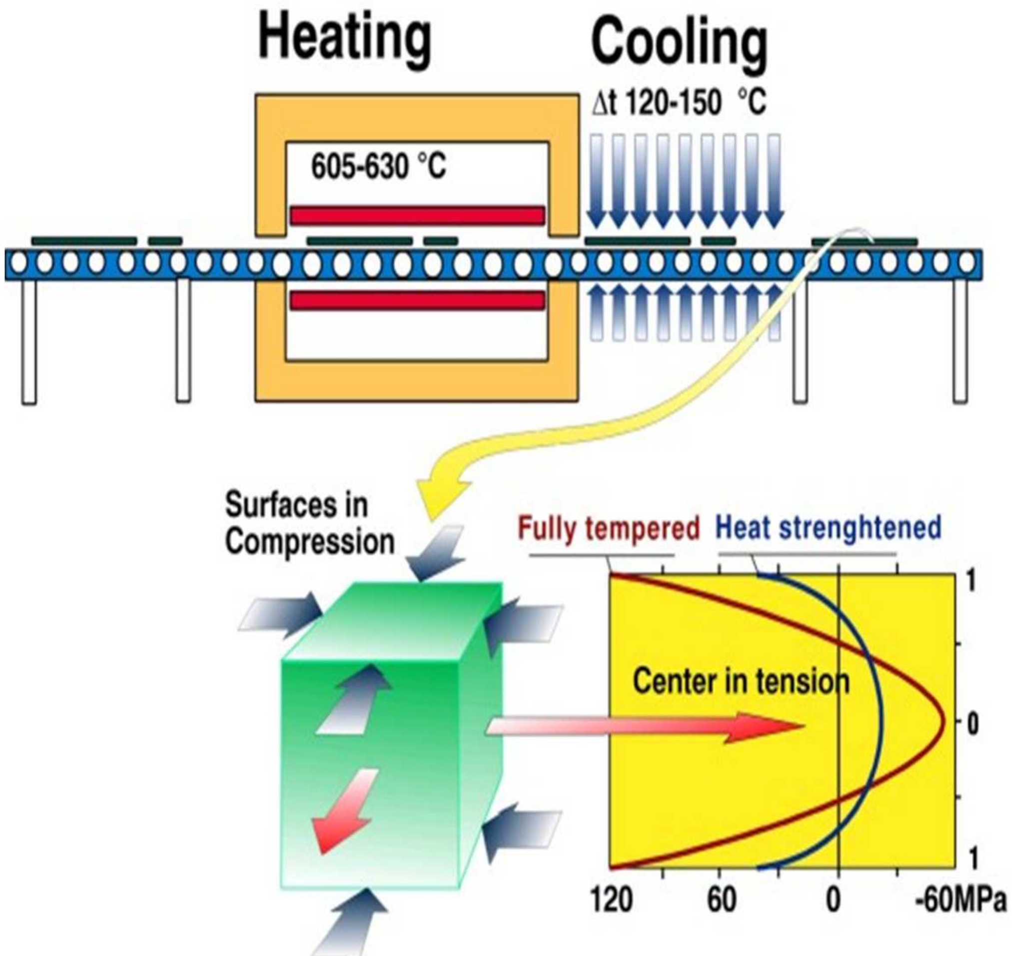
Machinery for the thermal tempering process



Temper equipment for flat glass

Fully tempered glass

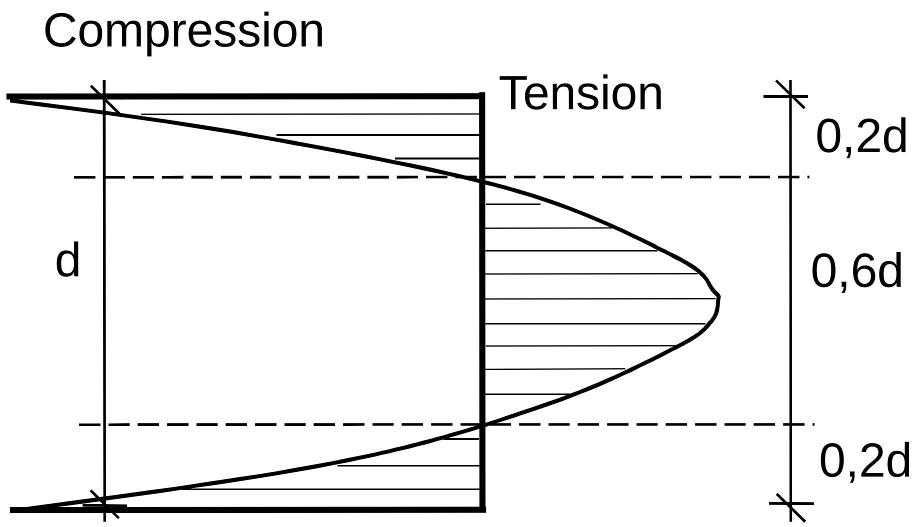
Tempering process



Fully tempered glass

- quenching (fast cooling) with air blown over both sides of pane
- cooling and stiffening first on the surface, delayed cooling and consolidation of the core → internal stress (parabolic distribution)

