THE STATE UNIVERSITY OF NEW JERSEY
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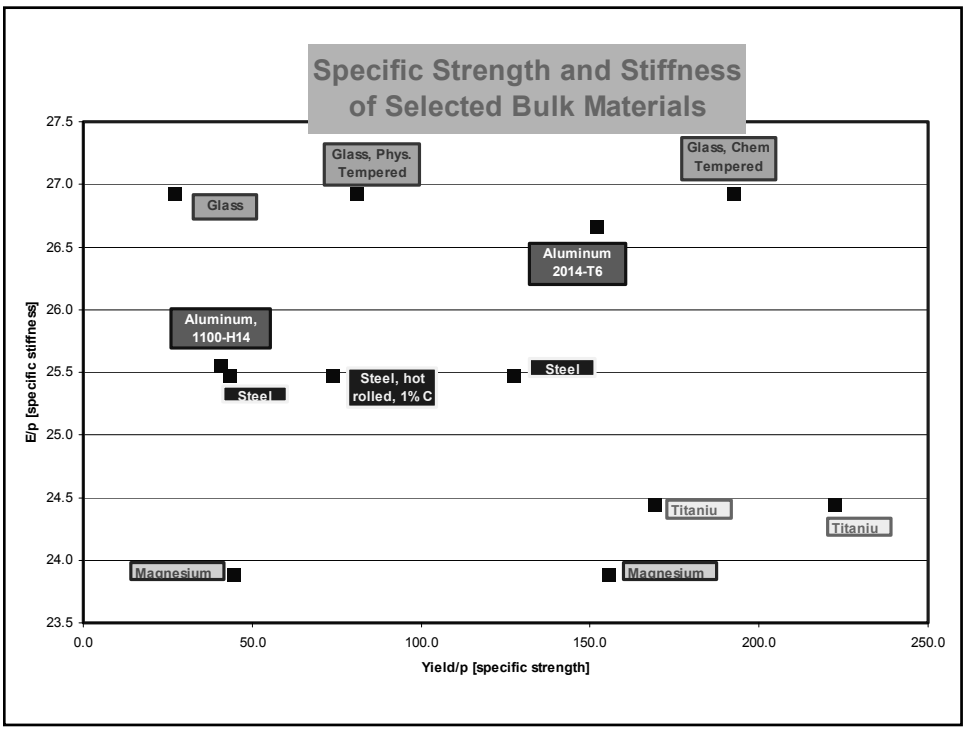
The Mechanical Properties of Glass

Theoretical strength, practical strength, fatigue, flaws, toughness, chemical processes

Glass Engineering
150:312

Professor Richard Lehman
Department of Ceramics and Materials Engineering
Rutgers University, New Brunswick, New Jersey, USA



Theoretical Strength of Glass

- **Most glasses have strong covalent bonds**
  - → Si-O bonds, 435 kJ/mole
  - → Yields theoretical strength of 17 GPa
- **Practical strength is much less**
  - → Depends on flaws, usually on surface
    - ✓ scratches
    - ✓ bubbles
    - ✓ inhomogeneities
    - ✓ inclusions
    - ✓ any mechanically distinguishable phase
  - → Manufactured glass has nominal strength of 70 MPa [10 KPsi]
  - → Design stresses often 7 MPa or less for high reliability structures
  - → Low surface area structures [e.g. fibers] have higher strengths

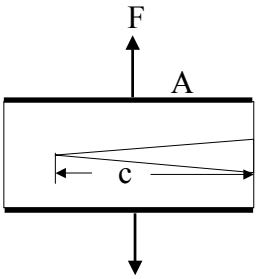
Units Primer

System	Property	Units	Fundamental	Conversion
Standard International	**Pressure, Stress**	**Pascal, Pa**	**N/m^2 $kg/m\text{-}sec^2$**	**1000 psi = 7 MPa**
	Toughness	**$MPa\text{-}m^{0.5}$**	**As above**	**N/A**
Customary American	**Pressure, Stress**	**Pounds per square inch**	**lbs (force)/in^2**	**1 MPa = 143 psi**

