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Fundamentals of Indentation Cracking in Glass: A Measure of Strength?

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Nippon Electric Glass Co., Ltd.

Continuous support for our works on mechanical properties of glass

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S. Iwata, H. Sawasato, and BS and MS students

Outline

1. Background
   - » Strong glasses around us
   - » What factors determine glass strength? ··· Cracks

2. Indentation cracking
   - » What factors affect indentation cracking?
     ··· Densification

3. Micro-photoelastic imaging technique
   - » Elastic and residual stresses around a ball indentation
   - » Compositional variation of the residual stress

4. Summary

Background

Strong glasses around us

Apple Store,
New York City

Glass House,
Milan, Italy

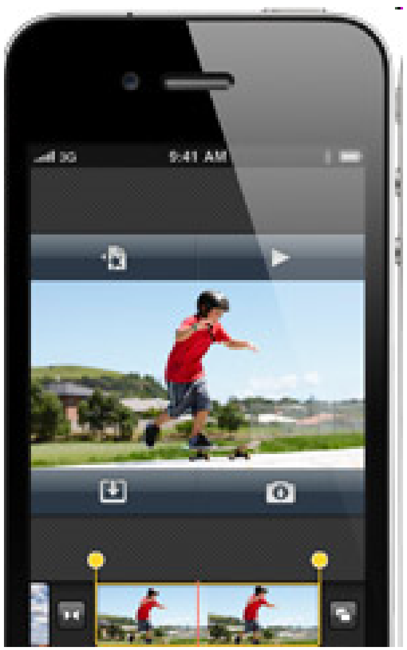
Glass Violin,
Hario Glass, Japan

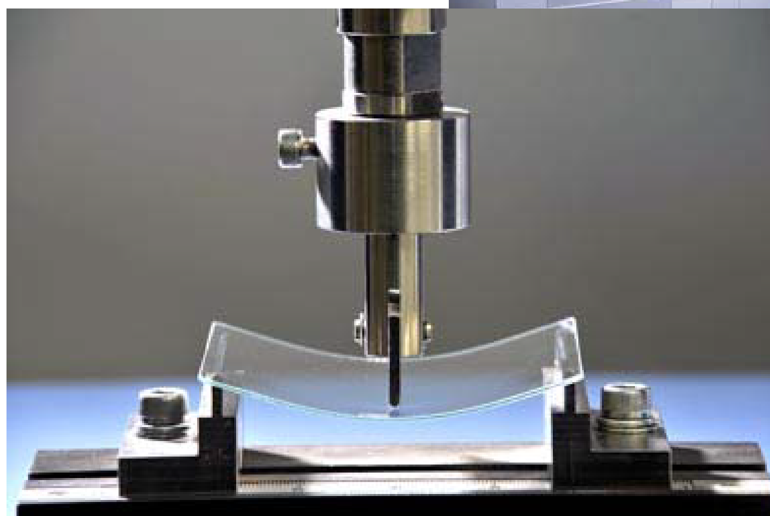
Background

Strong glasses around us

Schott AG
Xensation
(ion-exchanged)

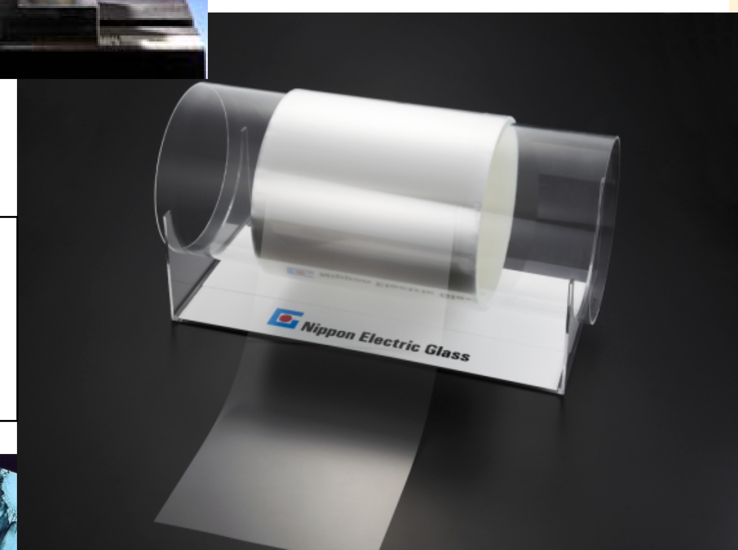
Corning
Gorilla
(ion-exchanged)

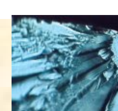




Asahi, AGC
Dragon trail
(ion-exchanged)

NEG
Thin-Film Glass
t = 0.05 mm





Background

<u>Fracture of glass is one of the crucial issues.</u>

iPad

Aquarium glass tank (Tempered)
in Toyohashi, Japan
A sea otter broke it using a shell.

Background

<u>We need a simple evaluation method of glass strength.</u>

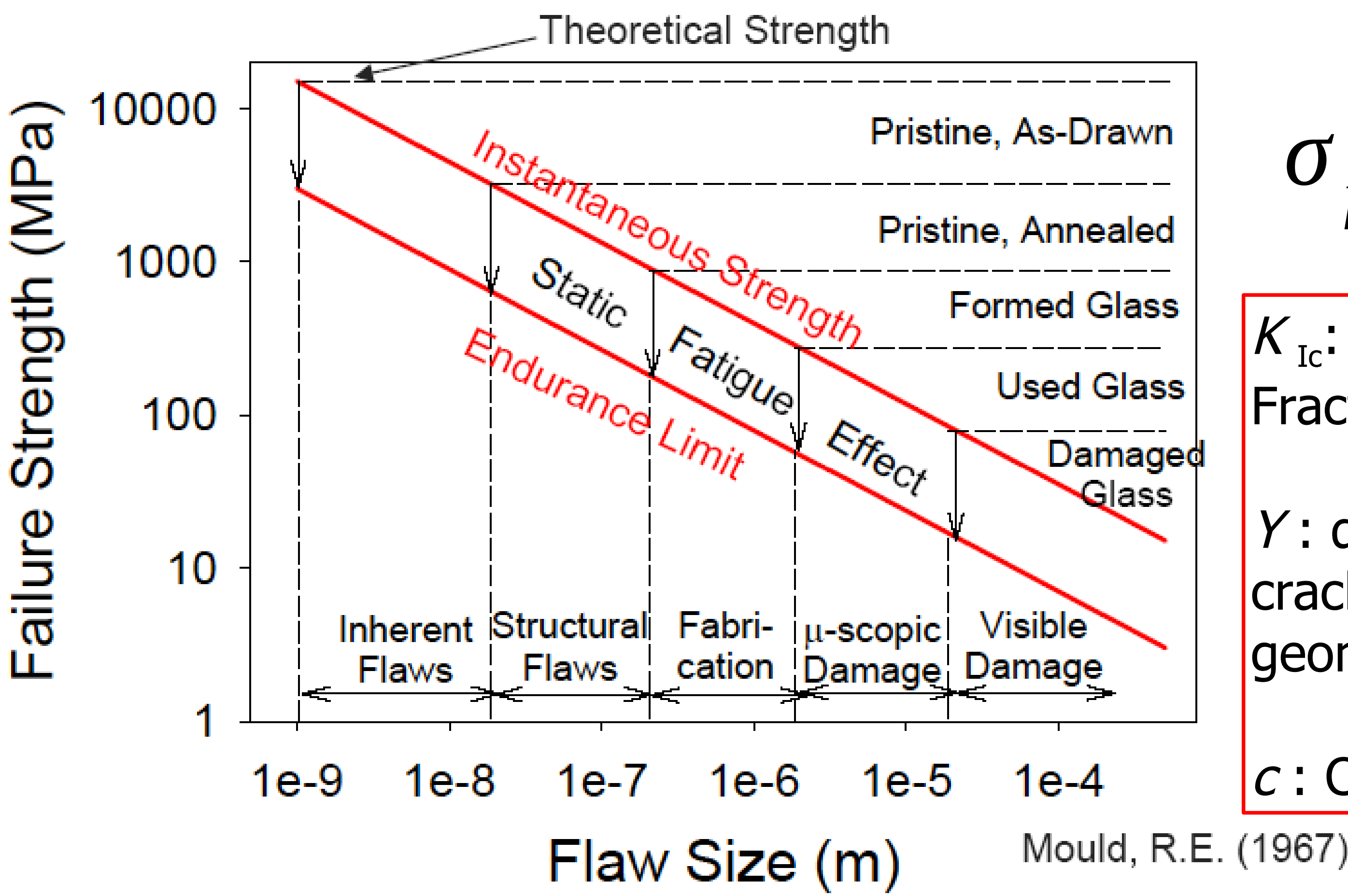
↓

We must know

What determines the glass strength?

Background

A larger crack results in a lower fracture stress.



$$\sigma_f = Y \frac{K_{Ic}}{\sqrt{c}}$$

K_{Ic}:
Fracture toughness

Y : depends on the crack and loading geometries.

c : Crack size

R.E. Mould, "The Strength of Inorganic Glasses," pp. 119 to 149 in Fundamental Phenomena in the Materials Sciences, V. 4 (1967)

Background

K_{Ic} of glass shows a less compositional variation.

Glass	Fracture toughness SEPB ($MPam^{1/2}$)
LCD backlight tube	0.73
LCD substrate	0.79
Microscope slide	0.76
CRT tube	0.71
PDP substrate	0.73
X-ray shield (lead glass)	0.66
Mother glass of glass-ceramic(Li-Al-Si)	0.84

Y. Kato *et al.*, *J. Non-Cryst. Solids* **356**(2010)1768.

$$\sigma_f = Y \frac{K_{Ic}}{\sqrt{c}}$$

K_{Ic}:
Fracture toughness

Y : depends on the crack and loading geometries.

Crack size ($\sqrt{c}$) is a critical factor of glass strength !

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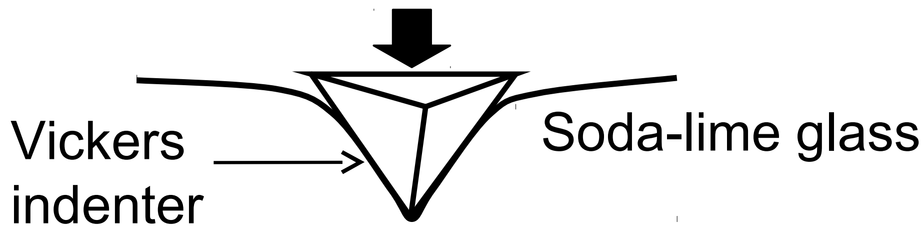
Indentation cracking

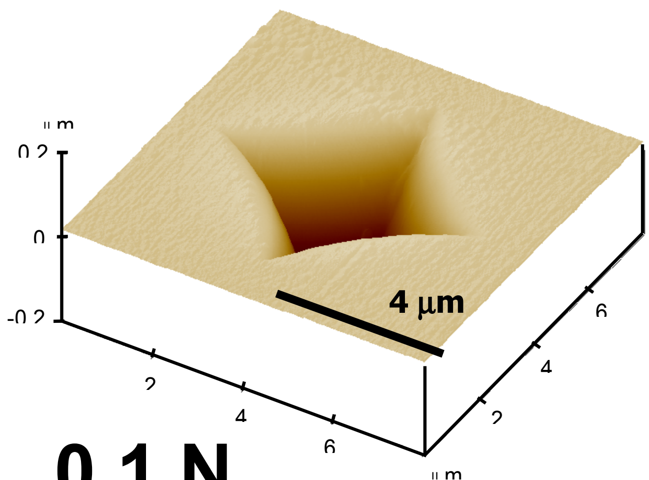
» One measure to evaluate Crack Resistance

» One of the simplest fracture tests

Indentation Cracking

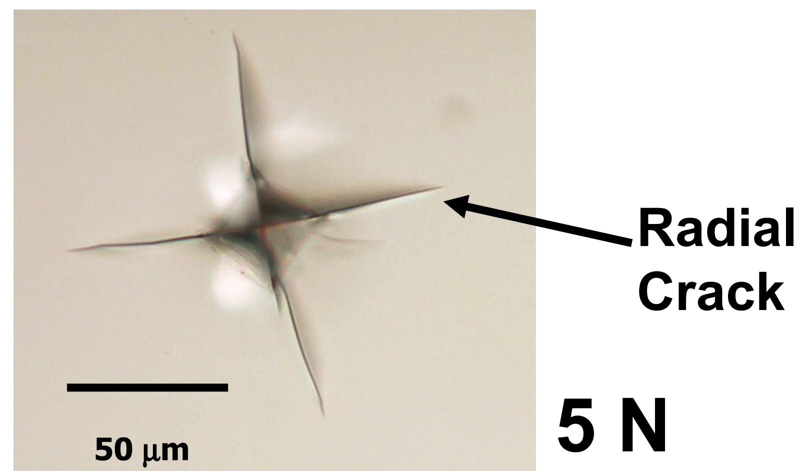
Indentation is used to model Contact Damage, or Crack Nucleation.