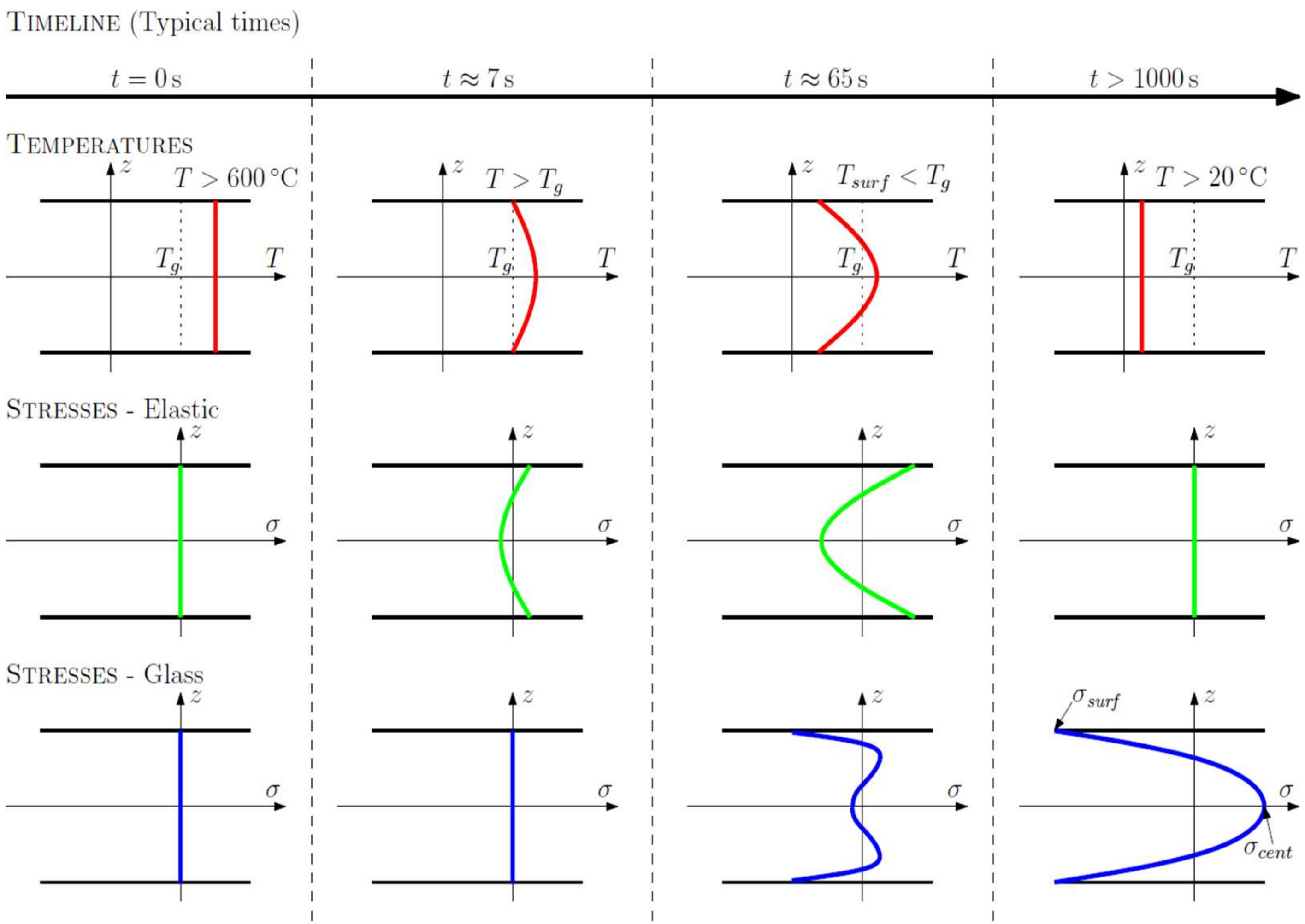
- **surface in compression (90 – 150 MPa), core in tension**



Fully tempered glass

Stress development with temperature

Elastic material vs. viscoelastic material



Objectives

Introduction

Strength of annealed glass

Fully tempered glass

Heat strengthened glass

NiS inclusions

Chemically strengthened glass

Strength of glass

Glass failure modes

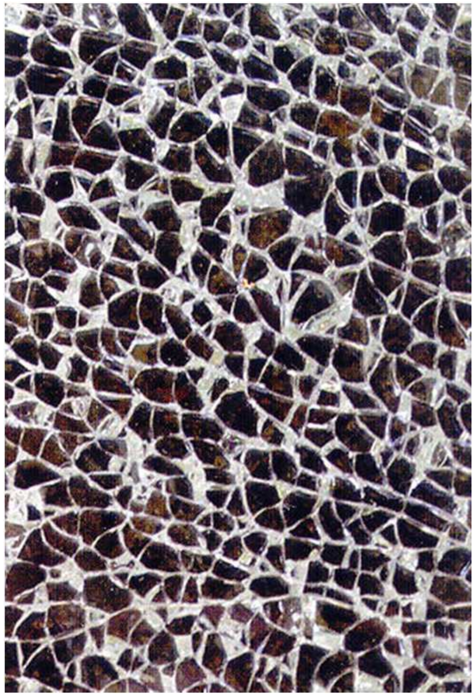
Fully tempered glass

ADVANTAGES

- high value of bending strength (compressive surface stress + tensile strength of annealed glass)
- 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

DISADVANTAGES

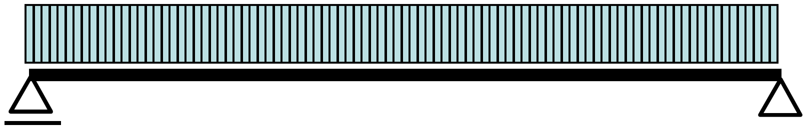
- thermal treatment after mechanical work (cutting, drilling, edge finishing)
- greater initial deformation – sinusoidal waves from transport roller
- spontaneous fracture by nickel sulphide inclusions