Practical Strength of Glass

- σ = failure stress, i.e. strength of the material
- c = flaw size in meters
- K_{IC} = Critical stress intensity factor for mode I crack propagation.
- K_{IC} has low values for brittle materials, high values for tough materials
- Value = 0.75 - 1.0 MPa-$m^{0.5}$ for glass

$$\sigma = \frac{K_{IC}}{\sqrt{\pi c}}$$



$$\sigma = \frac{F}{A}$$

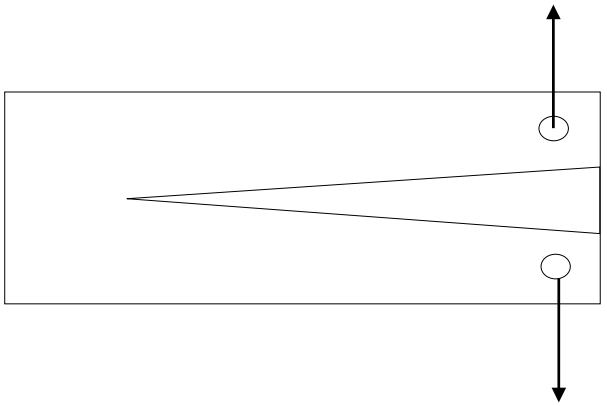
Flaw Sensitivity of Glass

- Calculated strengths of glass with various flaw sizes and K_{IC} values.
- Typical flaws size ranges and K_{IC} values are highlighted

	KIC			
	0.5	1	2	10
c, microns				
0.2	631	1262	2523	12616
0.4	446	892	1784	8921
0.8	315	631	1262	6308
1.6	223	446	892	4460
3.2	158	315	631	3154
6.4	112	223	446	2230
12.8	79	158	315	1577
25.6	56	112	223	1115
51.2	39	79	158	788
102.4	28	56	112	558
204.8	20	39	79	394
409.6	14	28	56	279
819.2	10	20	39	197
1638.4	7	14	28	139
3276.8	5	10	20	99

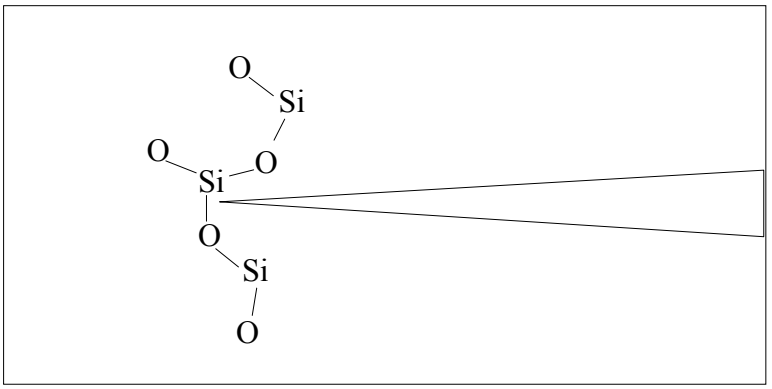
Measuring K_{IC}

- **Double Cantilever beam test apparatus for measuring K_{IC}**
- **Allows controlled propagation rate of flaw**



Chemical Aspects of Glass Strength

- **Fracture process is one of breaking bonds**
- **Si-O bonds are the principal bonds in silicate glasses**



Chemical Aspects of Glass Strength

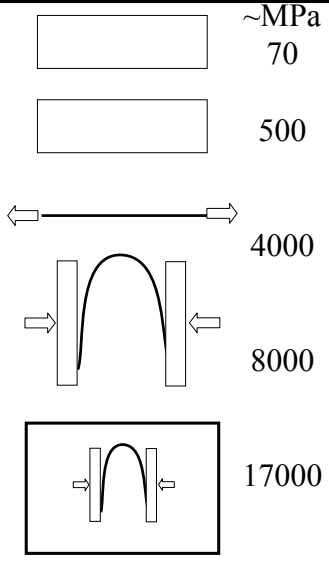
- **Si-O bonds are susceptible to scission by nucleophilic attack.**
- **Negatively charges attacking the positively charged nucleus**
- **Result:**

$$\equiv Si - O - Si \equiv + H_2O \Rightarrow 2\,[\equiv Si - OH]$$

The presence of water or other polar substances greatly accelerates the crack propagation process