0.1 N

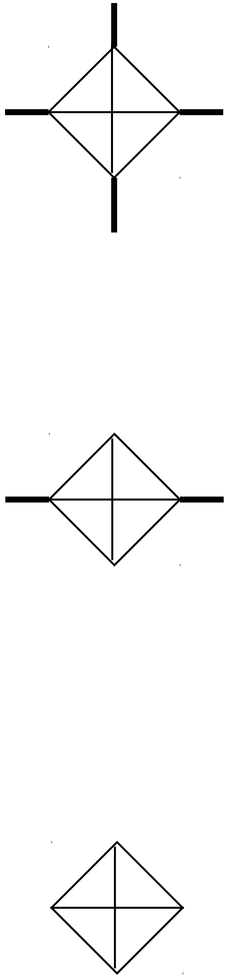
Increasing load



5 N

Comp. dependence of indentation cracking

M. Wada *et al.*, *Proc. Xth I.C.G.* **10**(1974)39.



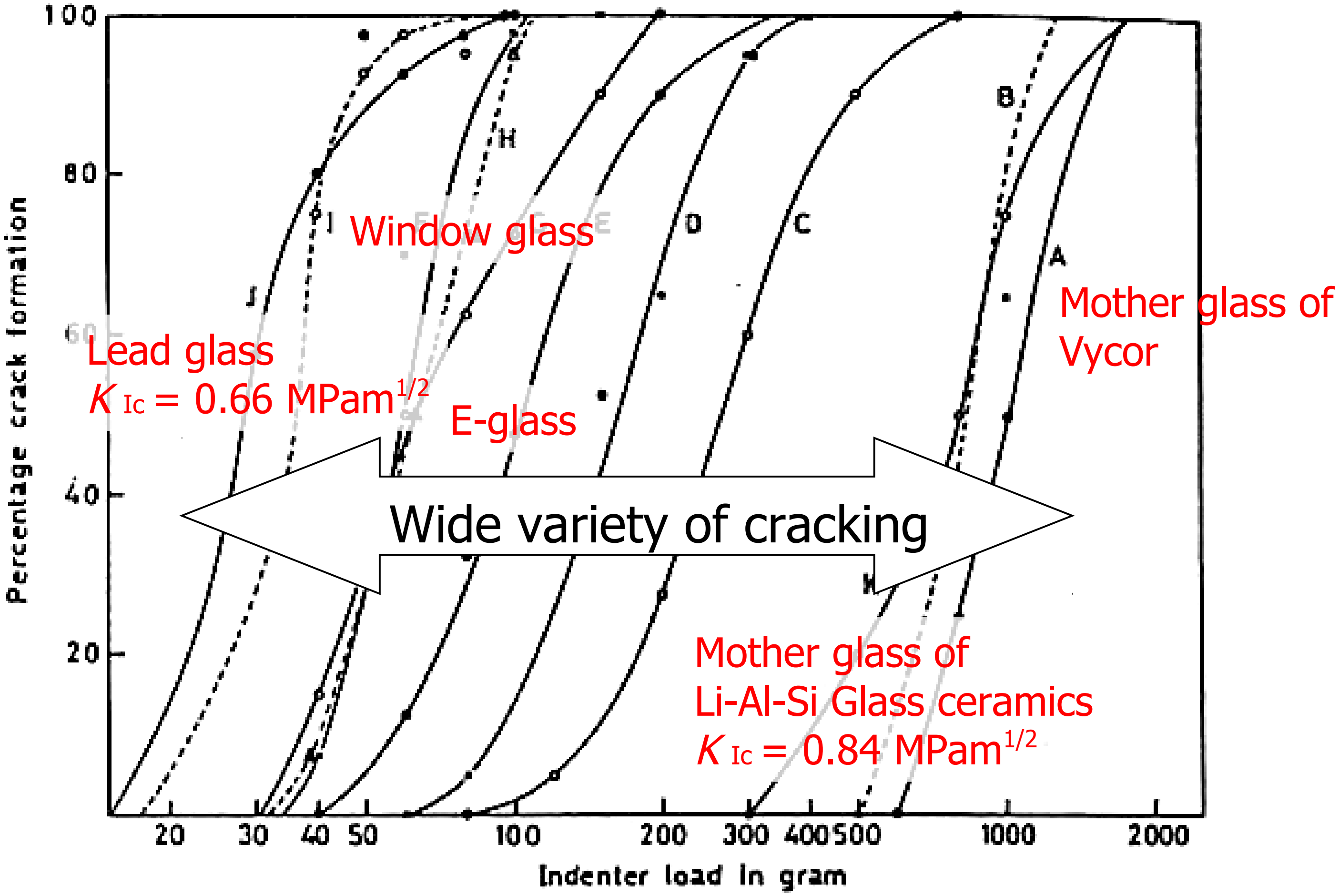
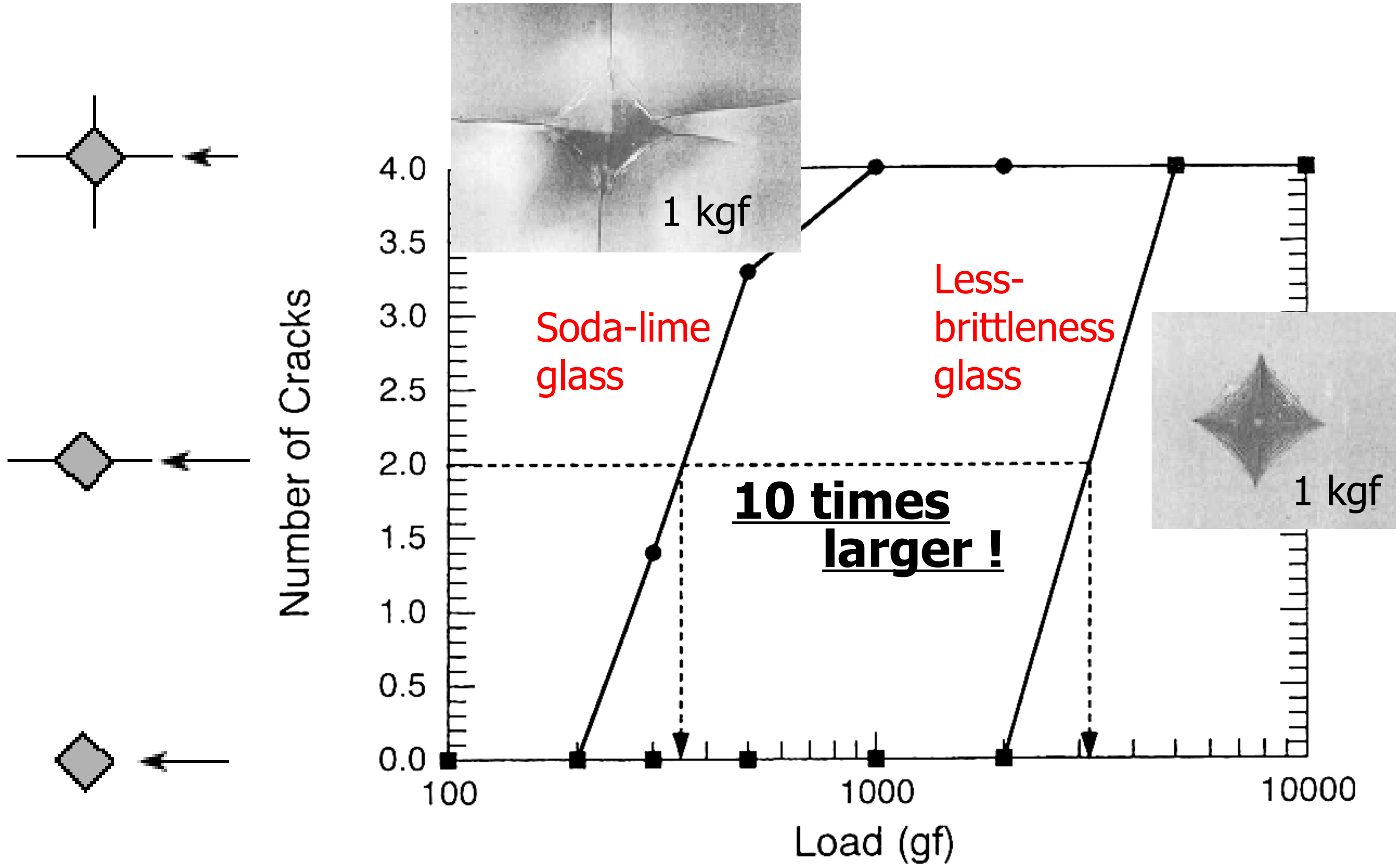


Figure 4. Crack resistances of various glasses.

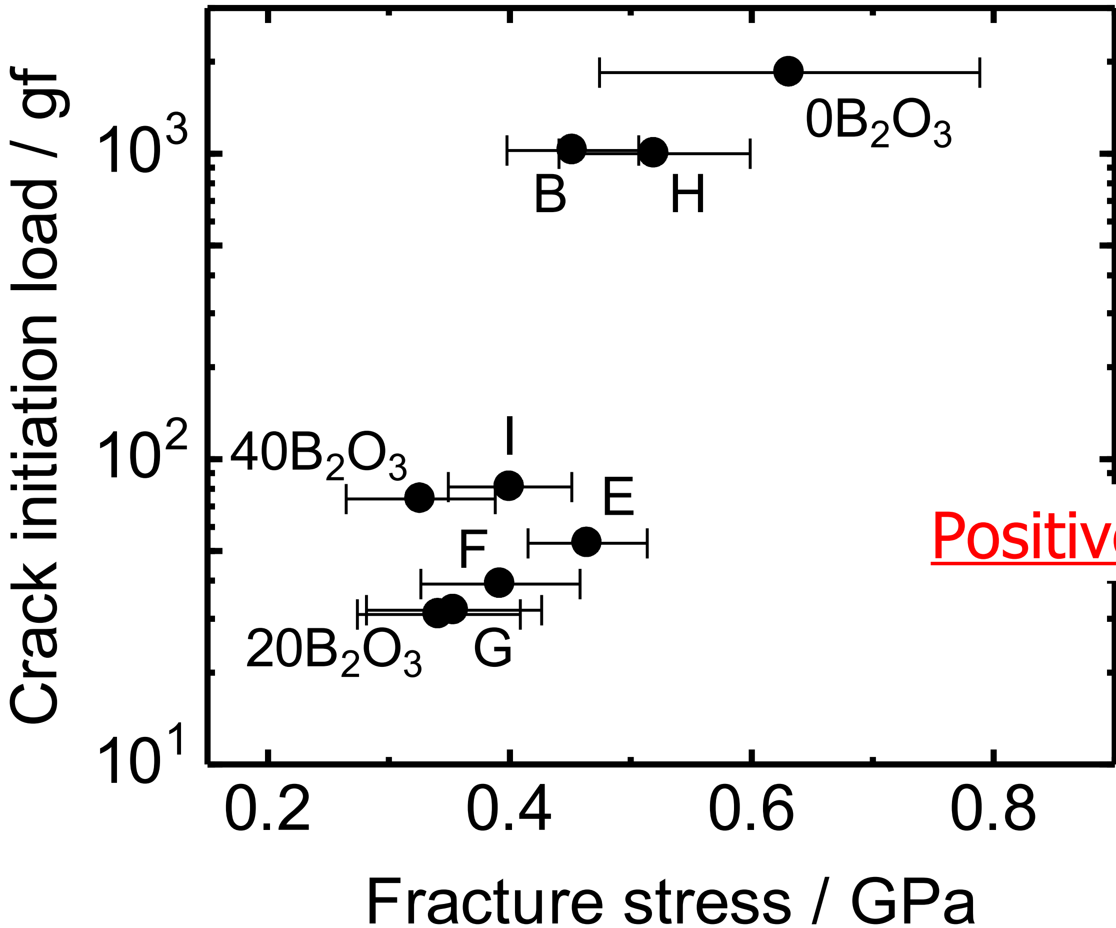
Comp. dependence of indentation cracking



J. Sehgal & S. Ito, *J. Am. Ceram. Soc.* **81**(1998)2485.

What factors determine the crack initiation load?

Relation between crack initiation load and Ring-on-Ring fracture stress



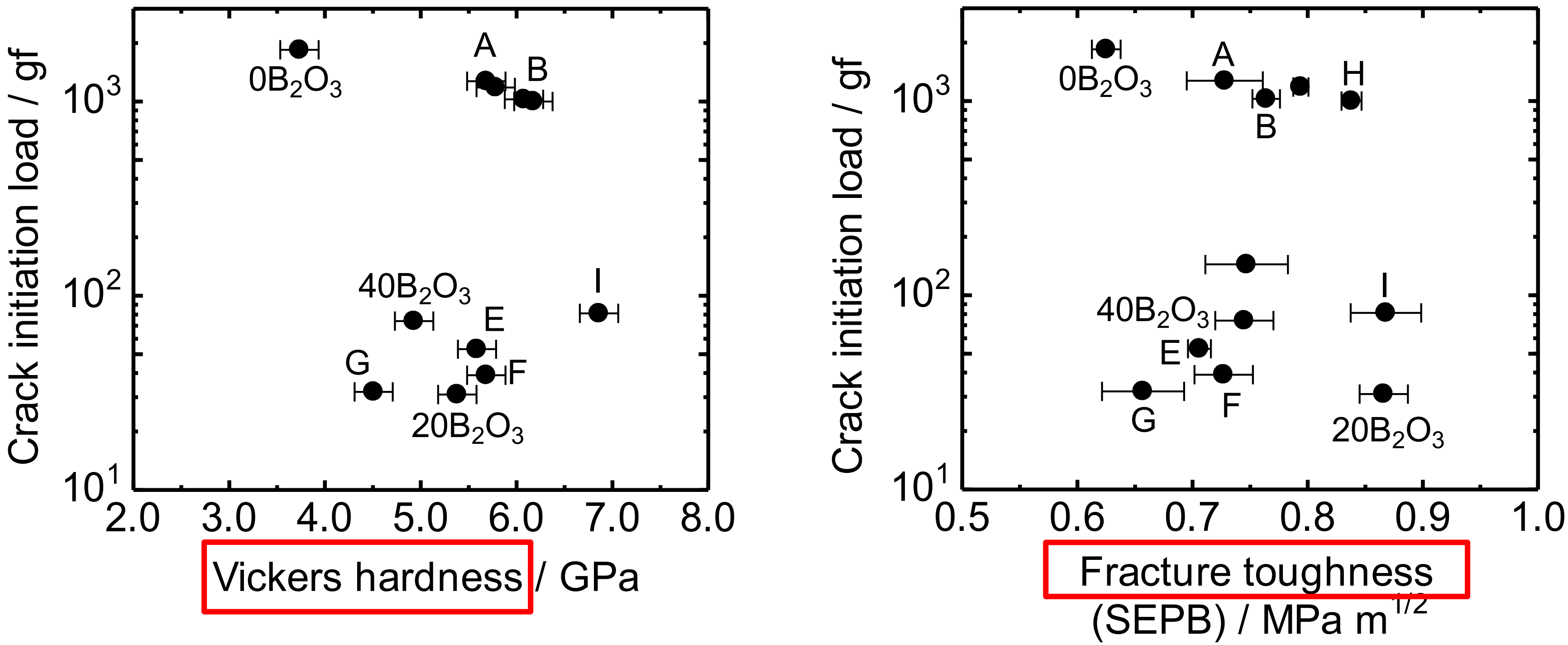
Positive relation ?

We are on the right track.

But, the compositional variation of ROR fracture stress is not so large.

No relation between crack initiation and other mechanical properties

S. Yoshida, *XIXth I.C.G. (2007)*
Y. Kato, *JNCS (2010)*



A: SiO_2-B_2O_3-K_2O	B: SiO_2-B_2O_3-Na_2O	C: SiO_2-Al_2O_3-B_2O_3
D: SiO_2-CaO-Na_2O	E: SiO_2-SrO-Na_2O	F: SiO_2-SrO-K_2O
G: SiO_2-B_2O_3-PbO	H: SiO_2-Al_2O_3-Li_2O	I: Li-Al-Si Glass-ceramics

$0B_2O_3$, $20B_2O_3$, $40B_2O_3$: (80-x)SiO_2-x B_2O_3-20Na_2O

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Even though the indentation load is identical,

the driving force for crack initiation would be different

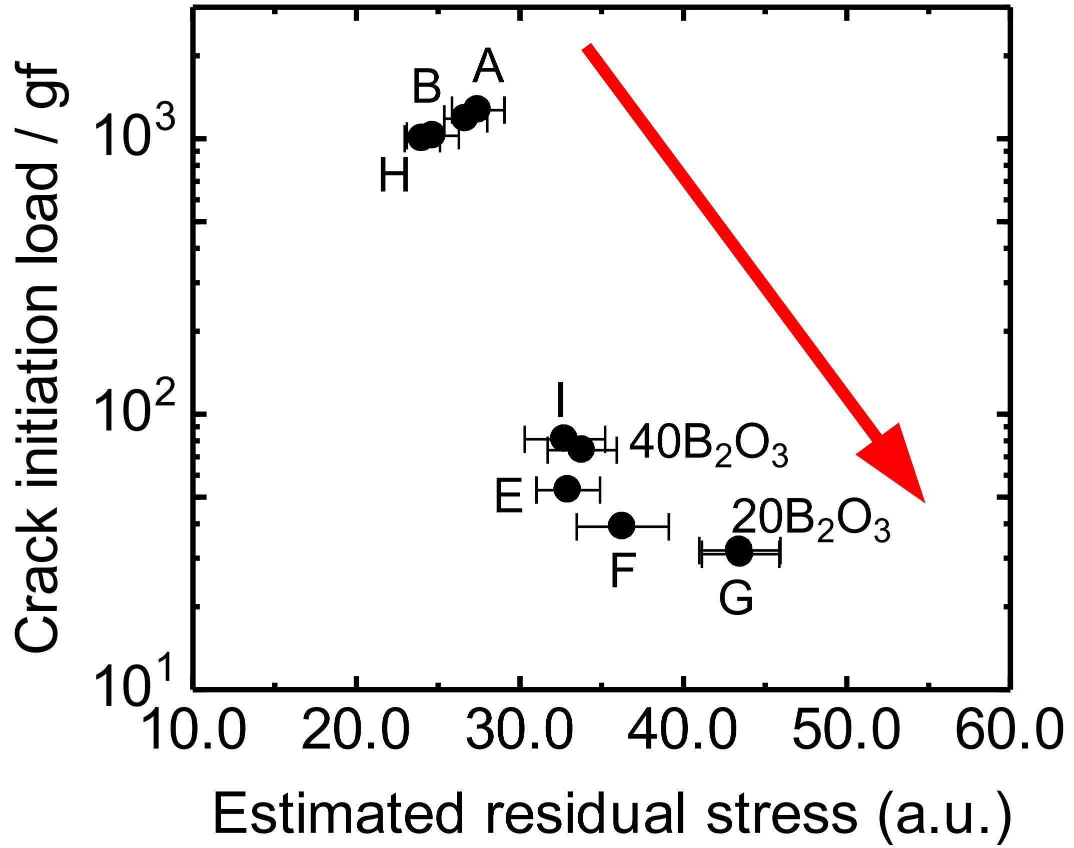
among glass compositions. (E/H are almost identical.)

(The driving force affects Brittleness (H/K),

Indentation toughness, or Crack initiation load.)

Crack initiation load decreases with increasing the estimated residual stress.

S. Yoshida, *XIXth I.C.G. (2007)*
Y. Kato, *JNCS (2010)*



Residual stress = Bulk modulus x **Volume strain**

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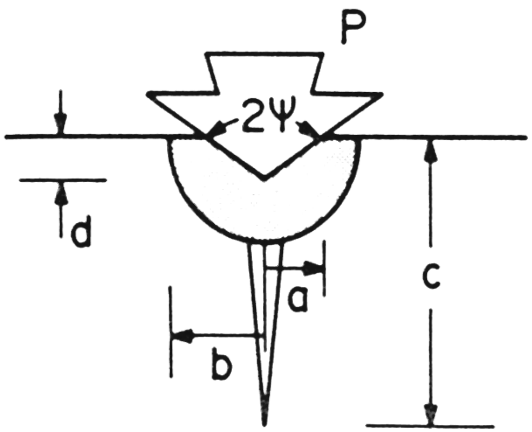
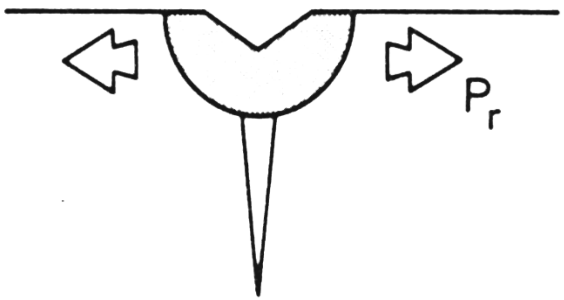
How can we estimate the residual stress?