Fracture pattern of tempered glass: small fragments or dice

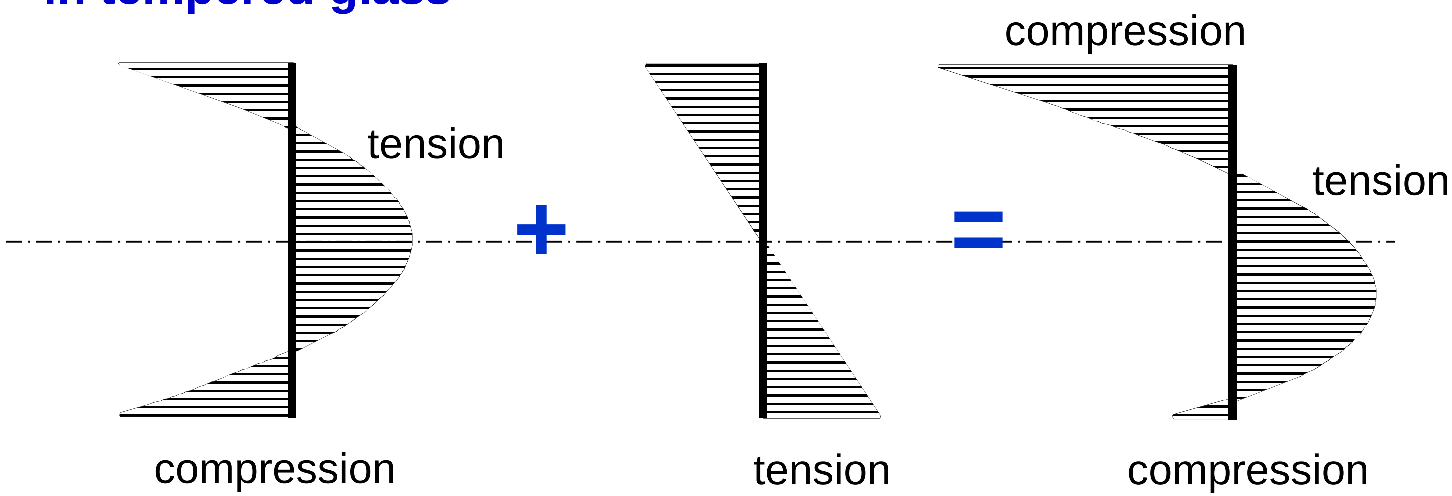
Fully tempered glass

TEMPERED GLASS UPON LOADING

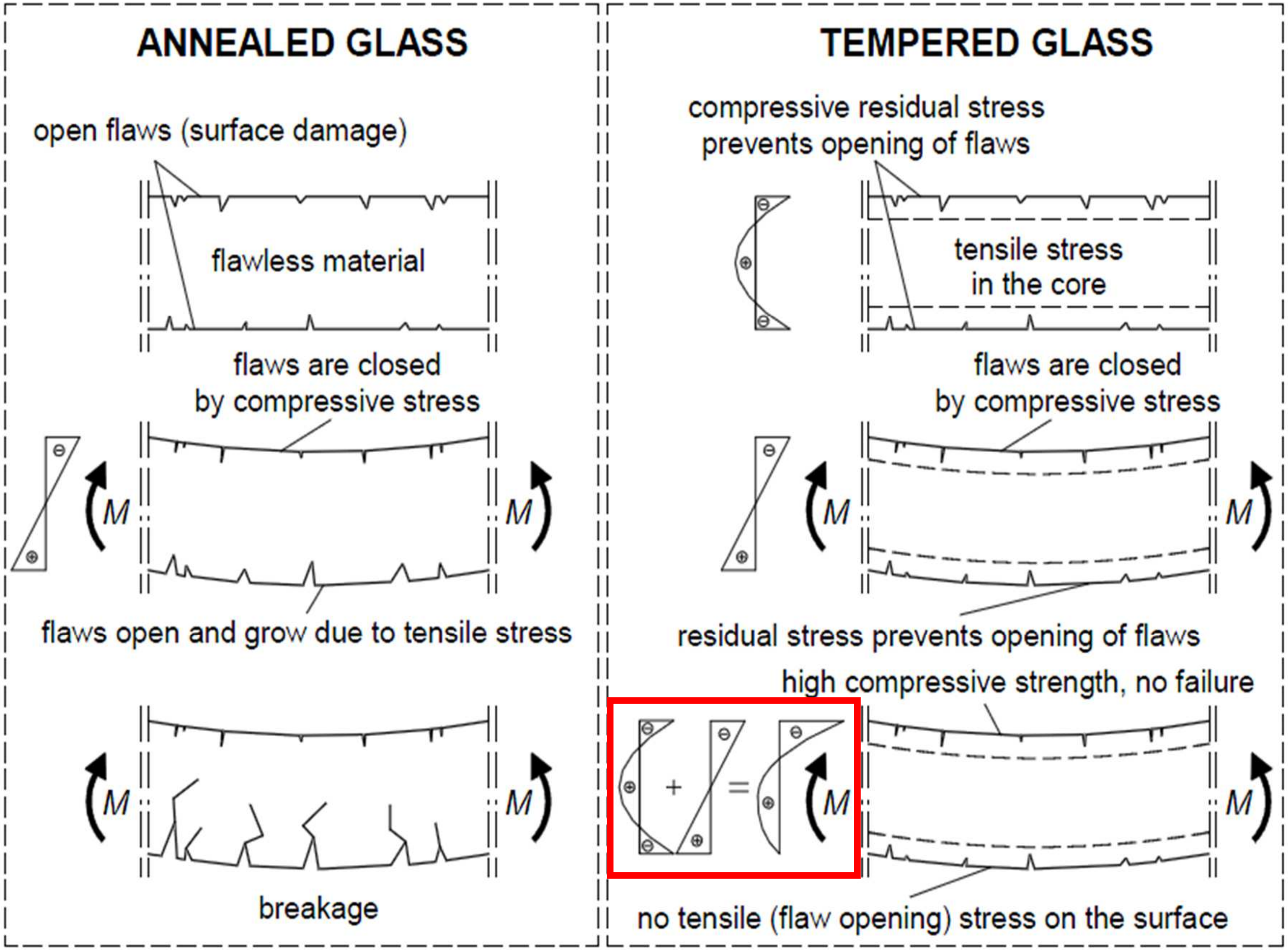


stress distribution in tempered glass

bending stress

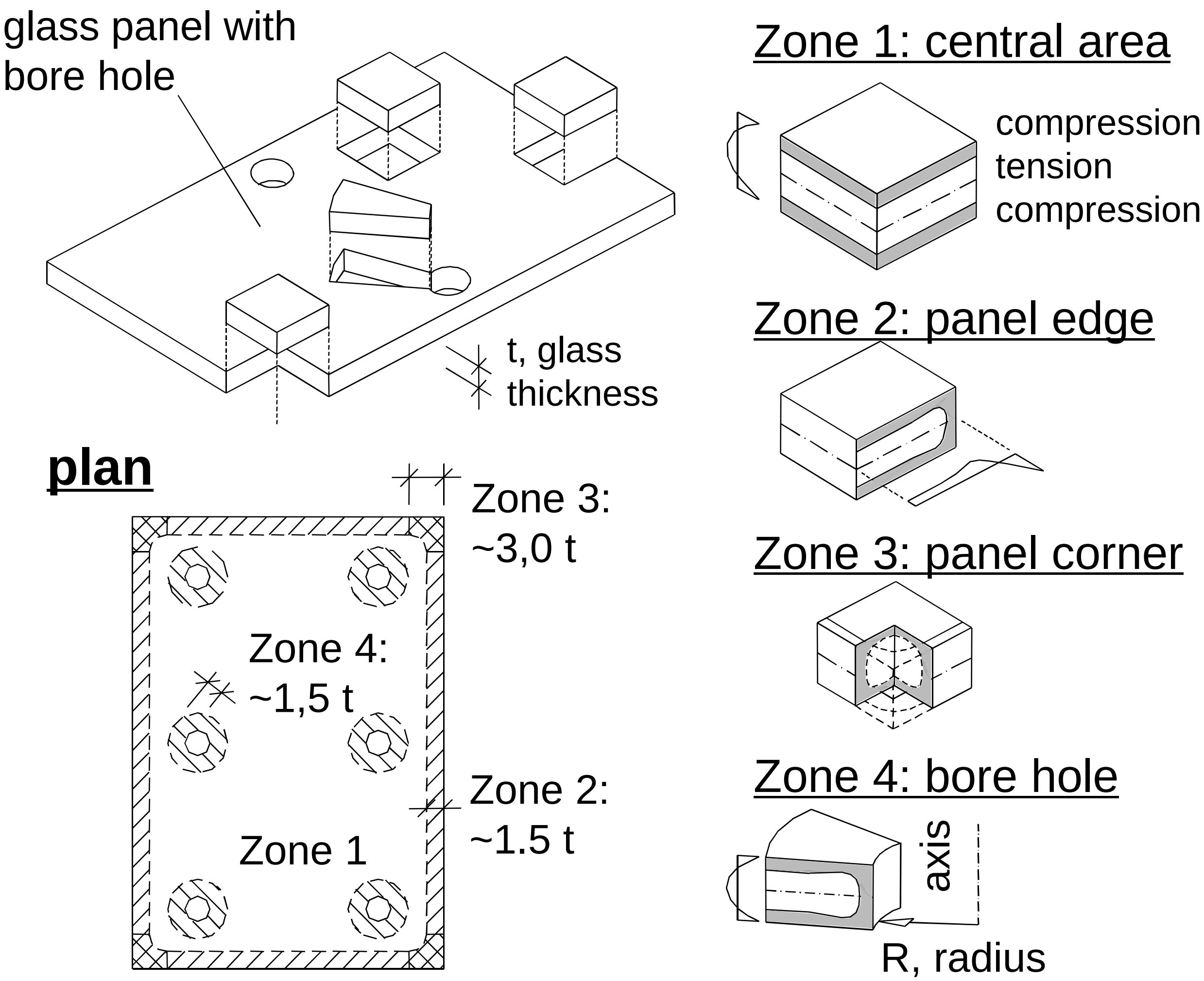


Resistance of Tempered Glass



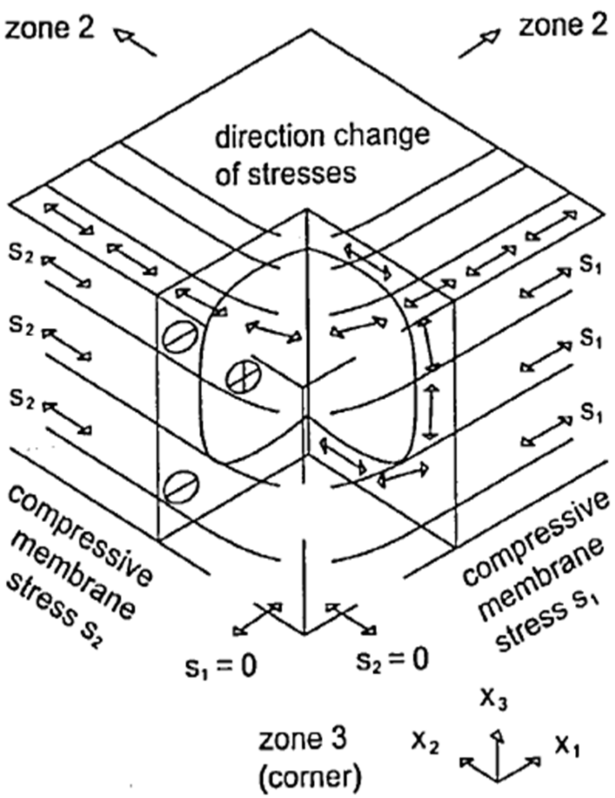