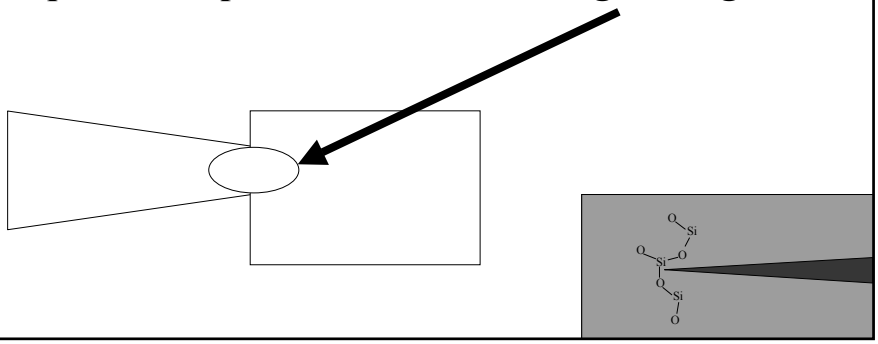
Experimental Demonstration of the Effects of Flaws and Chemical Attack on Glass Strength

- **Ordinary bulk glass as a nominal strength of 70 MPa**
- **Bulk synthetic glass [$SiCl_4$ - derived] has a strength of 500 MPa [7X increase] due to fewer impurity defects**
- **Drawing fibers from synthetic glass reduces the surface area under test and increases strength to 4 GPa for 10 cm gage length**
- **Bending fibers to test strength reduces gage length to a few microns. Strength increases to 8 GPa.**
- **Perform bending test in liquid nitrogen [77 K] to zero chemical effects. Strength is statistically the same as theoretical strength!**



Does Water Aid Fracture or Increase Strength? [It depends on form of the water!]

- **Water vapor promotes failure:**
  - → $SiO_2 + 2H_2O$ ➔ $Si(OH)_4$
  - → Bonds broken, glass fractured
- **Liquid water promotes crack blunting/healing**

