SOLAR GLASS TECHNOLOGY

# Strengthening of Solar Glass

*Developing Unbreakable Solutions*

From protective cover to structural backbone

THE THINNING CURVE

# Why Strength Matters

TRIVENI RENEWABLES PVT LTD

**Thinner, bigger, harder-working.** Larger formats, thinner 1.6–2.0 mm glass, heavier snow/wind loads, hailstorms and rough transport to more distant locations all push mechanical demands up while the material budget shrinks. Every step down in thickness has arrived with a step up in panel area

RELATIVE PANE SIZE

1.0× | 1.6× | 2.0× | ?

**ERA 1**
## 4.0 mm
PANEL AREA
1.0 – 1.25 m²
Tempered

**ERA 2**
## 3.2 mm
PANEL AREA
1.5 – 2.5 m²
Tempered

**ERA 3 ·**
## 2.0 mm
PANEL AREA
2.0 – 2.5 m²
Heat strengthened

**Upcoming :**
## 1.6 mm
PANEL AREA
Spec not yet defined
Treatment TBD

*Field data: glass breakage is now among the most reported module failure modes as thickness has decreased (NREL, 2025).*

**Thickness down 60% while panel area roughly doubles — strength has to come from consistent quality not mass.**

KNOW THE ENEMY

# How Solar Glass Fails

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### Edge chips & handling

Cutting, seaming and rough handling leave edge flaws — the #1 origin of field fractures.

### Scratches & abrasion

Surface scratches from processing, cleaning and soiling act as stress raisers.

### Inclusions & defects

Stones, bubbles and NiS inclusions create internal weak points and spontaneous breakage.

### Residual stresses

Poorly controlled annealing or quenching locks in tensile stress that helps cracks grow.

### Hail, wind & snow

Impact and sustained pressure loads flex large panes far beyond static ratings.

### Thermal shock & fatigue

Temperature gradients and daily cycling drive slow, subcritical crack propagation.

*The common thread: microscopic flaws — not bulk material — determine real-world strength.*

THE PHYSICS

# Fundamentals of Glass Strength

THEORETICAL STRENGTH

**~10–30 GPa**

PRACTICAL STRENGTH (FLOAT GLASS)

**~45–100 MPa** *— a 200–600× gap*

### Griffith fracture mechanics

Strength is set by the largest flaw: Tiny surface cracks concentrate stress enormously at their tips.

### Stress concentration

A 2 mm crack under just 50 MPa can see ~45 GPa at its tip — exceeding the bond strength of the glass itself.

### The engineering answer

Put the surface into compression. A crack cannot grow until applied tension first overcomes that built-in compressive layer.

**Design rule: strength is not a material constant — it is a defect statistic. Manage defects and surface stress, and 'weak' glass becomes strong.**

# Ways to Strengthen Glass

### Heat-strengthened

**≥ 31 MPa**
surface compression

- Slower air quench after reheating
- Large fragments on breakage
- Standard for 2.0 mm glass-glass modules
- Lowest cost, high throughput

***Today's workhorse***

### Fully tempered

**≥ 69 MPa**
surface compression

- Rapid air quench, deep compression
- Dice fragmentation
- Hard to temper below ~2.8 mm — flatness & yield suffer
- Moderate cost

***Strong but thickness-limited***

*Most 2 mm bifacial glass today is heat-strengthened*

THE PROCESS

# One furnace, different outcomes — it is all in the quench

All start as the same glass. How fast the surface is cooled decides the locked-in stress.

| | 1 — HEAT | 2 — COOL | 3 — LOCKED-IN STATE |
|---|---|---|---|
| **Annealed**<br>untreated float glass | **Heated in the float line**<br>Formed, then fed into the annealing lehr | **Cooled slowly over hours**<br>Surface and core cool at almost the same rate | **≈ 0 MPa compression**<br>No residual stress; strength depends only on surface flaws |
| **Heat strengthened**<br>HS · semi-tempered | **Reheated to ~620 °C**<br>Above the ~560 °C strain point in a horizontal furnace | **Moderate air quench**<br>Roughly half the blower pressure used for tempering | **≥ 31Mpa compression**<br>About 2× annealed strength; stiffer, flatter geometry |
| **Fully tempered**<br>FT · toughened safety glass | **Reheated to ~620–650 °C**<br>Same cycle, held close to the softening point | **Rapid high-pressure quench**<br>Surface freezes first; the core then pulls it into compression | **≥ 69 compression**<br>About 4× annealed strength; qualifies as safety glass |