Residual stress distribution

Zonation of toughened glass panel – different pre-stress distributions

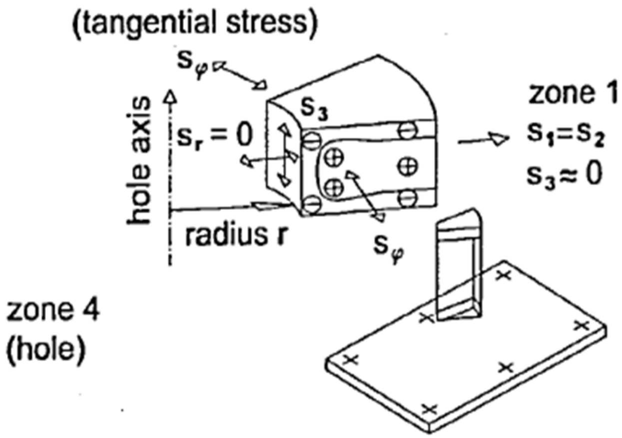


Residual stress distribution

Residual stress distribution at edges and holes



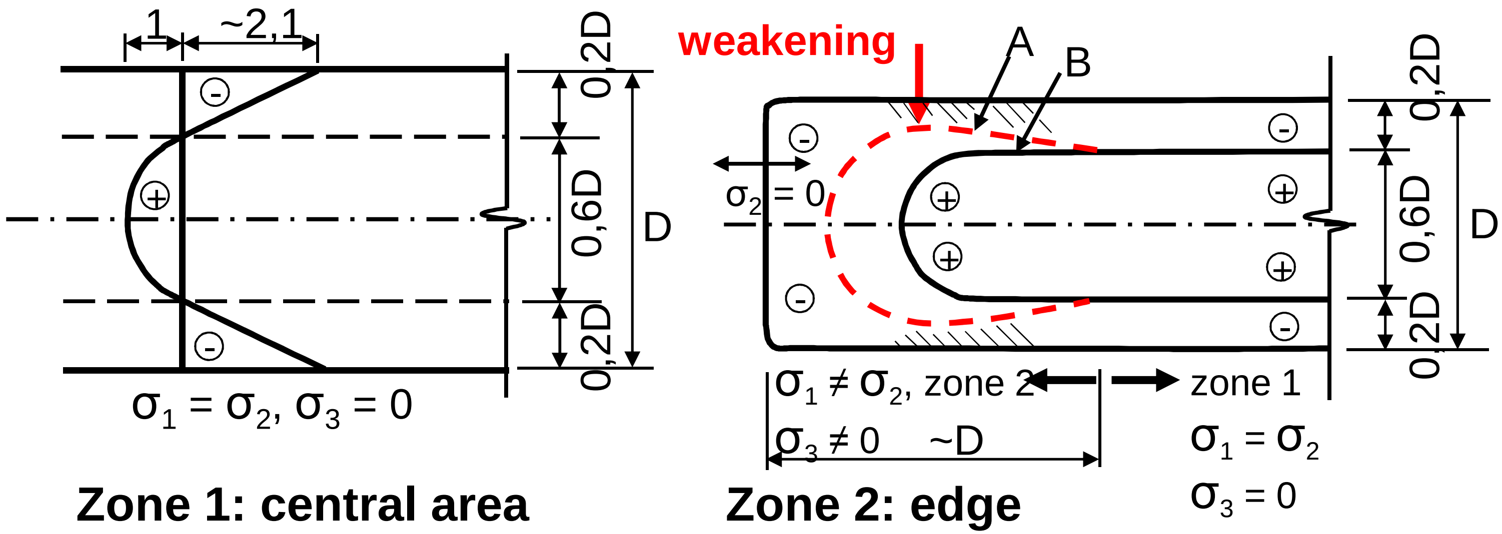
Edges and Corners



Holes

Residual stress distribution

Weakened areas of the edge stresses in comparison to the body stresses – tempered glass