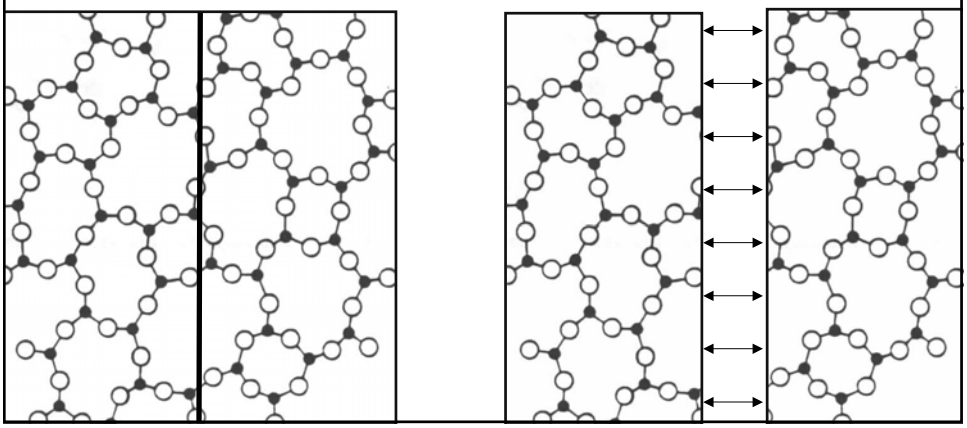


Mechanical Properties of Materials -- Comparison

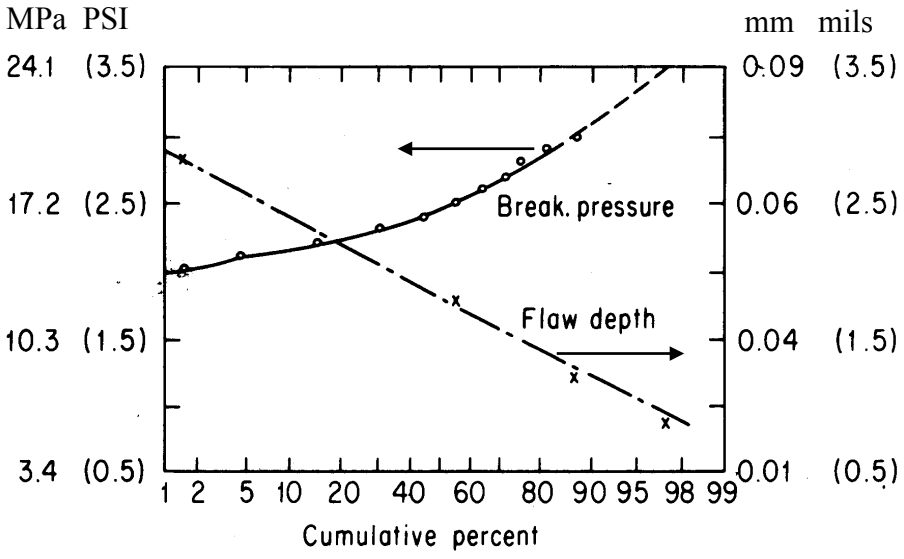
Material	Density	Modulus	Yield	Ultimate	Specific Yield	Specific Stiffness
Glass	2.6	70	70	70	26.9	26.9
Aluminum, Alloy 1100-H14	2.7	69	110	120	40.7	25.6
Steel, High Strength, low range	7.85	200	340	550	43.3	25.5
Magnesium, low	1.8	43	80	140	44.4	23.9
Steel, hot rolled, 1% C	7.85	200	580	960	73.9	25.5
Glass, Phys Tempered	2.6	70	210	210	80.8	26.9
Steel, High Strength, high range	7.85	200	1000	1200	127.4	25.5
Aluminum, Alloy 2014-T6	2.7	72	410	500	151.9	26.7
Magnesium, high	1.8	43	280	340	155.6	23.9
Titanium, low	4.5	110	760	900	168.9	24.4
Glass, Chem. Tempered	2.6	70	500	500	192.3	26.9
Titanium, high	4.5	110	1000	1200	222.2	24.4
Glass, Fibers	2.6	70	4000	4000	1538.5	26.9

Theoretical Strength of Glass

- **Theoretical strength of glass can be calculated from the energy needed to separate a plane of atoms, see diagram**
- **Si - O covalent bonds are strong, circa 104 kcal**
- **Calculated value gives: 18 GPa or 2.6 million Psi**
- **Most practical and design strengths are 1000 times less!**



Strength of Glass Decreases with Increasing Flaw Size



Strength of Glass from Various Processes

Condition of Glass	MPa	10^3 lb/in^2
Surfaces ground or sandblasted	10–28	1.5–4.0
Pressed articles	21–55	3.0–8.0
Blown ware:		
Hot iron molds	28–62	4.0–9.0
Paste molds	35–69	5.0–10.0
Inner surfaces	104–280	15.0–40.0
Drawn tubing or rod	41–104	6.0–15.0
Window glass	55–138	8.0–20.0
Fine fibers:		
Annealed	69–280	10.0–40.0
Freshly drawn	207–2758	30–400.0

*Effective duration of breaking load, 3 s.

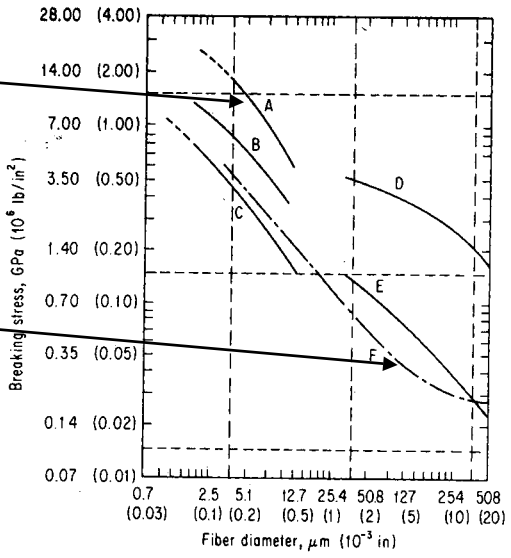
Strength Depends on Surface Condition

- **A pristine, protected surface is important for high strength**
- **Flaws concentrate stress and reduce strength**
- **Etching or fire-polishing can remove flaws**
- **Lacquer protects surfaces, mechanically and chemically**

	Flexural Strength,1 h load duration	
Surface Condition	**MPa**	**KPsi**
As Received	14	2.0
Severely Sandblasted	45	6.5
Acid Etched and coated with lacquer to protect surfaces	1725	250