<u>*Indentation Fracture (Median/Radial Crack)*</u>

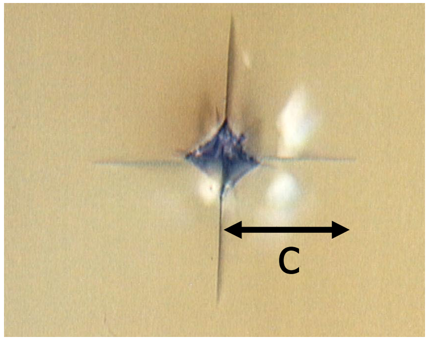
Lawn, Evans, Marshall(1980)



P_r: Residual force
for crack initiation



a: Contact size
b: Radius of plastic zone
c: Median crack length
d: Depth of impression
P: Indentation load
P_r: Residual force
for crack initiation



<u>Median/Radial cracks are generated by the residual force.</u>

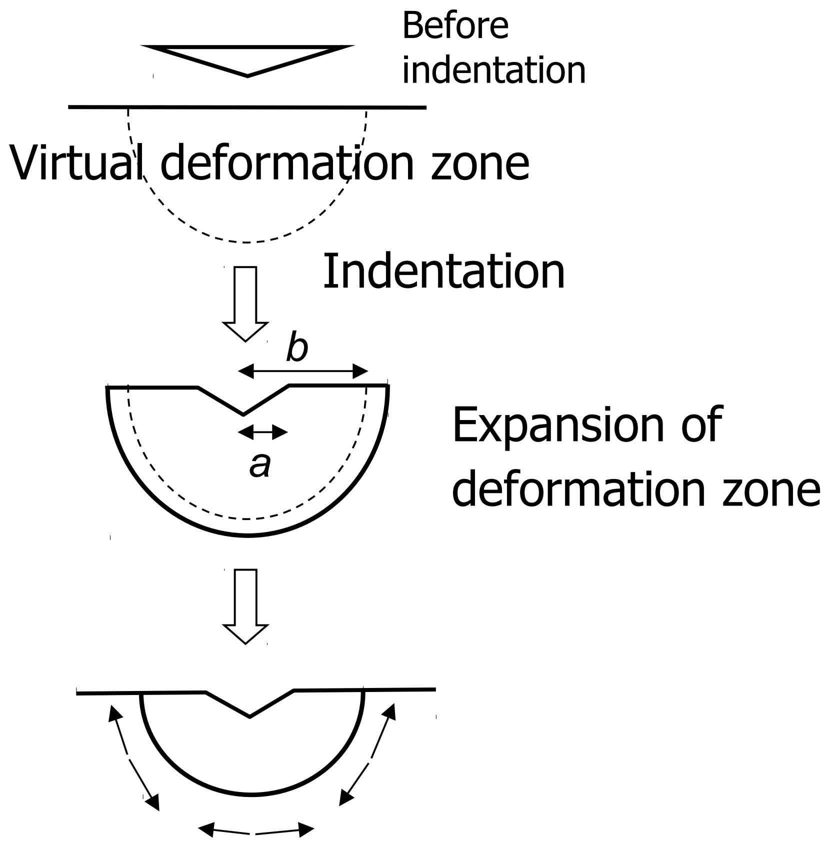
Indentation Fracture (Median/Radial Crack)

Residual stress ＝
Bulk modulus x Volume strain

$$\sigma_R = \kappa \frac{\Delta V}{V}$$

$\Delta V \propto a^3, \; V \propto b^3$

κ : Bulk modulus



Tensile stress
at the elastic/plastic interface

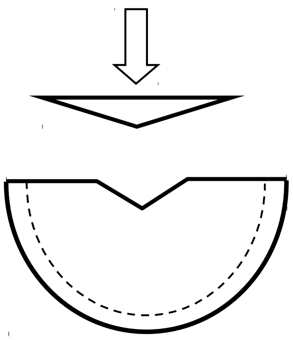
Lawn, Evans, Marshall(1980)

Indentation on glass @RT results in both

1. Shear flow (Volume conservative)

and

2. Densification (Shrinkage)



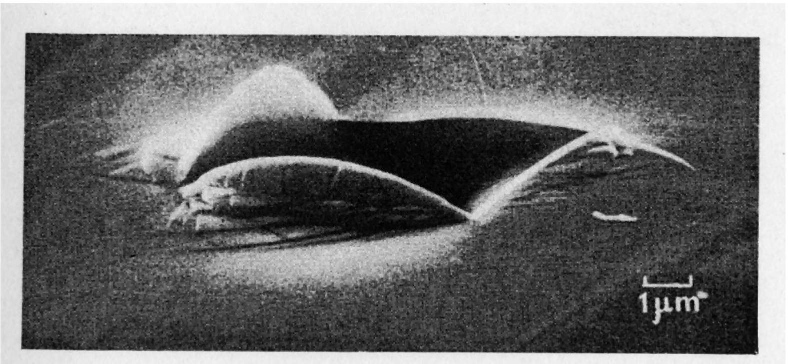
Expansion of plastic zone

Densification does not contribute to expansion of plastic zone.

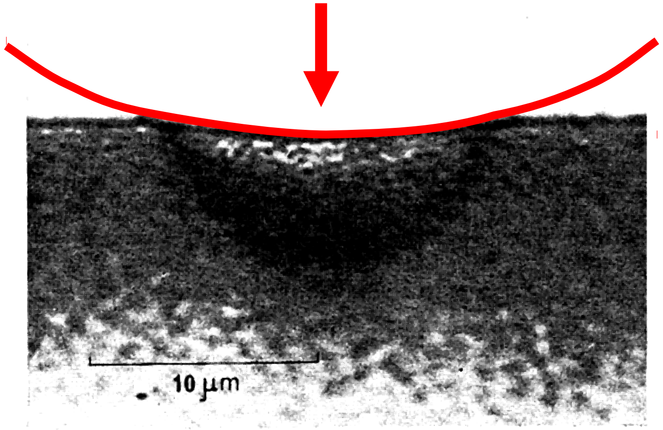
Indentation-induced flow and densification

Plastic flow and/or Densification

K.W. Peter, *J. Non-Cryst. Solids* 5(1970) 103.



Pyramidal indentation on soda-lime glass
(Opposite face angle = 70 °)
Cf. Vickers 136 °



Ball indentation on soda-lime glass
(Radius = 20 μm, Load = 100 gf)

Sharp indenter
Piling-up ! (Shear flow)

Blunt indenter
Densification !

What is Densification?

Glass increases in its density (or index) under a high compressive stress.

Under hydrostatic stresses

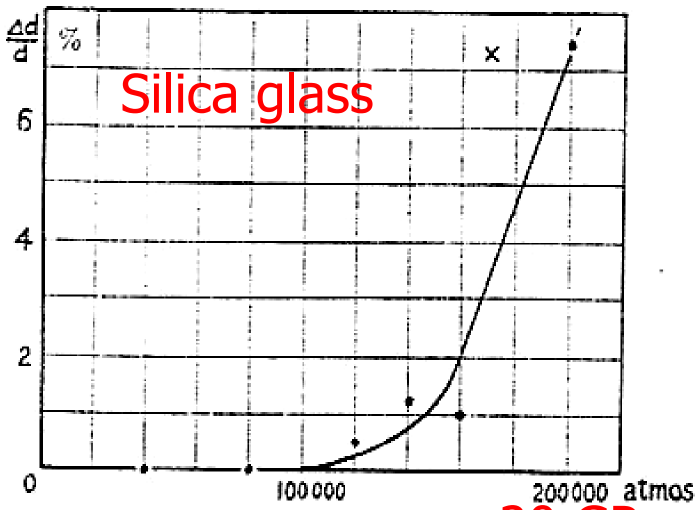


FIG. 3. Relative increase (percent) of density of vitreous silica as a function of applied pressure.

P.W. Bridgman and I. Simon, *J. Appl. Phys.*, **24**(1953)405.

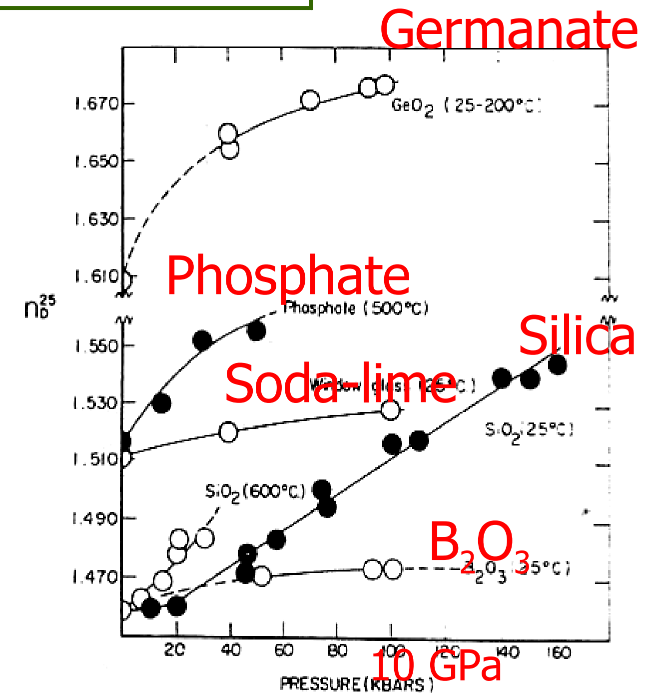


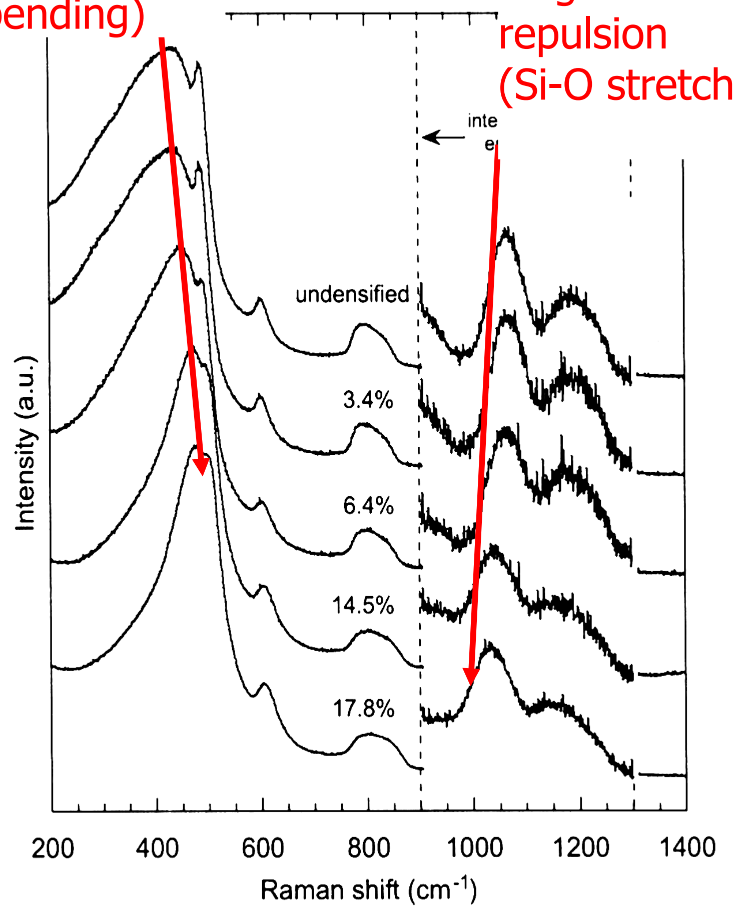
Fig. 1. Index of refraction of the quenched phase as a function of the pressure of the run. Each point represents a spread of ±0.005 index of refraction units.

H.M. Cohen and R. Roy, *J. Am. Ceram. Soc.*, **44**(1961)523.

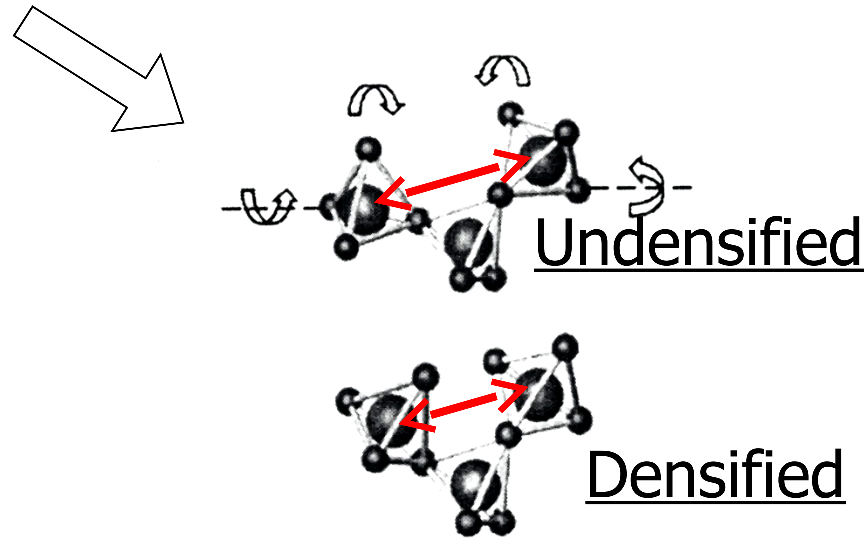
Raman spectra of hydrostatically densified silica glass

Decrease in
the bond angle
(Si-O-Si bending)

Increase in the Si-O bond
length because of Si-Si
repulsion
(Si-O stretching)

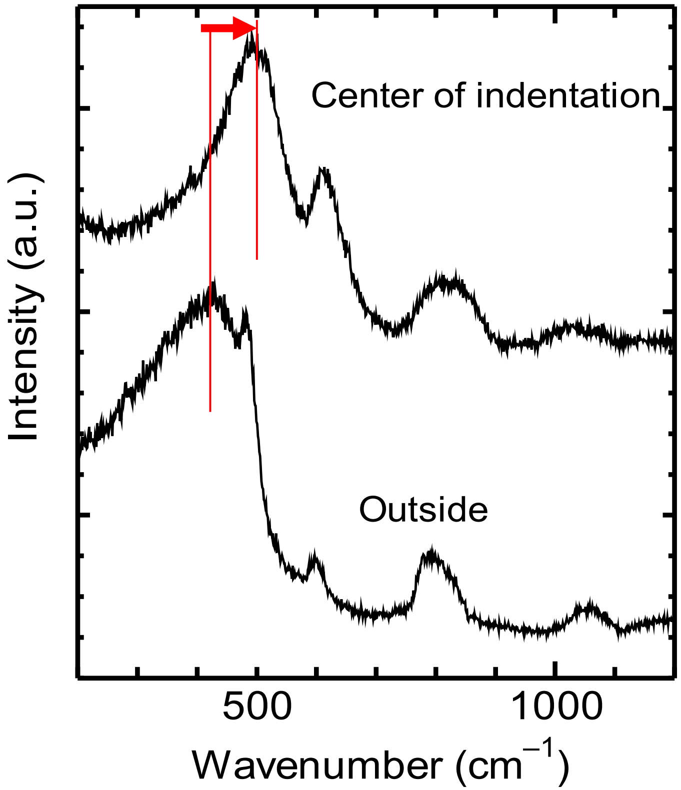


Poe *et al. J. Non-Cry.* (2004)

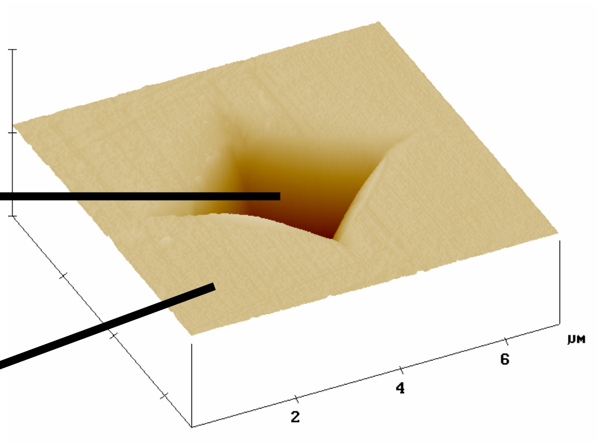


Sampath *et al., Phys. Rev. Lett.* (2003)

Indentation also induces densification



Raman spectra of silica glass



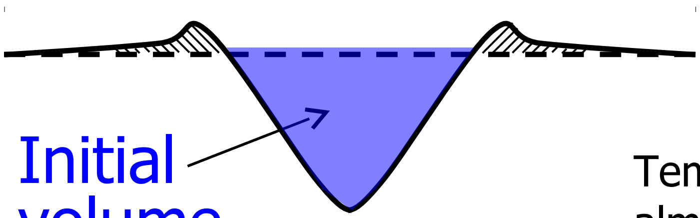
AFM image of Vickers indentation

How do we estimate
the densification contribution
to total indentation deformation ?