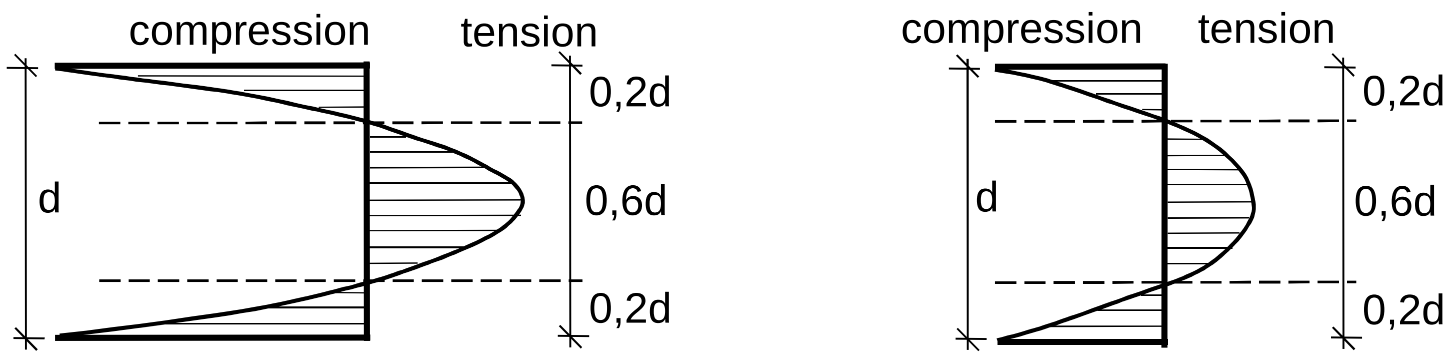


Zone 1: central area **Zone 2: edge**

Heat-strengthened glass

2. 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



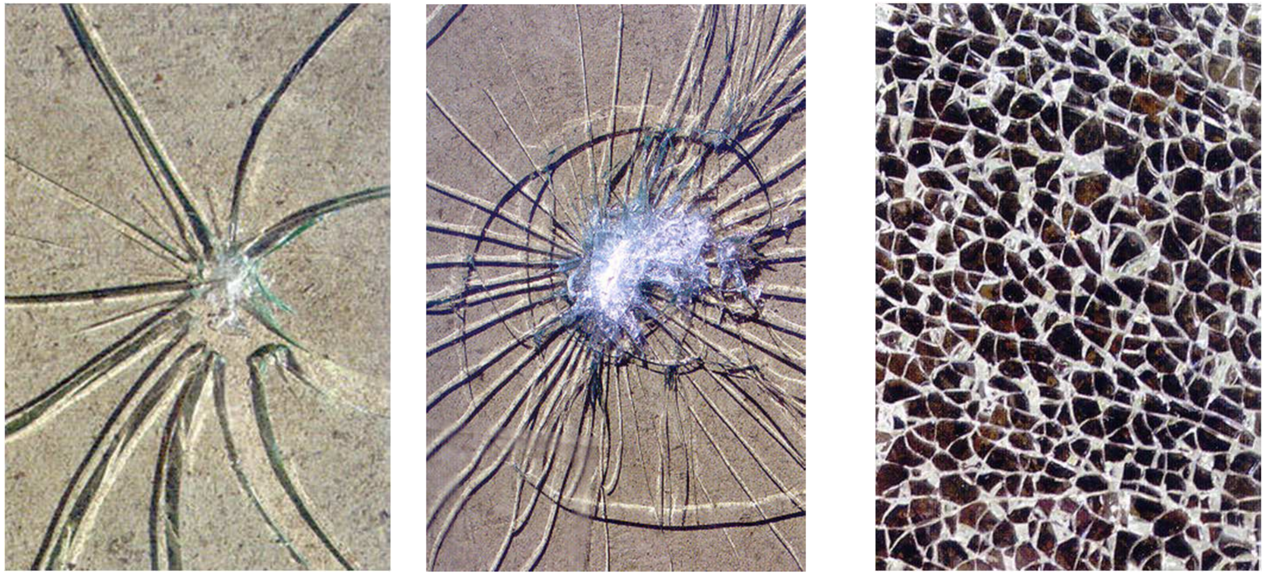
internal stress: 90 – 150 MPa

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 annealed, heat-strengthened glass and fully tempered glass