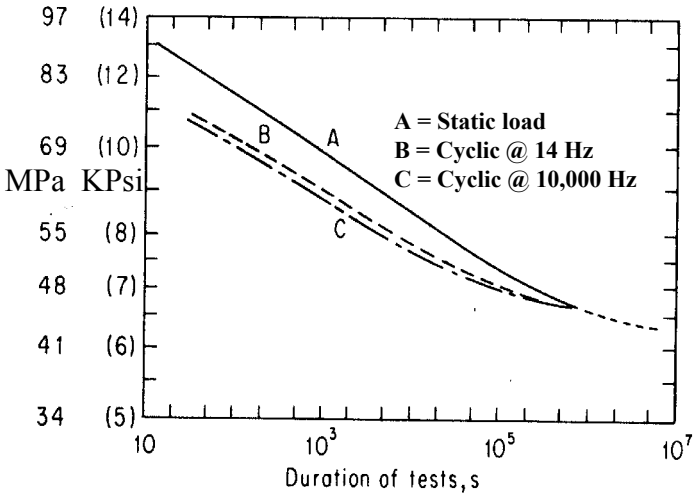
Effect of Glass Composition and Fiber Diameter on Tensile Strength

A = Fused silica in vacuum after baking
B = Fused silica in dry atmosphere
C = Fused silica in moist atmospher
D = Borosilicate glass in dry air
E = Borosilicate glass in air
F = Soda lime silicate glass in air

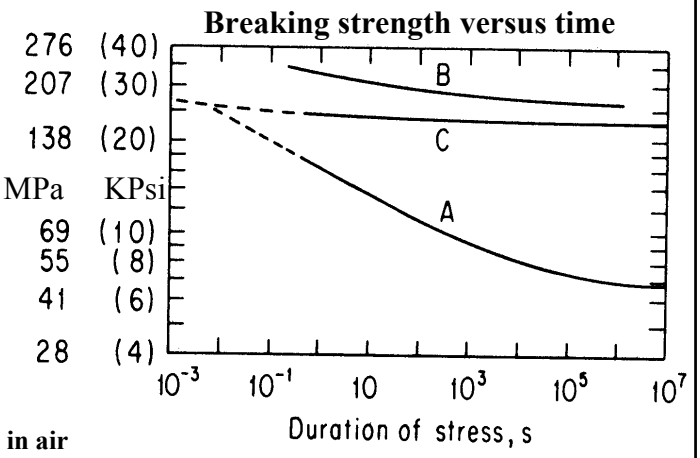


Fatigue Behavior of Glass

- **Breaking Stress versus duration**



Fatigue Behavior of Glass

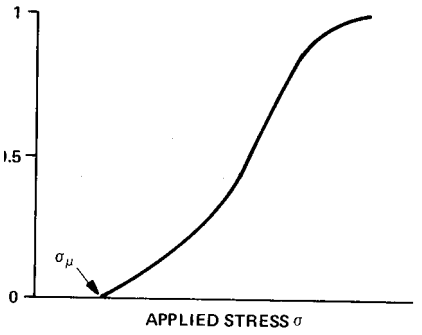


- **A = Annealed glass in air**
- **B = Tempered glass in air**
- **C = Annealed glass in vacuum.**

Glass Failure and Weibull Statistics

- **Glass failure does not follow normal statistics**
- **Weibull generated a new approach for brittle materials.**
- **σ_μ = threshold failure stress**
- **σ_o = characteristic stress**
- **m = Weibull modulus**

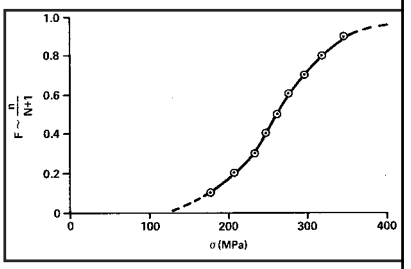
$$f(\sigma) = \left(\frac{\sigma - \sigma_\mu}{\sigma_o} \right)^m$$



Weibull Statistics -- Example

- **Sort measured strength data in ascending order**
- **Devise a way to calculate frequency, simple one shown**
- **Graph data on linear axes**