Determination of '%Densification'

Densified region can be relaxed by annealing at around T_g

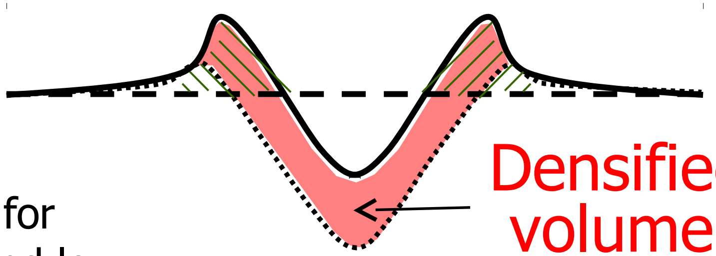
Mackenzie(1963), Neely & Mackenzie(1968), Yoshida (2001, 2005, 2007, 2010)

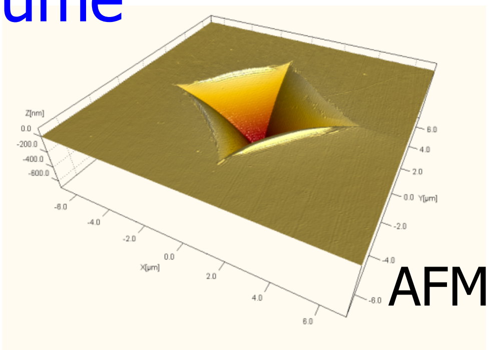


Annealing

$T_g \times 0.9$ (K)

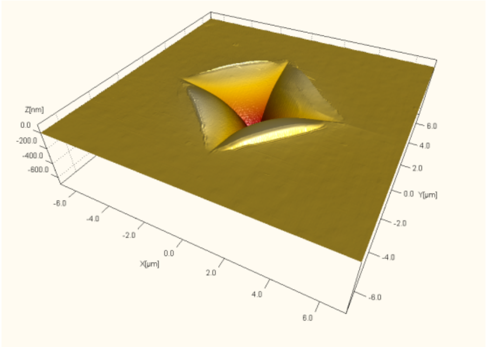
Temp. is high enough for almost full recovery, and low enough for viscous flow.





Shrinkage

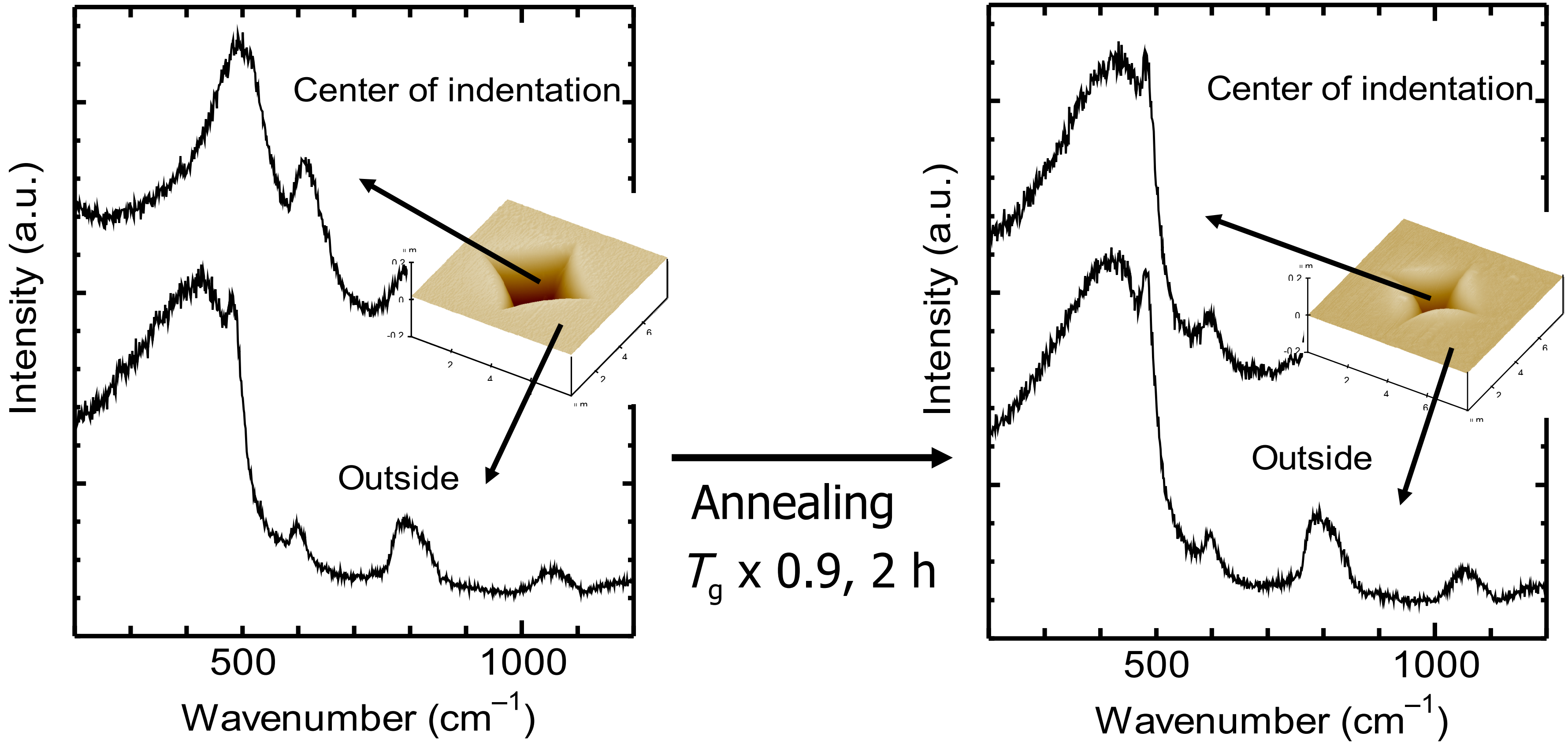
AFM image



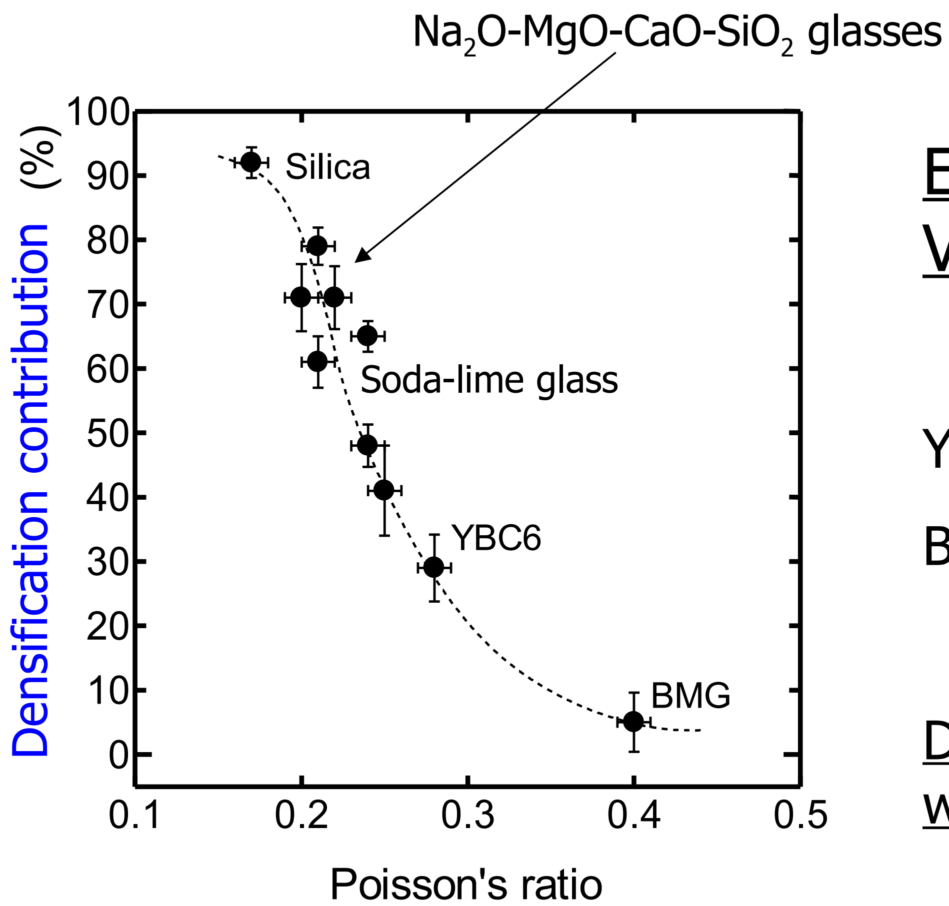
Densification contribution (%) = Densified volume / Initial volume

Raman spectra of silica glass before and after annealing

The densified structure is relaxed by annealing at Tg x 0.9.



Comp. dependence of densification contribution



Every glass is densified under Vickers indenter.

YBC6: Oxynitride glass

BMG: Bulk metallic glass

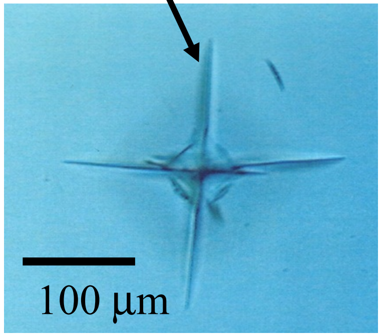
Densification contribution decreases with increasing Poisson's ratio.

Yoshida, J.-C. Sangleboeuf, T. Rouxel (2005), *J. Mater. Res.* ***20****, p. 3404.*

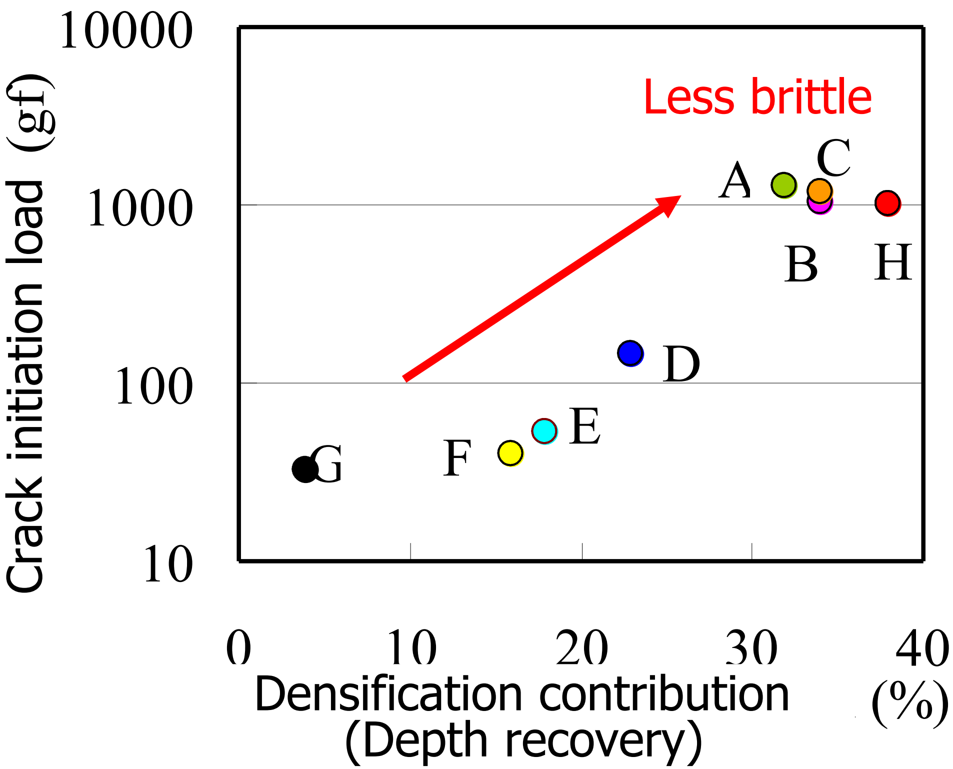
Higher %Densification, Better Crack Resistance!!

, because densification reduces the residual stress.

Radial crack



Aluminosilicate glass



Y. Kato *et al.*, *J. Non-Cryst. Solids* **356**(2010)1768.

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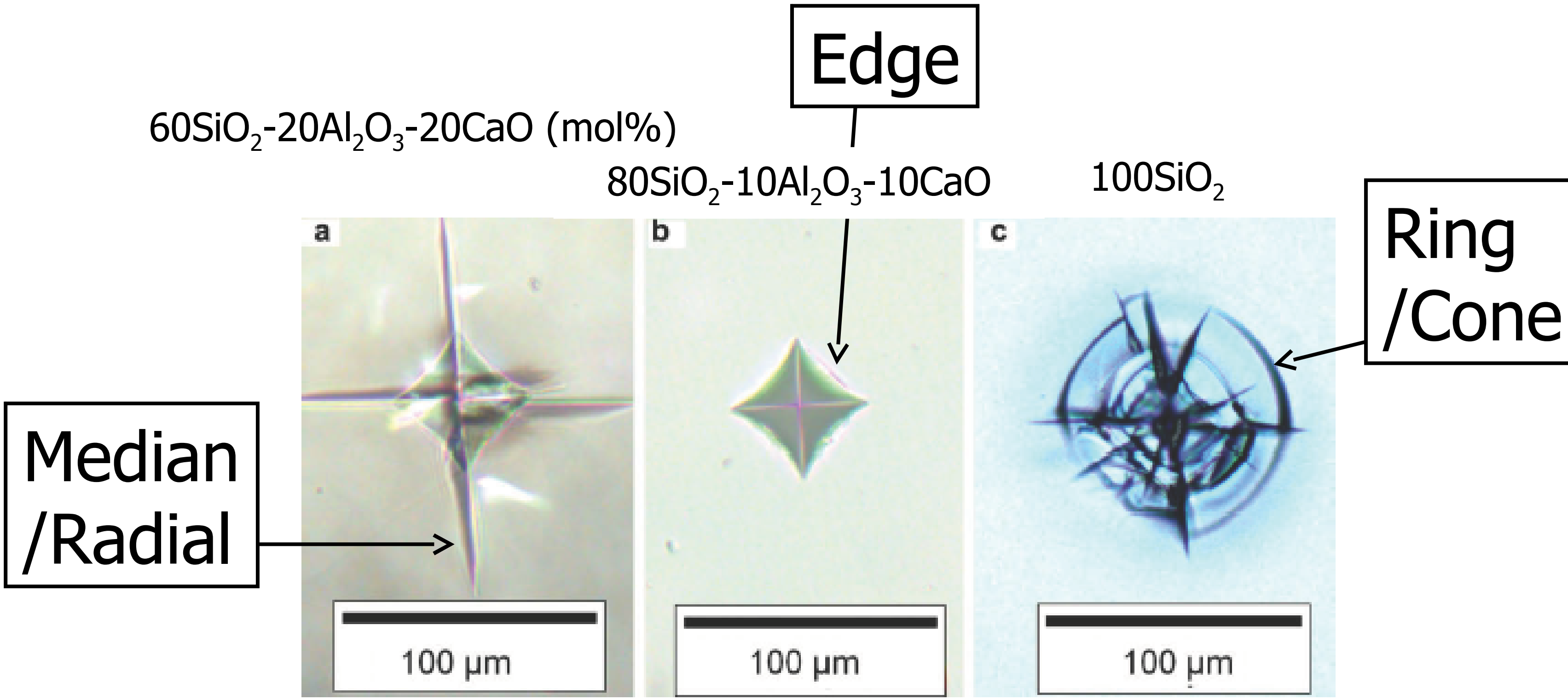
Indentation-induced densification is affected by

1. Glass composition, *J. Mater. Res.,* **20** (2005) 3404.
2. Indenter geometry (not shown today), *J. Mater. Res.,* **25** (2010) 2203.
3. Indentation load (not shown today), *Int. J. Mater. Res.,* **98** (2007) 360.
4. Fictive temperature (not shown today). *I.C.G.,* Salvador (2010) .
5. Water in glass (not shown today).

The stress is a tensor quantity, not a simple scalar.

We should know stress components.

A wide variety of crack morphology comes from different stress states.



Indentation imprints (1 kgf) on different glasses

T.M. Gross *et al.*, *J. Non-Cryst. Solids* **355**(2009)563.

One solution to obtain stress components is Birefringence technique.

With Dr. C.R. Kurkjian (Univ. Southern Maine)
Dr. A. Errapart (Tallinn Univ. Tech.)

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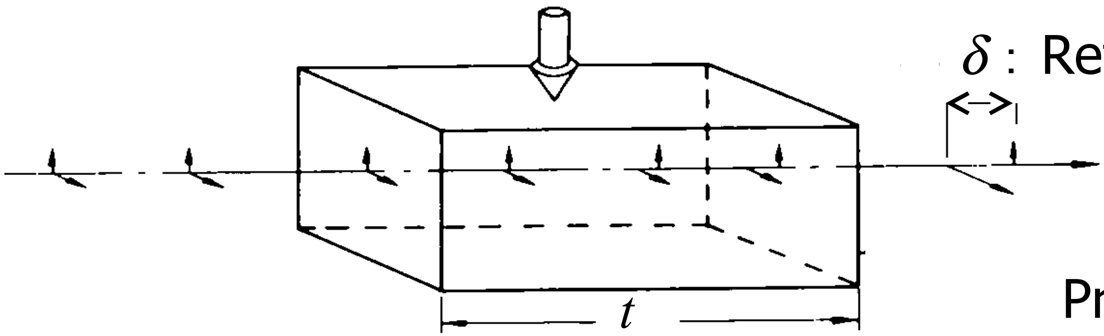
Birefringence, or Photoelasticity

2-Dimensional

$$\delta = (n_1 - n_2)t = C(\sigma_1 - \sigma_2)t$$

Stress Optical Coefficient: C

δ : Retardation $\Rightarrow$ $\sigma_1 - \sigma_2$



Principal stresses: σ_1 , σ_2
(Membrane stresses)

The stress state is biaxial.