Strength refined 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 are counted
- surface compression can be deduced from the number of fragments (higher number of fragments = increasing surface stress in given area)

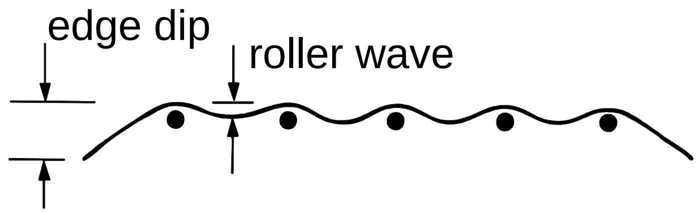
non-destructive tests: optical instrument – differential surface refractometr

Strength refined glass

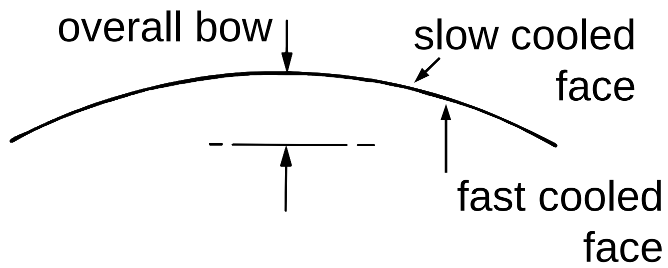
Initial deformation

- float glass – initial deformation < L/2500
- thermally strength refined glass – initial deformation in the shape of sinusoidal waves ~ L/300

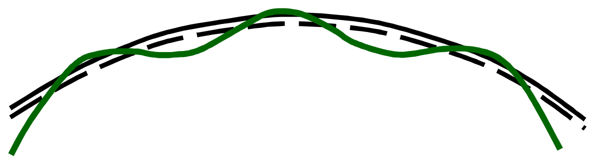
- *roller wave and edge dip caused by sagging in semi-molten state*



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



- *these two effects can occur together resulting like this shape*

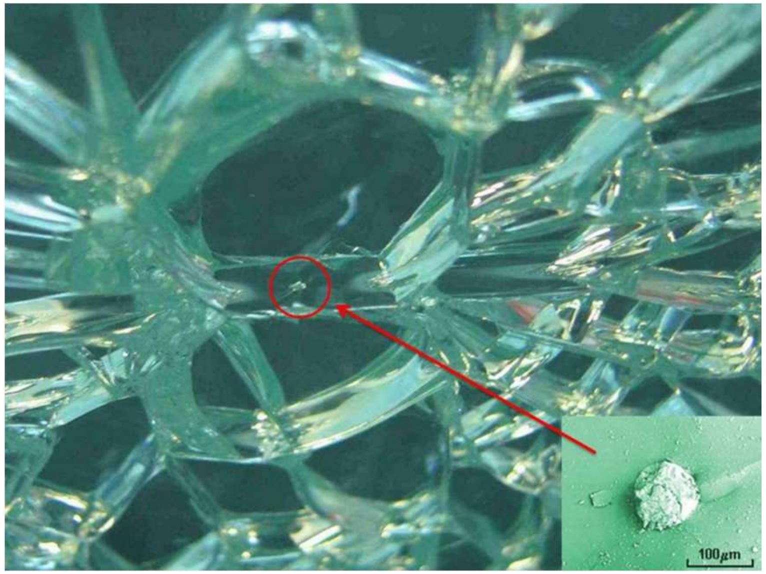


NiS inclusions

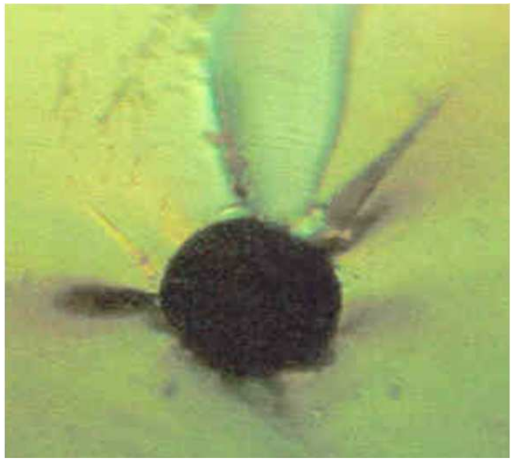
DISADVANTAGES of tempered glass

- spontaneous fracture: nickel sulphide inclusions (NiS), which expand their volume, up to about 2 years after production – invisible

- destructive HEAT-SOAK TEST (DIN 18516) (additional thermal test – heated up to 290 $\pm$ 10° C, constant temperature for 8 hours)



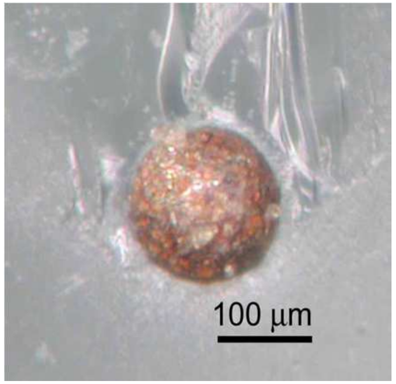
"butterfly" failure mode



NiS inclusions

NiS inclusions and related failure of tempered glass

- Spontaneous breakage – sudden failure of thermally tempered glasses (apparently) without external action.
- Phenomena is known since the 1960s.
- For high-rise buildings a big echo in media occurs generally („flying glass debris“).
- One reason for spontaneous breakage are small (50 µm to 500 µm diameter) that undergo a volume change.
- The typical breakage pattern („butterfly“) is one indication, but not a sufficient indication for NiS.
- Today, the heat-soak-test is the most efficient measure to bring panes with inclusions to failure in advance.