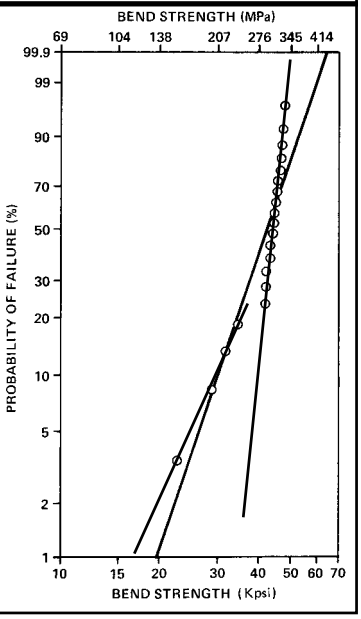
Number of ordered data	Measured strength σ (MPa)	Estimated probability of failure, $F \sim \frac{n}{N+1}$
1	178	0.1
2	210	0.2
3	235	0.3
4	248	0.4
5	262	0.5
6	276	0.6
7	296	0.7
8	318	0.8
9	345	0.9



Fatigue Behavior of Glass

- **Graph data on log - probability axes**
- **Data should give a straight line**
- **Blue line indicates one Weibull distribution at high strengths -- intrinsic behavior of process**
- **Red line indicates a second flaw distribution at lower strengths**

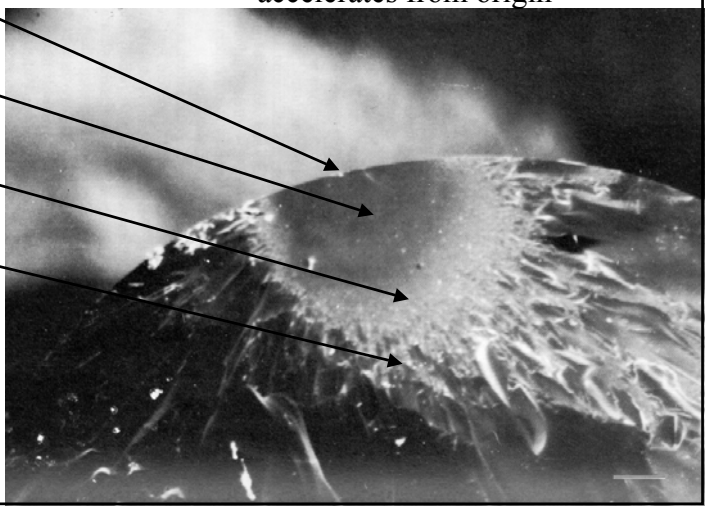
- **Approach to increase glass strength**
  - → Determine cause of red line failures
    - ✓ Begin at weakest failure and work up
    - ✓ Can estimate flaw size from Griffin relationship
  - → Eliminate or fix process step that generates failures
  - → Move on to next distribution



Fracture Behavior of Glass

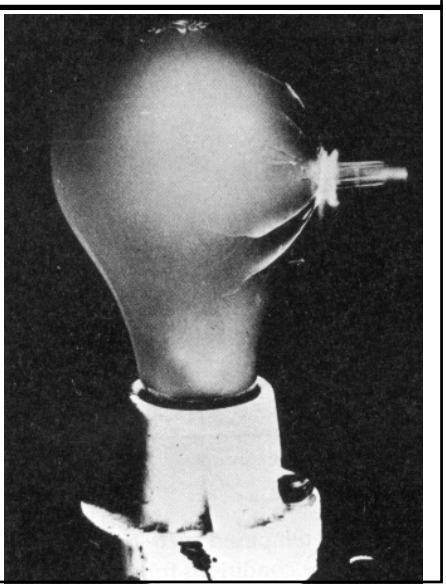
- **Origin**
- **Mirror**
- **Mist**
- **Hackle**