Principal refractive indices: n_1, n_2

Determination of stress distribution

H. Aben, C. Guillemet, *Photoelasticity of Glass* , Springer (1993)
J. Anton, A. Errapart, H. Aben, L. Ainola, *Exp. Mech.* **48**(2008)613.

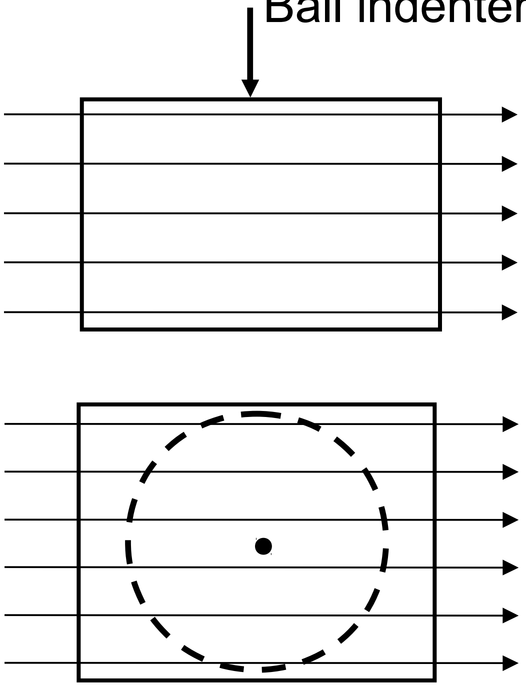
3-Dimensional

$$\delta = C\int(\sigma_1 - \sigma_2)dt$$

Ball indenter

Cross-section:

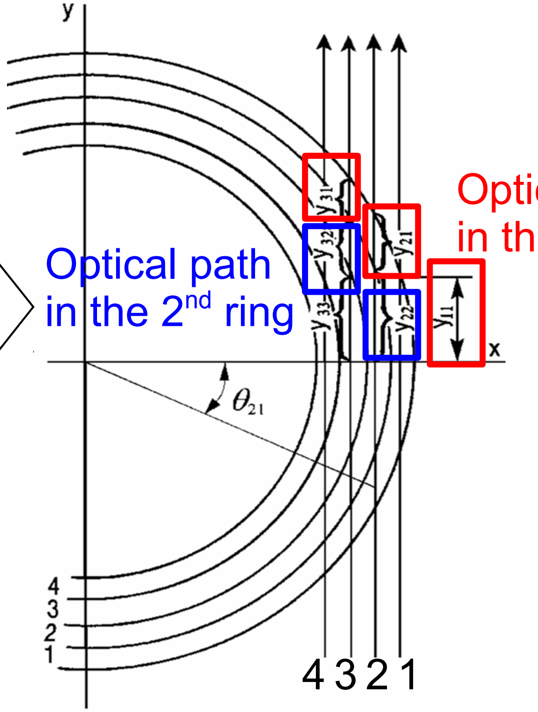
Top view:



Schematic of transmitted light through a square fiber

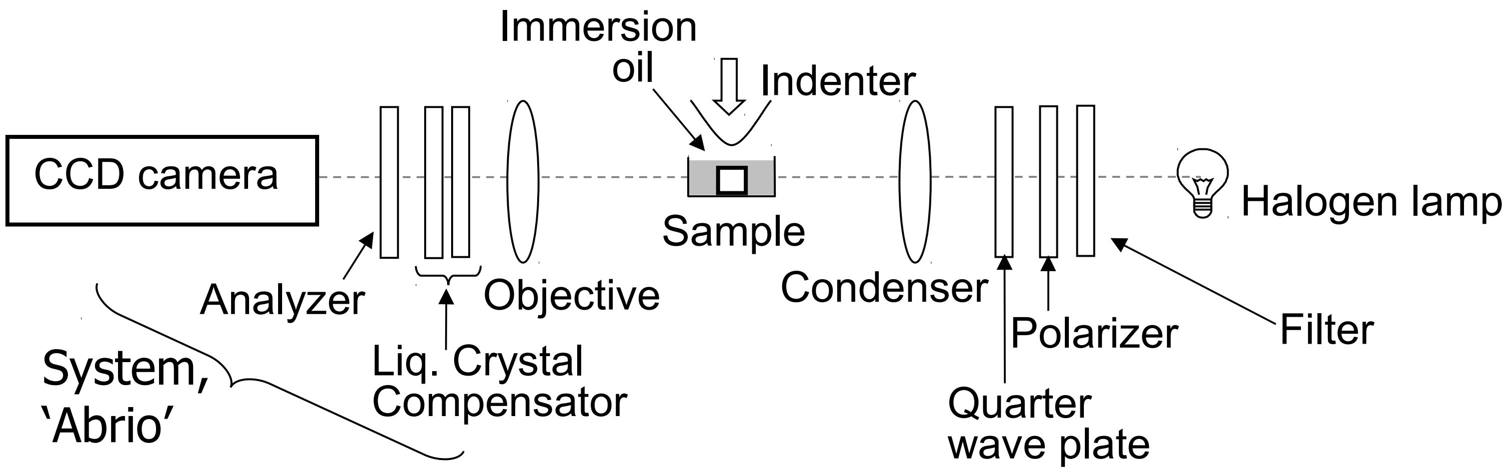
Onion peeling method

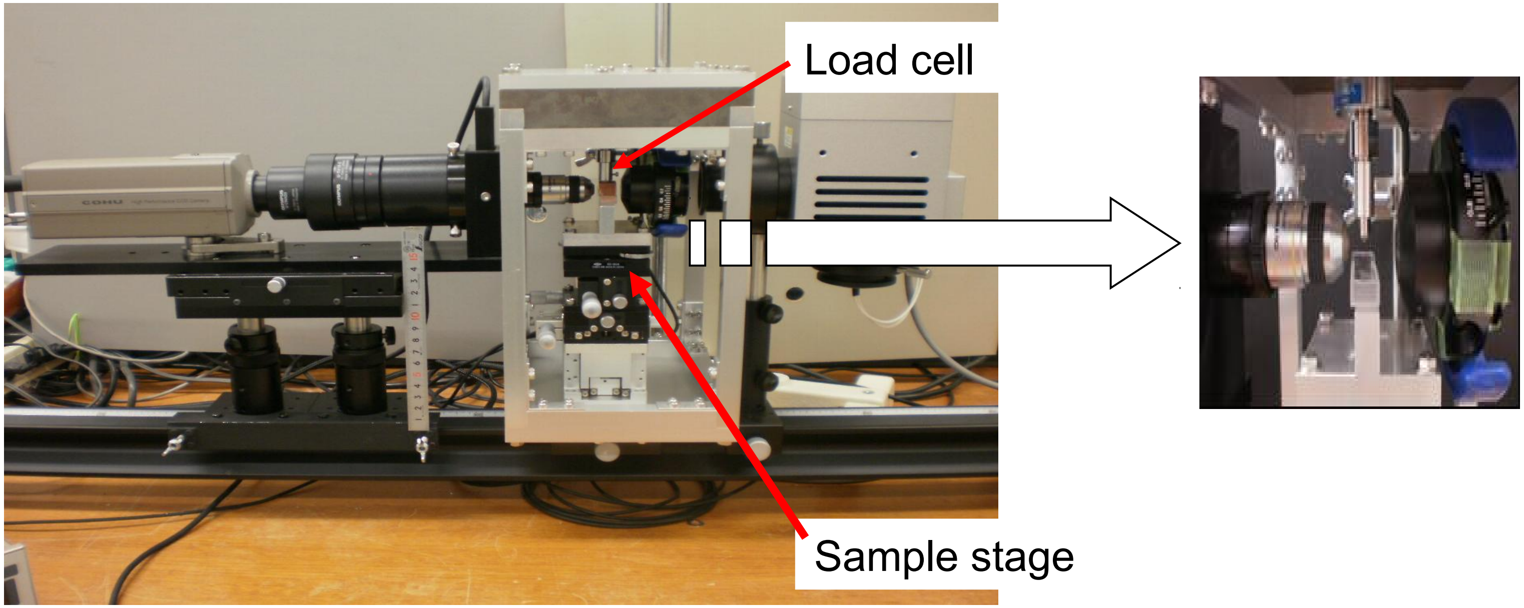
Stresses are calculated in layer-by-layer manner.



In-situ imaging system with an indenter

S. Yoshida *et al.*, *J. Non-Cryst. Solids* **358** (2012)3465.





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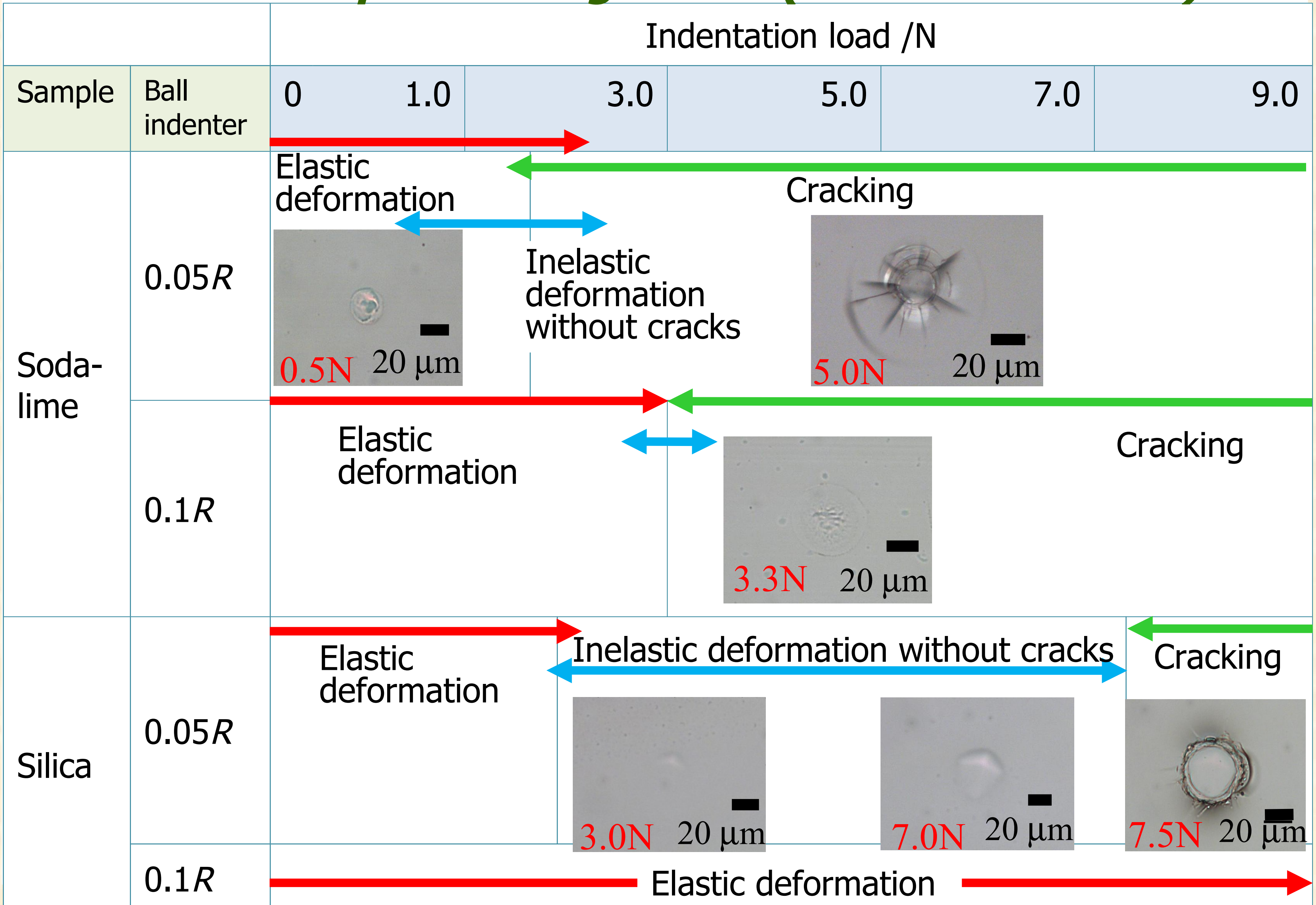
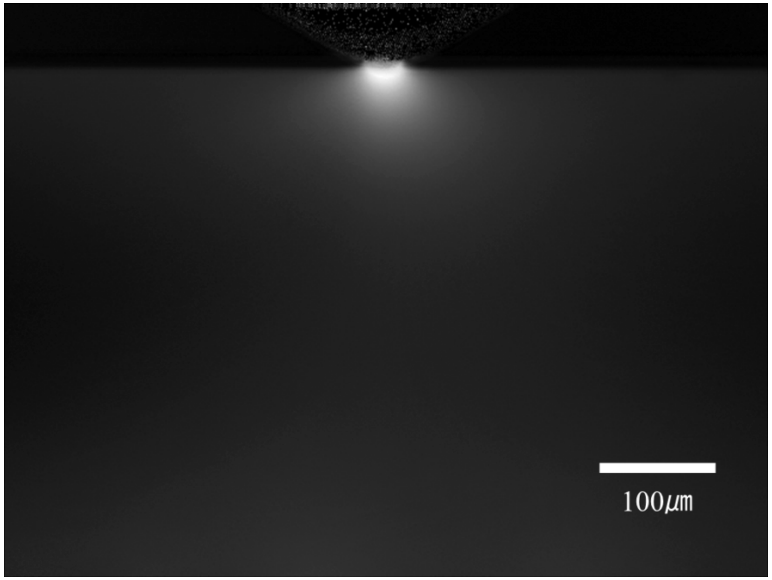
Mechanical responses of glasses (Ball indentations)



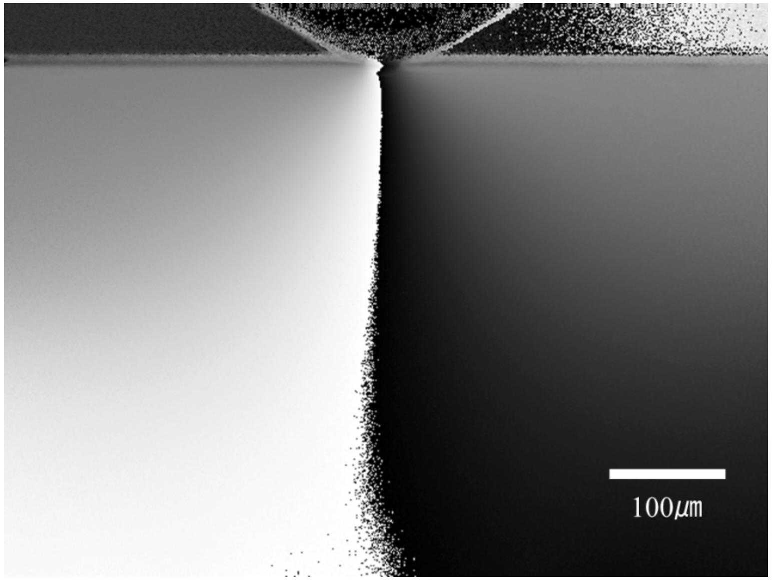
BR images during indentation

Soda-lime glass
R = 0.1 mm indenter
Indentation load = 3.0 N

During loading
<u>Only Elastic.</u>



Retardance
0 ~ 250 nm
Black to White

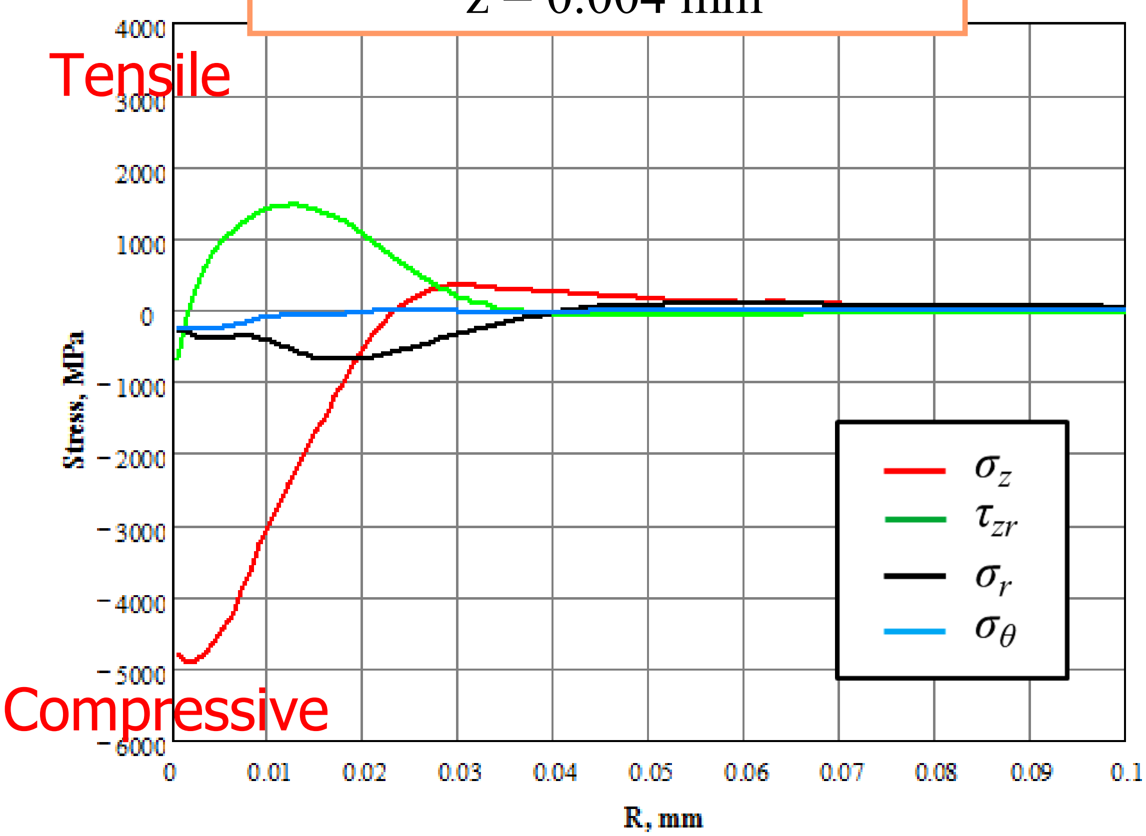


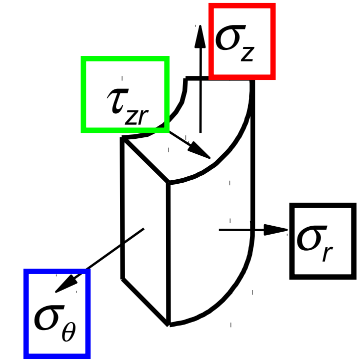
Slow axis orientation
0 ~ 180 º
Black to White