**Same glass, same furnace — the quench rate alone sets whether you get 0, ~35 or ~85 MPa of surface compression.**

THE PROPERTIES

# What the locked-in stress gives you

Composition is identical across all three — every difference below comes from the residual surface compression.

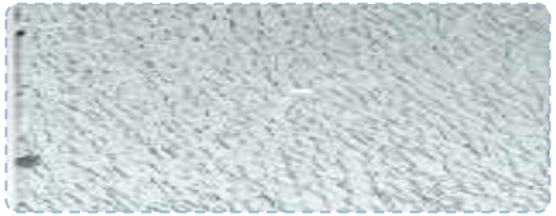
| PROPERTY | Annealed<br>untreated | Heat strengthened<br>HS | Fully tempered<br>FT |
|---|---|---|---|
| **Surface compression** | ≈ 0 MPa | >31 MPa | ≥ 69 MPa (typ. 90–120) |
| **Design bending strength** | ~19 – 28 MPa | >70 MPa | > 90 MPa |
| **Strength vs annealed** | 1× | ~2× | ~4× |
| **Thermal shock tolerance** | ~40 °C ΔT | ~100 °C ΔT | ~200 °C ΔT |
| **Cutting / drilling after** | Yes — fully fabricable | No — process before treating | No — process before treating |
| **Optical distortion / roll wave** | None | Low | Moderate (quench marks) |
| **Spontaneous NiS breakage** | Not a risk | Very low | Real risk (heat-soak to mitigate) |

BREAKAGE PATTERN

Fragment size falls as stored energy rises — the visual signature of each treatment.

**Large, sharp shards**

**Large fragments, radial cracks**



**Small, dice-like fragments**

STRENGTH IS MADE, NOT TESTED-IN

# Manufacturing: Where Strength Is Won or Lost

1

### Composition & melting

Batch purity, redox control, fewer stones, seeds & NiS inclusions

2

### Forming & ribbon

Thickness uniformity and pristine surfaces off the float/rolled line

3

### Edge finishing

Grinding & seaming quality — edges are where most cracks start

4

### Tempering

Furnace temperature uniformity + quench design set the stress profile

5

### Inspection

Inline optics & polariscopy catch flaws and residual-stress outliers

**Every step either adds a flaw or removes one.** Residual stress control and edge quality are the two highest-leverage variables — a perfect temper cannot rescue a chipped edge.

PROVE IT

# Testing & Qualification

### Mechanical strength

- Ring-on-ring — surface strength free of edge effects
- Four-point bending — edge + surface strength, Weibull statistics
- Fragmentation count — verifies temper level (EN 12150)
- Ball drop & hail impact — IEC 61215 impact survival, 25 mm+ hail
- Dynamic mechanical load — cyclic wind/snow pressure (±1000 Pa+)

### Environment & diagnostics

- Thermal cycling −40/+85 °C — expansion mismatch endurance
- Damp heat 85 °C / 85% RH — surface & interlayer durability
- Thermal shock — resistance to rapid gradients
- Polariscopy / scattered light — maps residual stress non-destructively
- Fractography — reads broken glass to find the true root cause

***Strength data is statistical: report Weibull modulus and characteristic strength, never a single number.***

CLOSING

# Not Unbreakable Glass — an Unbreakable System

The goal is a glass-module system that survives manufacturing, transport, installation and decades in the field — engineered through defect control, compressive stress

*Thank you • Questions welcome*

KEY TAKEAWAYS

- Reliability is the next competitive differentiator
- Strength = defect control + engineered compressive stress
- PV needs stronger, thinner, lighter glass
- Mastering strengthening earns premium positioning