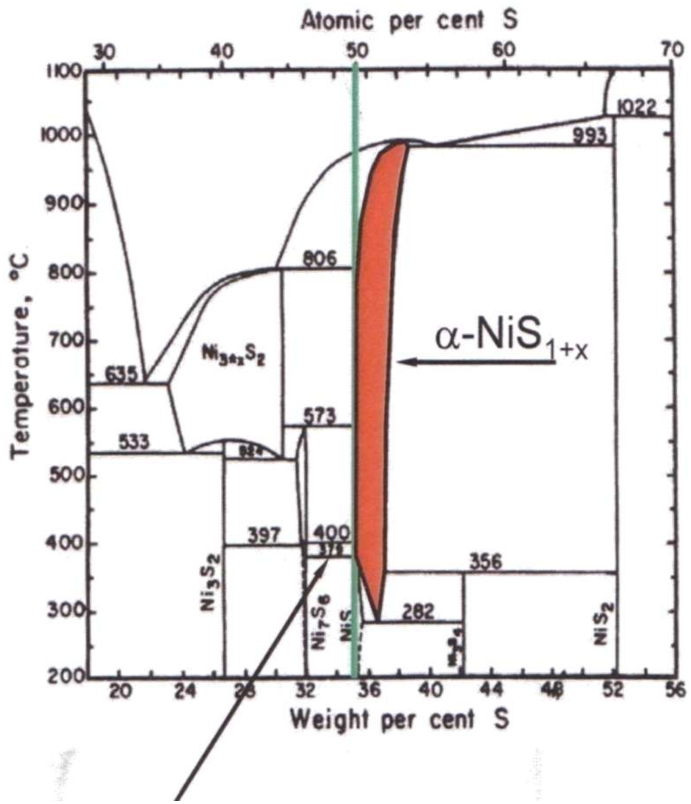


light microscope pictures

NiS inclusions

NiS inclusions – phase change mineral

- Nickel-Sulphide is a mineral with a high- and a low-temperature phase.
- NiS undergoes a temperature-related, time-dependent phase change in glass at temperatures < 379° C from a-NiS to b-NiS which is connected to a volume increase.
- The volume increase leads to failure in thermally tempered glass if the inclusion is in or near the tension zone of the temper stress.
- 1 g of Nickel can affect days of the production of a typical Float-line!



phase change at temperatures that are present during tempering

Heat soak testing

Objectives

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Strength of annealed glass

Fully tempered glass

Heat strengthened glass

NiS inclusions

Chemically strengthened glass

Strength of glass

Glass failure modes

Heat-Soak-Test (HST)

- continuous heating
- temperature: 280-320° C
- holding temperature: 290-300° C
- holding time ≥ 2 or 4 hours
- cooling

- phase change of NiS is strongly accelerated
- panes break already in the oven

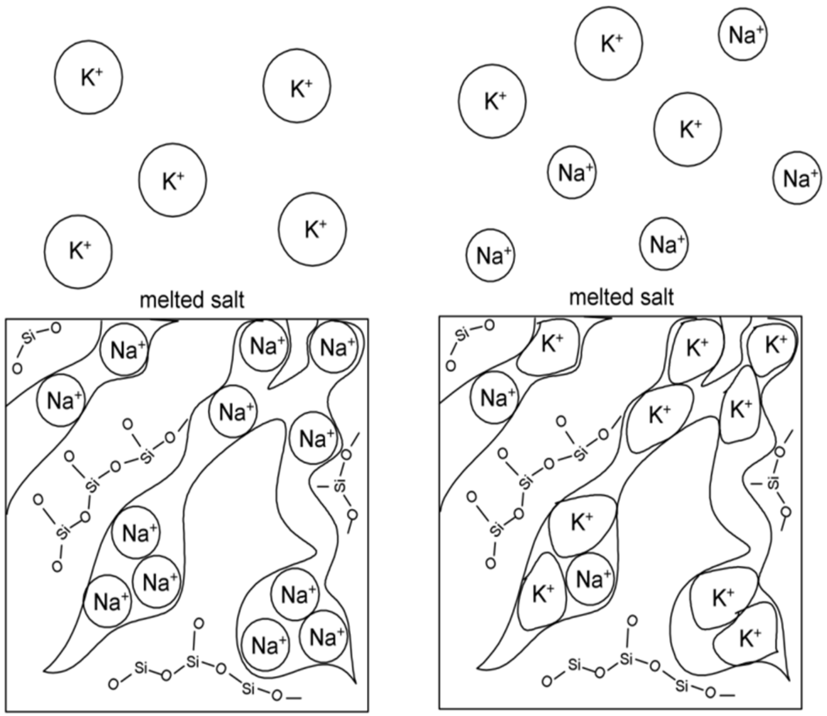
- *Open question: failure probability after heat soaking? – some research available*
- *Quality measures (e.g. color change stamps, nano-marking …)*

SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

3. Chemically strengthened glass

Process for chemically strengthening

- chemical pre-stressing is realized by ionic exchange
- glass pane is immersed in a hot molten salt (hot potassium chloride bath) – at elevated temperature about 500° C
- smaller sodium ions in the glass surface are exchanged for the larger potassium ions
- fracture behaviour corresponds to float glass