Elastic stresses (SLS)

Soda-lime, R = 0.1 mm, Load = 3.0 N

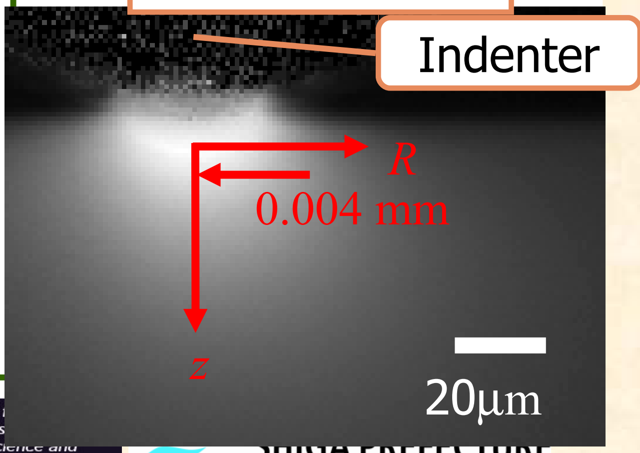
Stresses from BR images
z = 0.004 mm



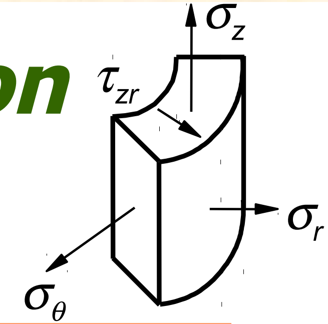


σ_z : Axial stress
τ_{zr} : Shear stress
σ_r : Radial stress
σ_θ : Circumferential, or hoop, stress

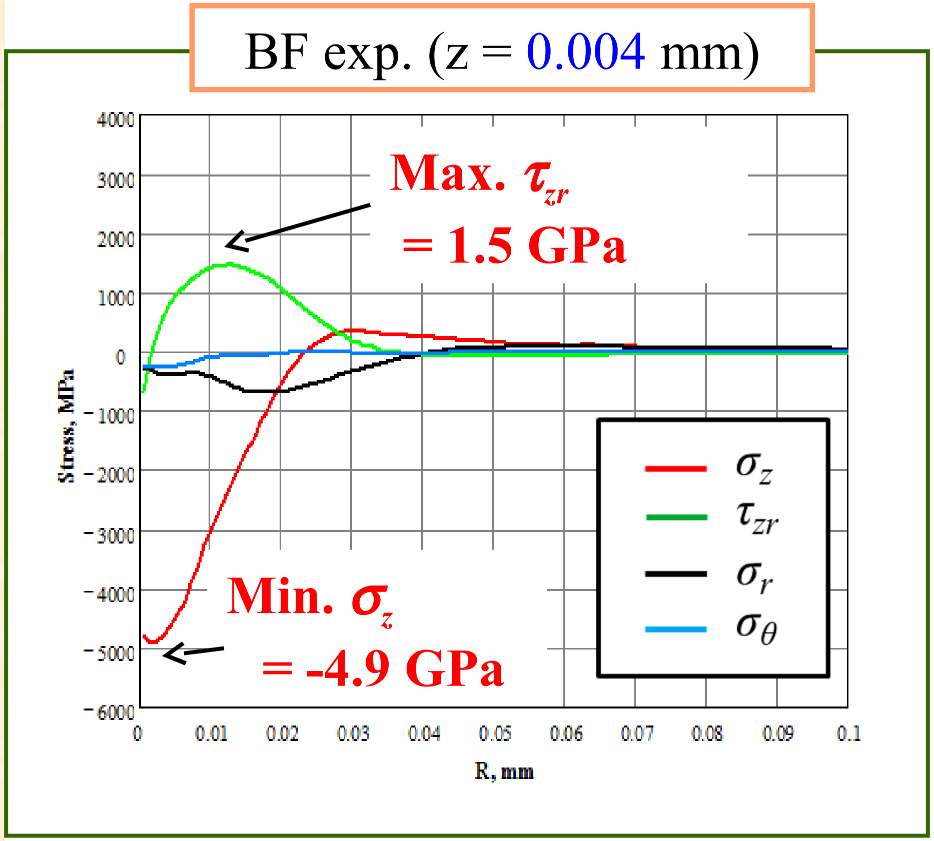
Retardance

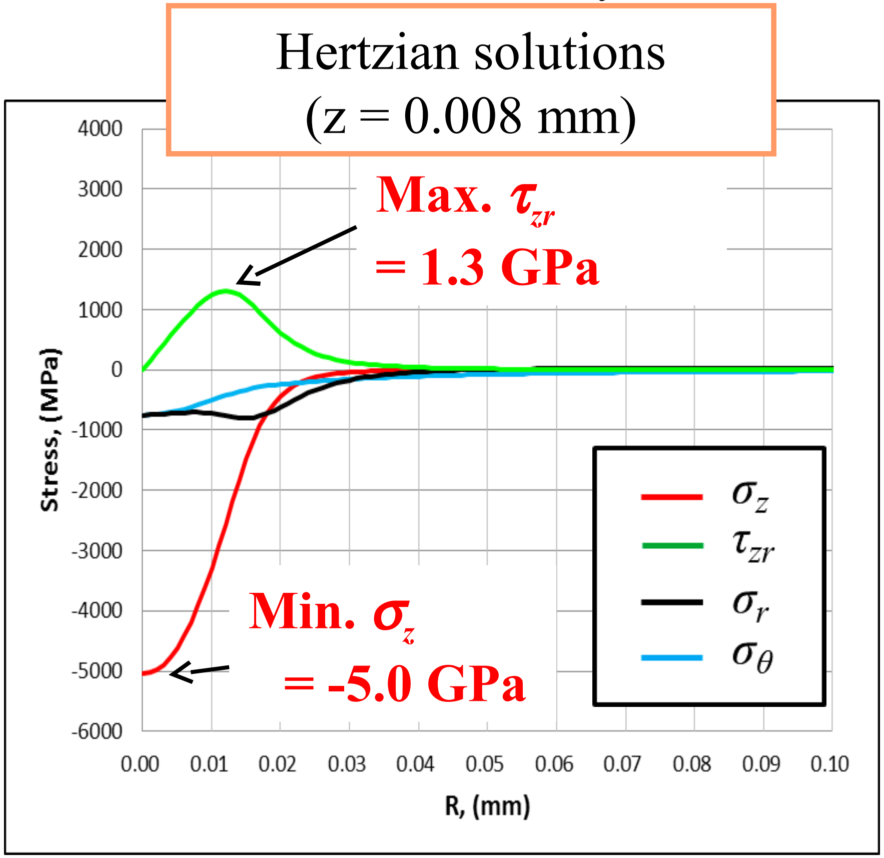


Comparison with analytical solution



Soda-lime, R = 0.1 mm, Load = 3.0 N





Obtained stresses are in agreement with Hertzian solutions.

Evaluation to Residual indents

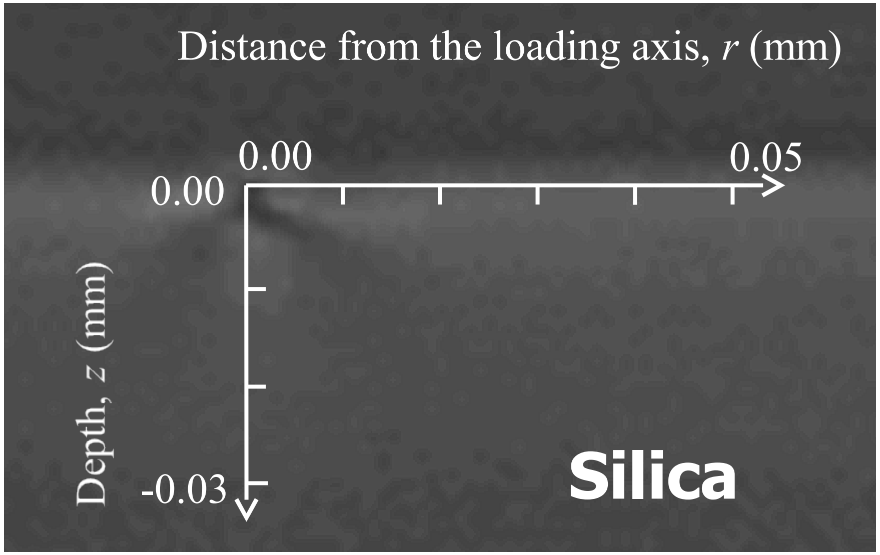
» Silica (Anomalous)
» 25Na_2O-75SiO_2 (mol%) (Normal)

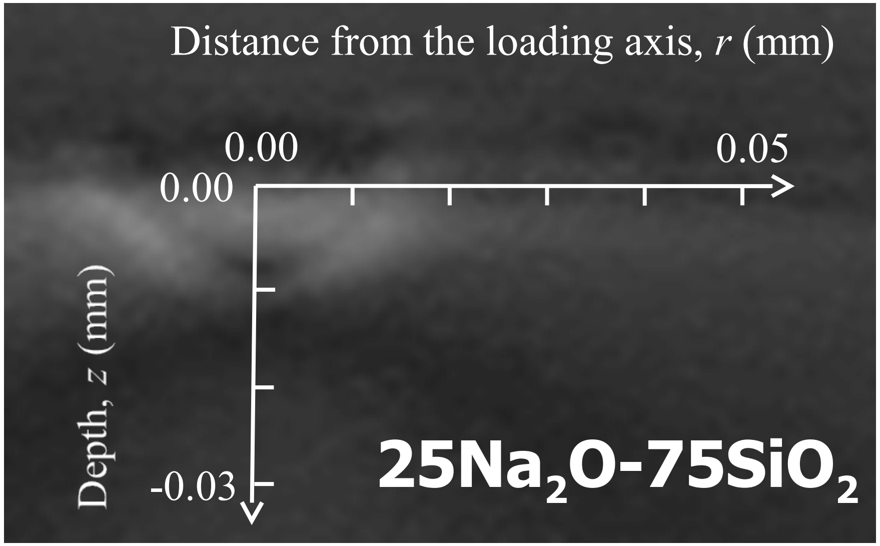
Residual stresses

Retardation maps
with
Coodinates for stress calculation

Ball (R=0.05mm)
Max. load = 3.0 N

Quite different !





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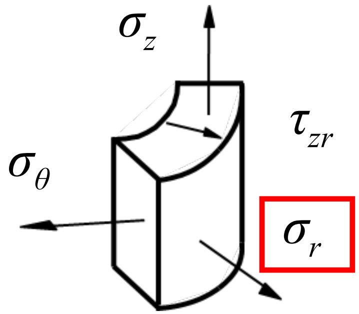
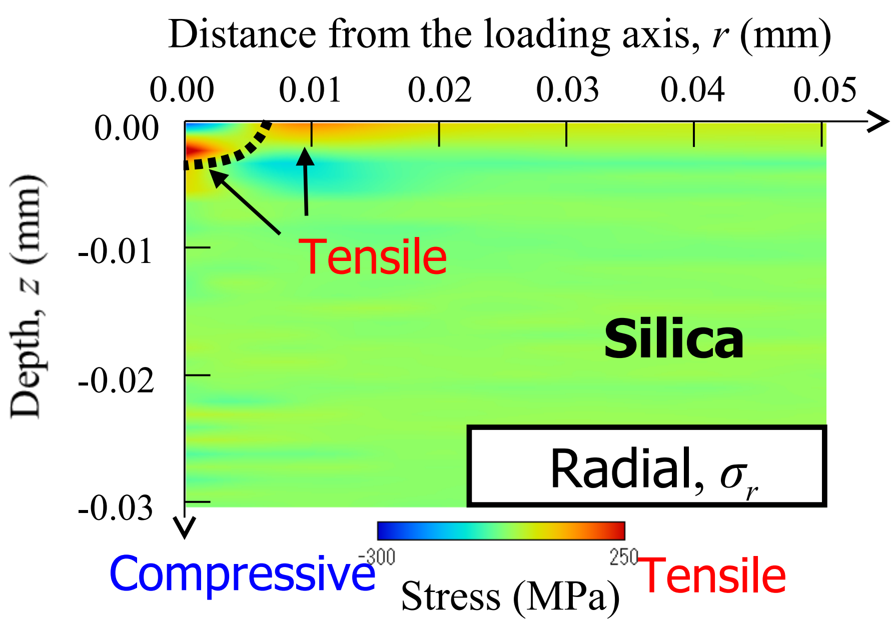
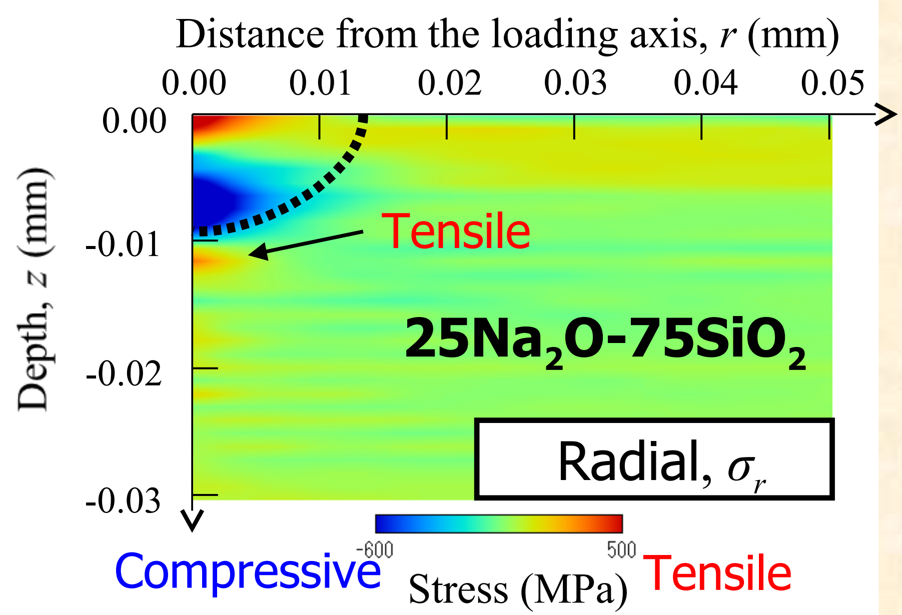
Residual stresses
Stress mapping (Radial stress)