Features form as crack accelerates from origin



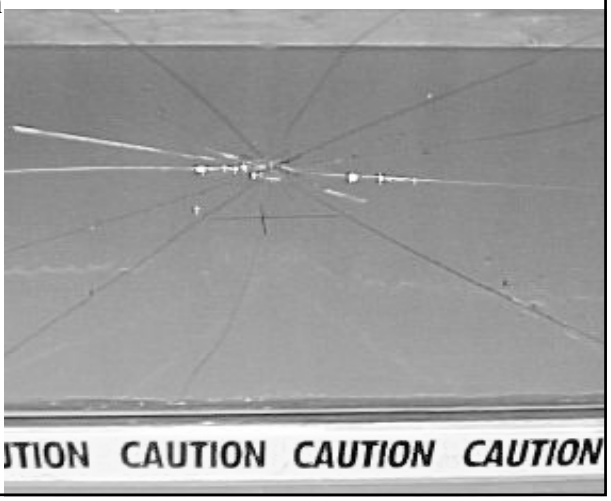
Crack Propagation in Glass

- **Bullet velocity = 800 m/s**
- **Fracture velocity = 1500 m/s**
- **Shock wave velocity = 4500 m/s**
- **Exposure time = 1 μs**



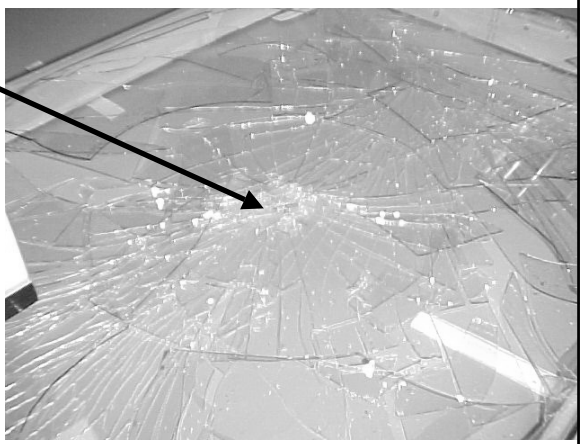
Fracture Behavior of Glass

- Low Energy Impact
- Distinct point of origin
- Low to moderate radial cracking
- Few fragments



Fracture Behavior of Glass

- High Energy Impact
- Distinct point of origin
- Extensive radial and circumferential cracking pattern
- Many fragments



Fracture Behavior of Glass

- **Impact failure of tempered glass**
- **Enormous number of small fragments**
- **Glass not penetrated in this instance**
- **Glass continues to support some load.**

Methods for Strengthening Glass

Treatment	Approximate maximum strengthening factor
Quench-hardening	6
Ion exchange	10
Surface crystallization	17
Ion exchange and surface crystallization	22
Etching	30
Fire-polishing	200
Second-phase particles	2

- **Fire Polishing improves strength the most**
- **Quench-hardening is most common commercially**

ASTM Test Specifications and Methods for Glass

Specifications for:

§C 1053 – 90	Borosilicate Glass Pipe and Fittings for Drain, Waste, and Vent (DWV) Applications
F 105 – 72 (1991)	Borosilicate Sealing Glass, Type 58
C 599 – 91	Conical Process Glass Pipe and Fittings
§C 1036 – 91	Flat Glass
§C 1048 – 92	Heat-Treated Flat Glass—Kind HS, Kind FT Coated and Uncoated Glass
C 1172 – 91	Laminated Architectural Flat Glass
F 79 – 69 (1991)	Sealing Glass, Type 101
E 211 – 82 (1990)	*Cover Glasses and Glass Slides for Use in Microscopy (see Vol 14.02)*
D 581 – 94	*Glass Fiber Greige Braided Tubular Sleeving (see Vol 07.01)*
D 578 – 90	*Glass Fiber Yarns (see Vol 07.01)*
E 438 – 92	*Glasses in Laboratory Apparatus (see Vol 14.02)*
D 579 – 90	*Greige Woven Glass Fabrics (see Vol 07.01)*
D 580 – 94	*Greige Woven Glass Tapes and Webbings (see Vol 07.01)*

Test Methods for:

C 724 – 91	Acid Resistance of Ceramic Decorations on Architectural-Type Glass
C 735 – 93	Acid Resistance of Ceramic Decorations on Returnable Beer and Beverage Glass Containers
C 1203 – 91	Alkali Resistance of a Ceramic-Glass Enamel, Quantitative Determination of
C 675 – 91	Alkali Resistance of Ceramic Decorations on Returnable Beverage Glass Containers
C 336 – 71 (1991)$^{\epsilon 1}$	Annealing Point and Strain Point of Glass by Fiber Elongation
C 598 – 93	Annealing Point and Strain Point of Glass by Beam Bending
C 146 – 94a	Chemical Analysis of Glass Sand
§C 169 – 92	Chemical Analysis of Soda-Lime and Borosilicate Glass
§C 225 – 85 (1994)$^{\epsilon 1}$	Chemical Attack, Resistance of Glass Containers to
C 657 – 93	D-C Volume Resistivity of Glass
C 693 – 93	Density of Glass by Buoyancy
C 729 – 75 (1990)	Density of Glass by the Sink-Float Comparator
C 676 – 93	Detergent Resistance of Ceramic Decorations on Glass Tableware
C 770 – 77 (1989)$^{\epsilon 1}$	Glass Stress—Optical Coefficient, Measurement of
C 813 – 90 (1994)	Hydrophobic Contamination on Glass by Contact Angle Measurement
C 147 – 86 (1991)$^{\epsilon 1}$	Internal Pressure Strength of Glass Containers
C 730 – 85 (1989)$^{\epsilon 2}$	Knoop Indentation Hardness of Glass
C 927 – 80 (1993)$^{\epsilon 1}$	Lead and Cadmium Extracted from the Lip and Rim Area of Glass Tumblers Externally Decorated with Ceramic Glass Enamels
C 1279 – 94	Non Destructive Photoelastic Measurement Edge and Surface Stresses in Annealed, Heat Strengthened and Fully Tempered Flat Glass
§C 148 – 92	Polariscopic Examination of Glass Containers
C 601 – 85 (1991)	Pressure Test on Glass Pipe
C 429 – 82 (1991)$^{\epsilon 1}$	Sieve Analysis of Raw Materials for Glass Manufacture
§C 338 – 93	Softening Point of Glass
C 158 – 84 (1989)$^{\epsilon 1}$	Strength of Glass by Flexure (Determination of Modulus of Rupture)
C 978 – 87 (1991)$^{\epsilon 1}$	Photoelastic Determination of Residual Stress in a Transparent Glass Matrix Using a Polarizing Microscope and Optical Retardation Compensation Procedures
C 777 – 93	Sulfide Resistance of Ceramic Decorations on Glass

ASTM Test Specifications and Methods for Glass
[Continued]

Test Methods for:

§C 149 – 86 (1991)$^{\epsilon 1}$	Thermal Shock Resistance of Glass Containers
C 600 – 85 (1991)	Thermal Shock Test on Glass Pipe
C 623 – 92	Young's Modulus, Shear Modulus, and Poisson's Ratio for Glass and Glass-Ceramics by Resonance
F 218 – 68 (1989)	*Analyzing Stress in Glass (see Vol 5.02)*
F 21 – 65 (1989)	*Hydrophobic Surface Films by the Atomizer Test (see Vol 10.05)*
F 22 – 65 (1992)	*Hydrophobic Surface Films by the Water-Break Test (see Vol 10.05)*

Practices for:

C 912 – 93	Designing a Process for Cleaning Technical Glasses
C 824 – 91	Expansion, Linear Thermal, of Vitreous Glass Enamels and Glass Enamel Frits by the Dilatometer Method, Specimen Preparation for Determination of
C 1256 – 93$^{\epsilon 1}$	Interpreting Glass Fracture Surface Features
C 829 – 81 (1990)	Measurement of Liquidus Temperature of Glass by the Gradient Furnace Method
C 965 – 81 (1990)$^{\epsilon 2}$	Measuring Viscosity of Glass Above the Softening Point
F 14 – 80 (1991)	Reference Glass-Metal Bead-Seal, Making and Testing
F 140 – 83 (1991)	Reference Glass-Metal Butt Seals and Testing for Expansion Characteristics by Polarimetric Methods, Making
F 144 – 80 (1991)	Reference Glass-Metal Sandwich Seal and Testing for Expansion Characteristics by Polarimetric Methods, Making
C 224 – 78 (1994)$^{\epsilon 1}$	Sampling Glass Containers
E 165 – 94	*Liquid Penetrant Inspection Method (see Vol 03.03)*
F 35 – 68 (1988)	*Minute Crystalline Particle Contaminants by X-Ray Diffraction, Identification of (see Vol 10.05)*

Terminology of:

C 162 – 94c	Glass and Glass Products