before ion-exchange   after ion-exchange

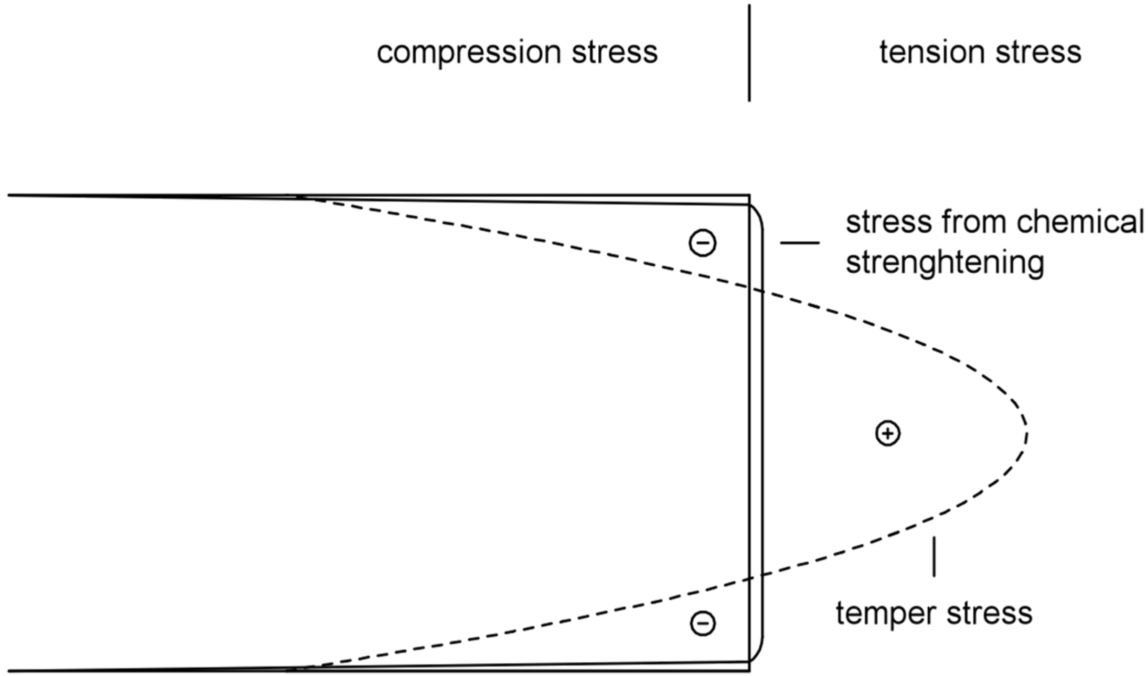
Chemically strengthened glass

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



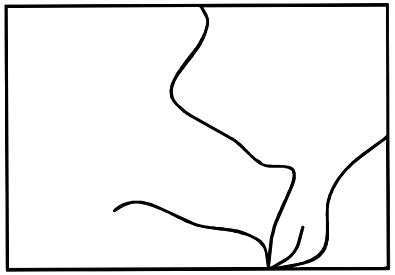
Strength of glass

Residual stress and strength in thermally treated glass

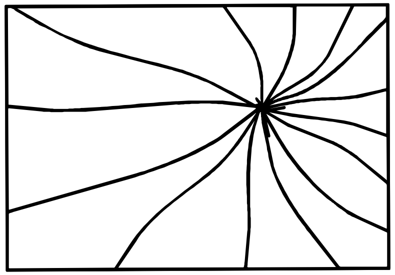
Property	Tempered Glass	Heat Strength. Glass	Chemically strength. Glass
Surface compression stress	100 - 160 MPa	40 – 60 MPa	300 – 900 MPa
Core tension stress	50 - 80 MPa	20 – 30 MPa	depends on height of compression zone
Characteristic bending strength (5%-fractile, after European standards)	120 MPa	70 MPa	150 MPa - to be used with great caution due to vulnerability of compression zone
Allowable stress in a global safety concept	50 MPa – 70 MPa	29 MPa – 40 MPa	not given
Fracture pattern	small dices, ca. 1 cm^2	big pieces, comparable to annealed glass	big pieces, comparable to annealed glass
Compression zone	20% of thickness	20% of thickness	typically about 100 μm

Glass failure modes

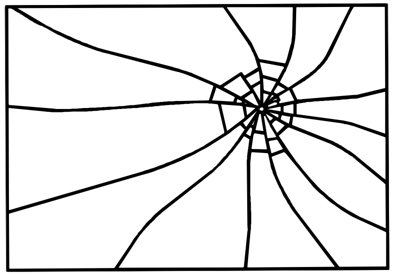
Typical glass failure



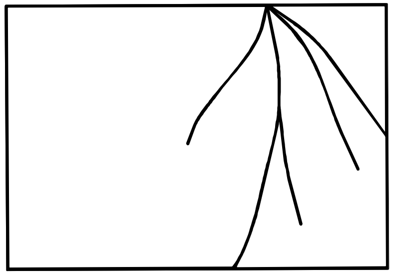
a) thermal failure



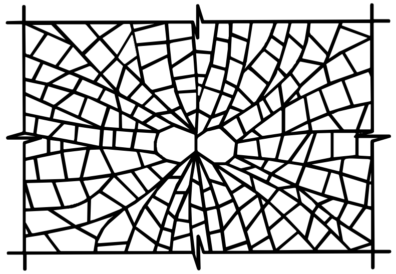
b) hard body impact



c) soft (spherical) body impact



d) hard spot on the edge



e) inclusion

- instability failure – compression member or flexural member
- overstressing of the glass in tension – by excessive uniform load, blast, impact, thermal stresses or uneven / inappropriate supports
- surface and edge defects
- solid inclusions

Typical glass failure

Objectives

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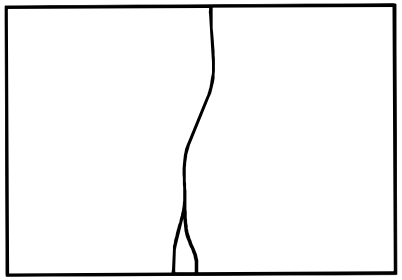
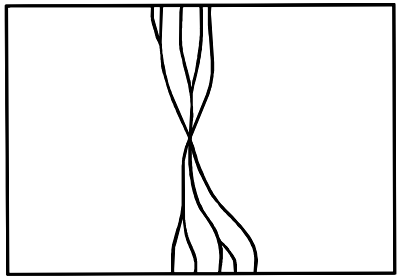
Strength of glass

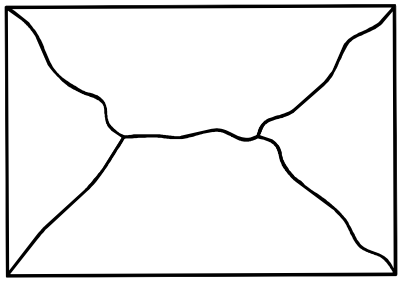
Glass failure modes



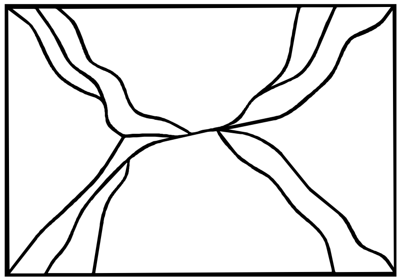
f) uniform lateral load, 2-edge support, low load intensity



g) uniform lateral load, 2-edge support, high load intensity



h) uniform lateral load, 4-edge support, low load intensity



i) uniform lateral load, 4-edge support, high load intensity

It is possible to recognize:

- failure origin
- failure patterns – crack in annealed glass often nucleate roughly perpendicular to the major principle stresses
- topographical features – e.g. presence of localized crushing on the surface of glass indicates impact from hard object

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