Ball (R=0.05mm)
Max. load = 3.0 N

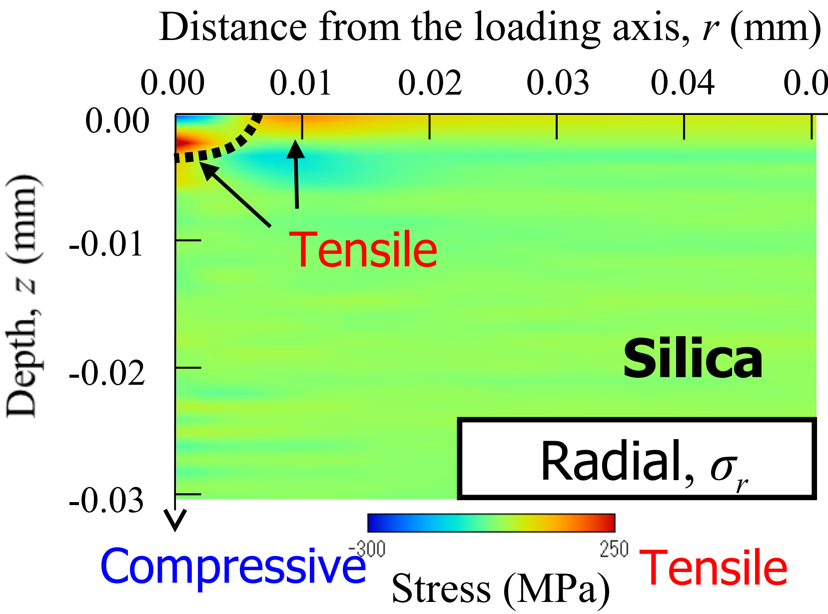


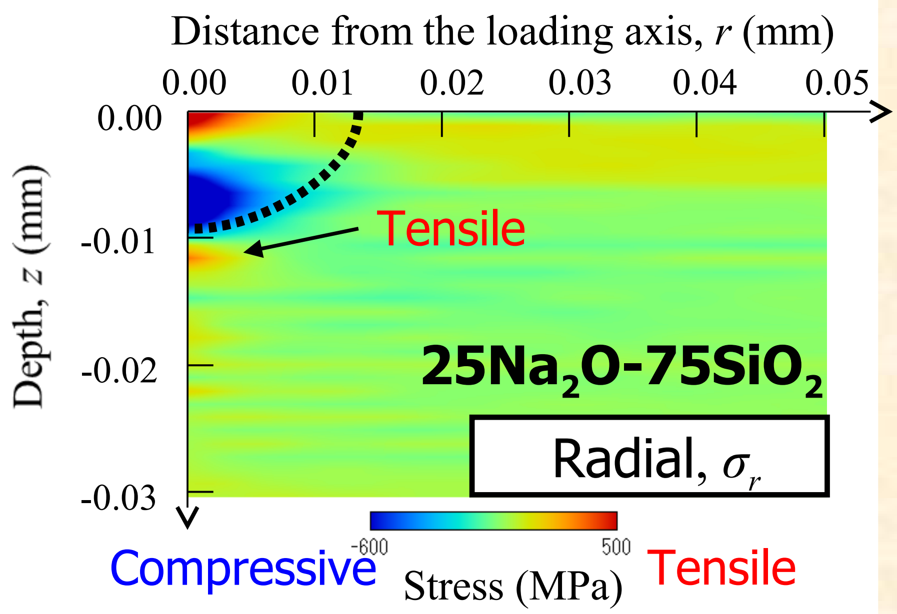
: Plastic zone

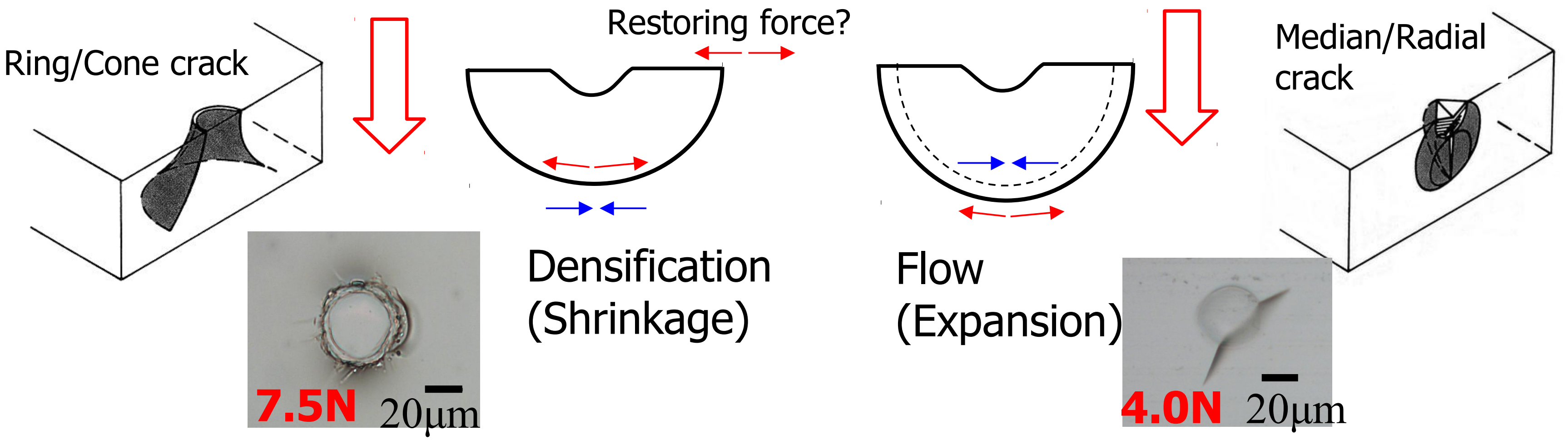




Residual stresses and crack morphology







BR(Birefringence) stresses after unload tell us where a crack will initiate.

Summary

1. Residual stress after indentation is critical for understanding the compositional variation of glass strength.

2. Densification of glass affects the residual stress.

3. Microscopic BR (birefringence) technique is useful in order to evaluate stress components around the indent.

4. Our BR work has just started, but important.
   We have various unsolved questions.

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Keynote Topic Discussion Points

Material questions:

-Why glass for this application?

Good transparency and high scratch resistance

-What other materials could serve this purpose?

Polymers

-What trends will influence product development in the future? How will the products change?

Watch the Corning's Video ! Mobile items and Tablets

-How will product trends impact the future use of glass and property/processability requirements?

Watch the Corning's Video more !

Key challenge/Key breakthrough questions:

-What are the key scientific challenges related to the topic of your presentation, and more generally the field of your expertise?

Toward Ultra-tough glasses !

-How critical are they to the advancement of the relevant technology?

They promote the market for glass products.

-Can you identify whether the challenge is with regard to limitations of specific property, performance or fabrication process? Establish target values, where possible.

Theoretical strength X 1/10 would be a goal.

Key challenge/Key breakthrough questions: (continued)

-What would be a key breakthrough and when might it occur?

Glasses would replace Polymers.

-How are these breakthroughs likely to occur? University discovery? Industry? University-Industry collaboration?

From Industry, because processing technology (especially surface. Polishing or coating) is a key issue. But, I hope that University will help the success.

Success questions:

-What will be a topic stating an exceptional success to be published in a well-known high-ranked research journal in 2025 concerning your R&D field?

(please give a title of a publication in 2025, you would like to read)

'New evaluation techniques of fracture strength and fracture toughness of 10-μm glass film'

Related Broad Discussion Points

Future R&D directions questions:

-What are the most critical scientific questions (be specific and list not more than 2 or 3 per topic);

What is the structural flaw?

How, Where, and When does a crack nucleate?

-With the given/limited R&D resources, on which R&D topics should we concentrate/reinforce? Which activity should be reduced?

Every topic is important, should not be reduced.

Continuous efforts (even under the limited condition) are important.

Do not make the missing years for each research.

-How much glass research is needed or optimum?

I have no idea. Depending on the scale of glass industry. (In Japan, $17 billion/year)

-What kind of education is needed to enable glass research?

International workshop in order to exchange skills and ideas

-What are strategies for better communication and collaboration in the glass community?

International meeting for a limited research area (like ICG's TC or FFAG)

Related Broad Discussion Points (continued)

Boundary conditions questions:

-Which changes in boundary conditions are foreseeable in your R&D field (legal, economical, …)?

Collaboration between Surface and Mechanical

Or between Structure(modeling) and Mechanical

-Do you see a possibility to influence/change/improve the boundary conditions (funding, networks,…)?

The project by Prof. Lothar Wondraczek @ Jena is one example.

"Topological Engineering of Ultrastrong Glasses"

Glass community questions:

-which actions do you suggest to improve the situation in your field?

Collaborations with other industries (energy? medical?).

-More lobbying activity in the political arena?

I have no idea. Sometime, it is important to get a big project.

-topical position papers?

Works of NGF(New Glass Forum in Japan) or GIC(Glass Inducstrial Conference in Japan) in my country ?

Unsolved Questions

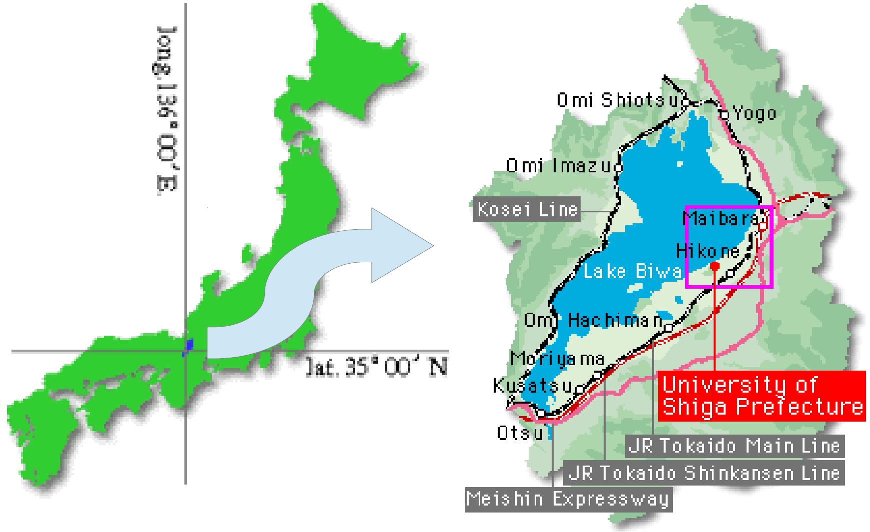
1. What is the origin of the residual RADIAL stress of silica glass ?
   The cavity model is not enough to explain it.

2. What is the crack nucleation mechanism ?
   From flaw-free surface
   or From indentation-induced shear defects ?

3. How can we calculate the stresses inside the plastic zone. (e.g. “black hole” in a retardation image)

4. How can we calculate the stress components around a non-axisymmetrical indent (e.g. Vickers) ?

Brief biography



Name: **Satoshi YOSHIDA**

Associate Professor of
The University of Shiga Prefecture (USP), Japan

1995 - Research Associate of USP

2004-2005 Guest Professor of Univ. Rennes, France
(with Profs. T. Rouxel and J.-C. Sangleboeuf)

2007 - Associate Professor of USP

Member of TC06(mechanical properties) in I.C.G.
Commitee member of FFAG (Flow and Fracture of Advanced Glasses)

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Annealing weakens E-glass fiber, but HF etching recovers its strength

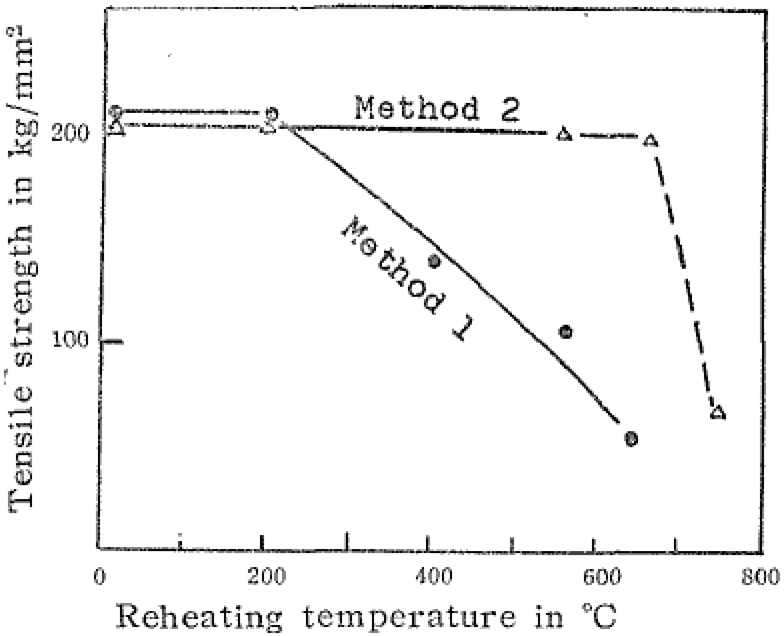

Fig. 2. Relation between tensile strength and reheating temperature of the fiber 12 μ in diameter.
●, before etching ; △, after etching.

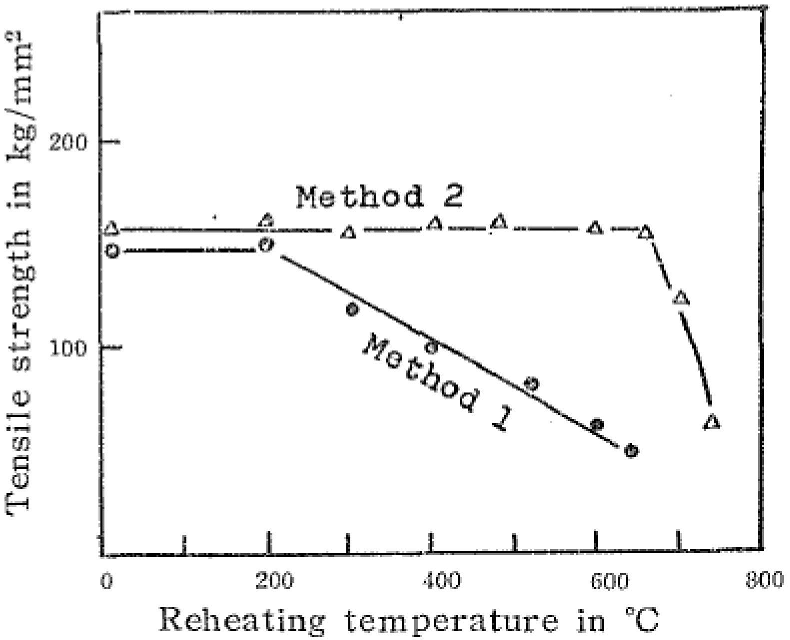

Fig. 3. Relation between tensile strength and reheating temperature of the fiber 22 μ in diameter.
●, before etching ; △, after etching.

S. Sakka, *J. Ceram Soc. Jpn.* **65**(1957)190.

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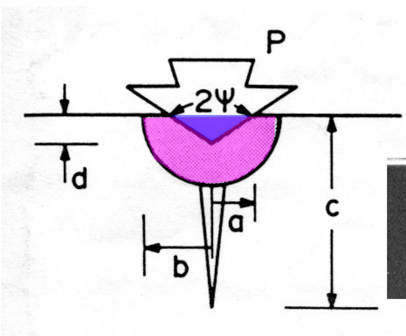
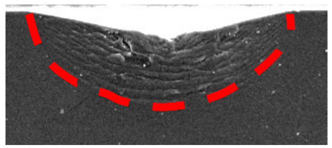
Indentation Fracture toughness, K_c





■ = ΔV
■ = V

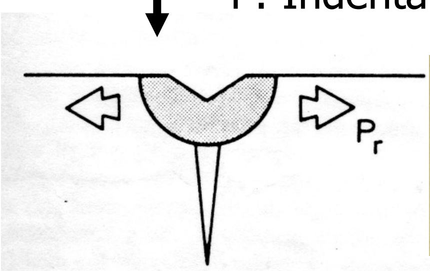
Volume strain

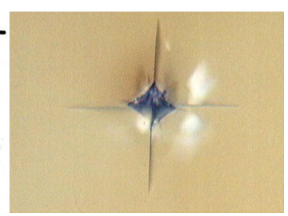
$$\sigma_R \propto \kappa \boxed{\frac{\Delta V}{V}} \propto \kappa \frac{a^3}{b^3}$$

$$P_r \propto \sigma_R b^2 \qquad H \propto P / a^2$$

σ_R : Residual stress
κ : Bulk modulus
ΔV : Indent volume
V : Plastic zone volume

a: Contact radius
b: Plastic zone radius
c: Median crack length
d: Depth of indent
P: Indentation load





P_r: Driving force of cracking

Indentation fracture toughness

$$K_c \propto \frac{P_r}{c^{3/2}} \propto \sigma_R \frac{b^2}{c^{3/2}} \propto \frac{E}{H}\left(\frac{a}{b}\right)\frac{P}{c^{3/2}}$$

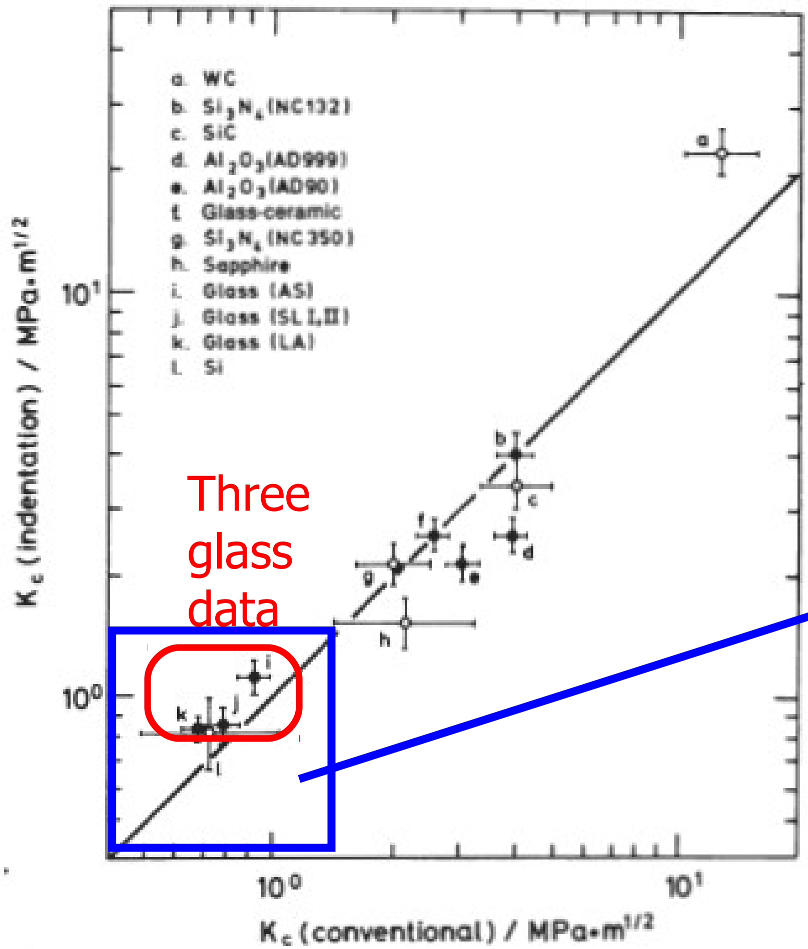
$$K_c = 0.016\left(\frac{E}{H}\right)^{1/2} \frac{P}{c^{3/2}}$$

$$\frac{a}{b} \propto \left(\frac{E}{H}\right)^{-1/2}$$

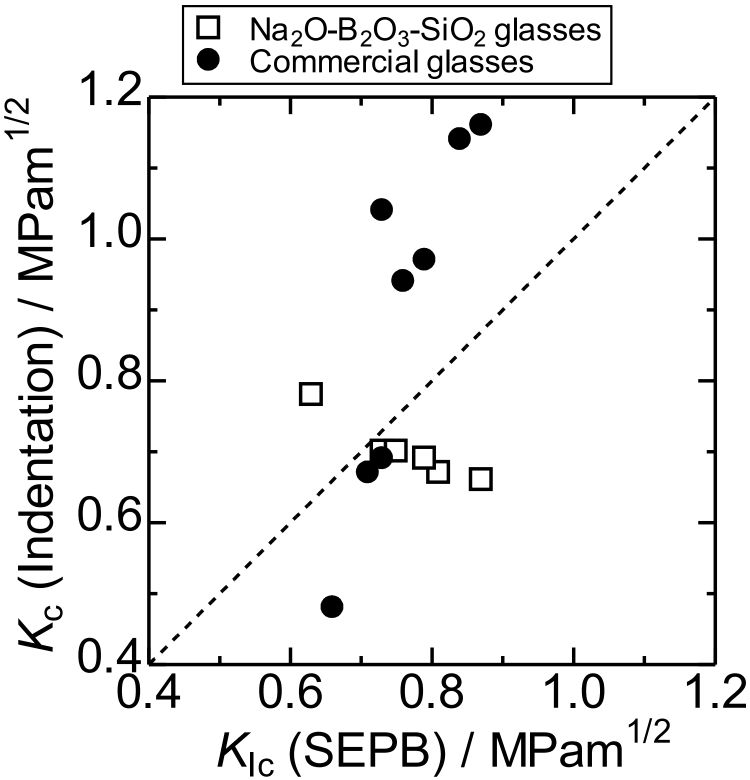
Empirical relationship

Anstis *et al.*(1981)

Indentation toughness is not Real toughness



Relation between K_c and K_{Ic}

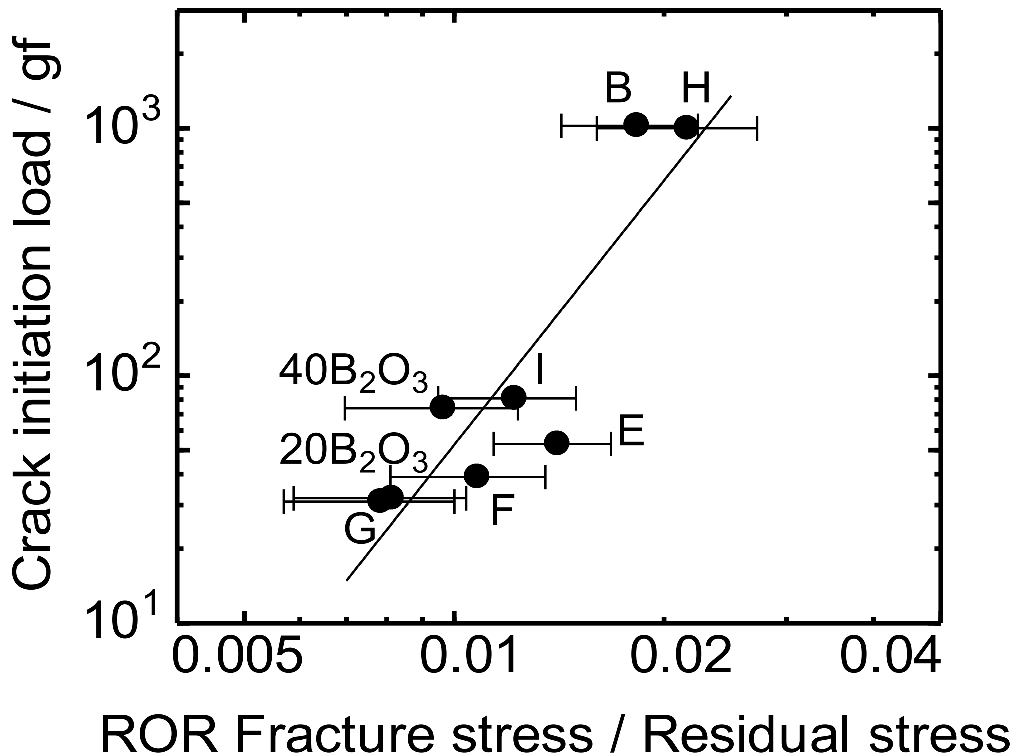


K_c and K_{Ic} for other glasses (unpublished data)

Estimation of residual stress is wrong!
(at least for glasses)

Anstis *et al., J. Am. Ceram. Soc.* **64**(1981)531.

Relation between Crack initiation load and Ring-on-Ring fracture stress normalized by Residual stress



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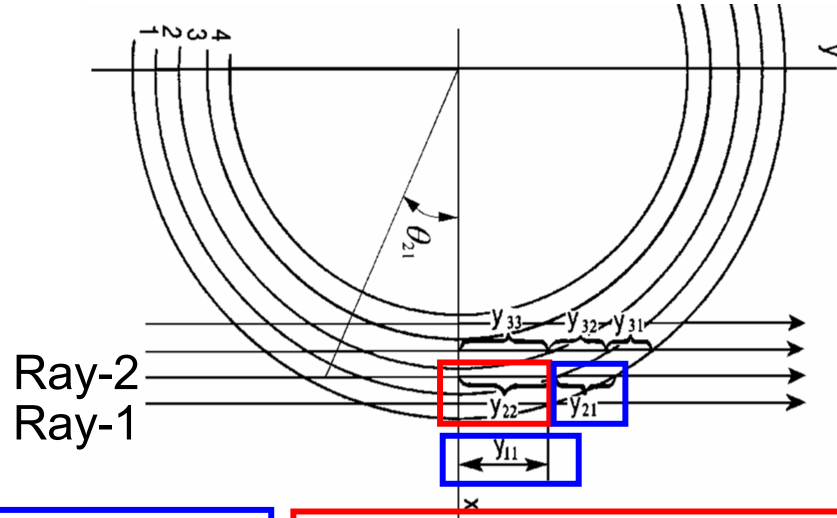
Determination of stress distribution

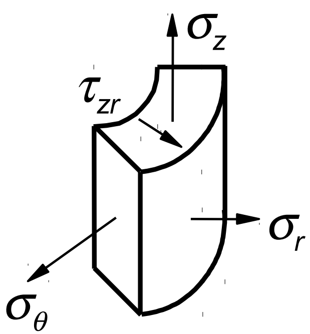
H. Aben, C. Guillemet, *Photoelasticity of Glass* , Springer (1993)
J. Anton, A. Errapart, H. Aben, L. Ainola, *Exp. Mech.* **48**(2008)613.

Ex.
Determination of Shear stress distribution



$$\tau_{zx} = \tau_{rz}\cos\theta$$

C : Stress optical coefficient



Axisymmetric state of stress

$$\tau_{rz}^{(1)} = \frac{V^{(1)}}{4Cy_{11}}$$

Shear stress in Ring 1

$$\tau_{rz}^{(2)} = \frac{V^{(2)} - 4Cy_{21}\tau_{rz}^{(1)}\cos\theta_{21}}{4Cy_{22}}, \cdots\cdots$$

Shear stress in Ring 2

y_{ij} : Half of the path length of the Ray i in the Ring j

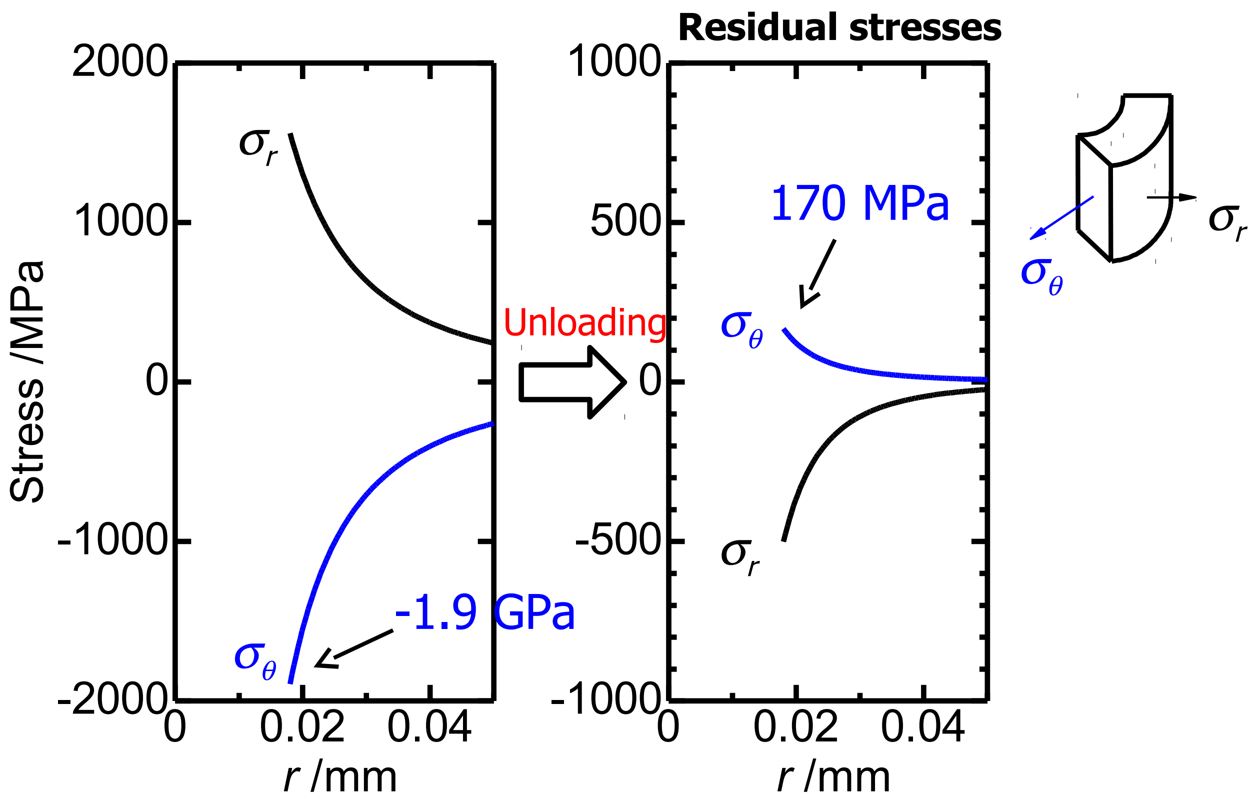
$V^{(\mathrm{i})}$: Exp. parameter of the Ray i, $\quad V = \delta\sin 2\phi = 2C\int_{-y_x}^{y_x}\tau_{zx}\,dy$

δ : Retardation
ϕ : Azimuth of principal stress

Estimation of residual stresses (Yoffe's model)

E.H. Yoffe, *Philos. Mag. A* **46**(1982)617.
R.F. Cook & G.M. Pharr, *J. Am. Ceram. Soc.* **73**(1990)787.

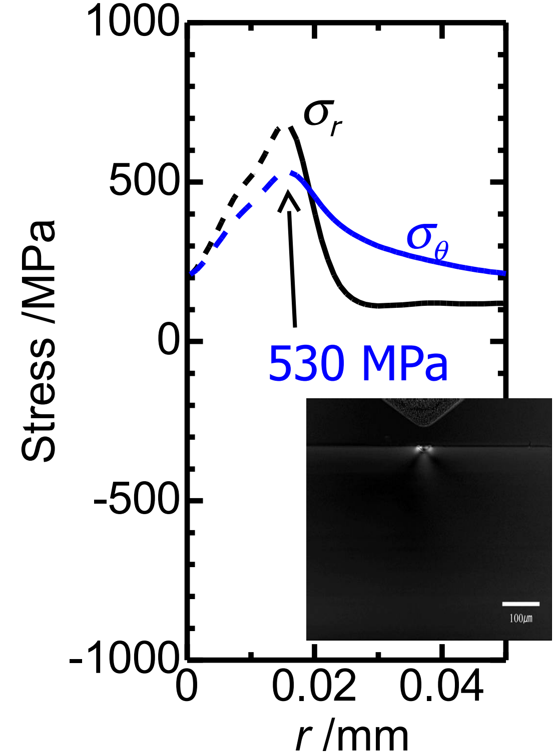
Yoffe's model (Silica glass) Stresses at z = 0



Maximum load

Complete unloading

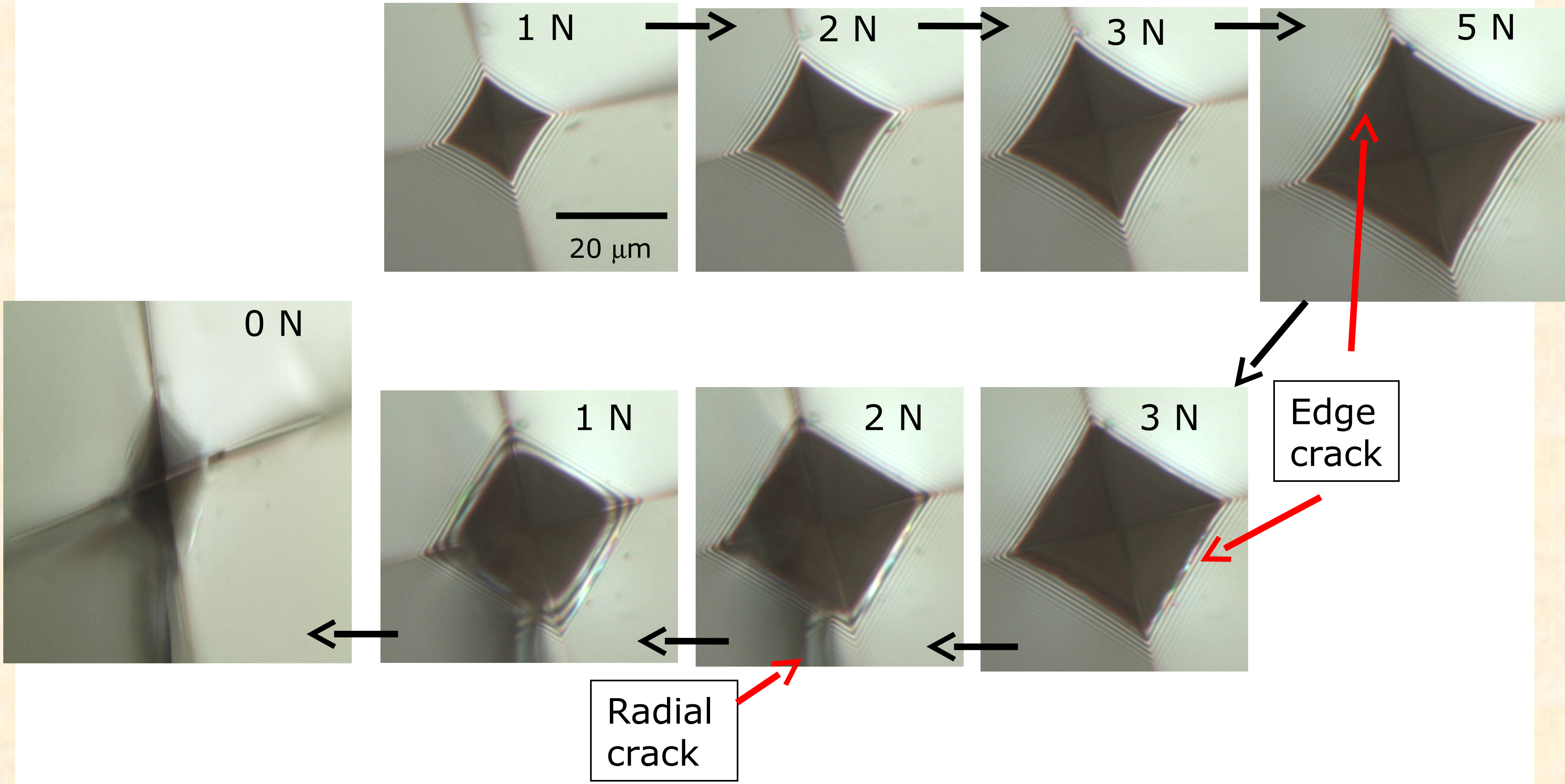
BR residual stresses
at z = 0



Yoffe's model reproduces (only) the Hoop residual stress, σ_θ.
A modified model will be needed for σ_r.

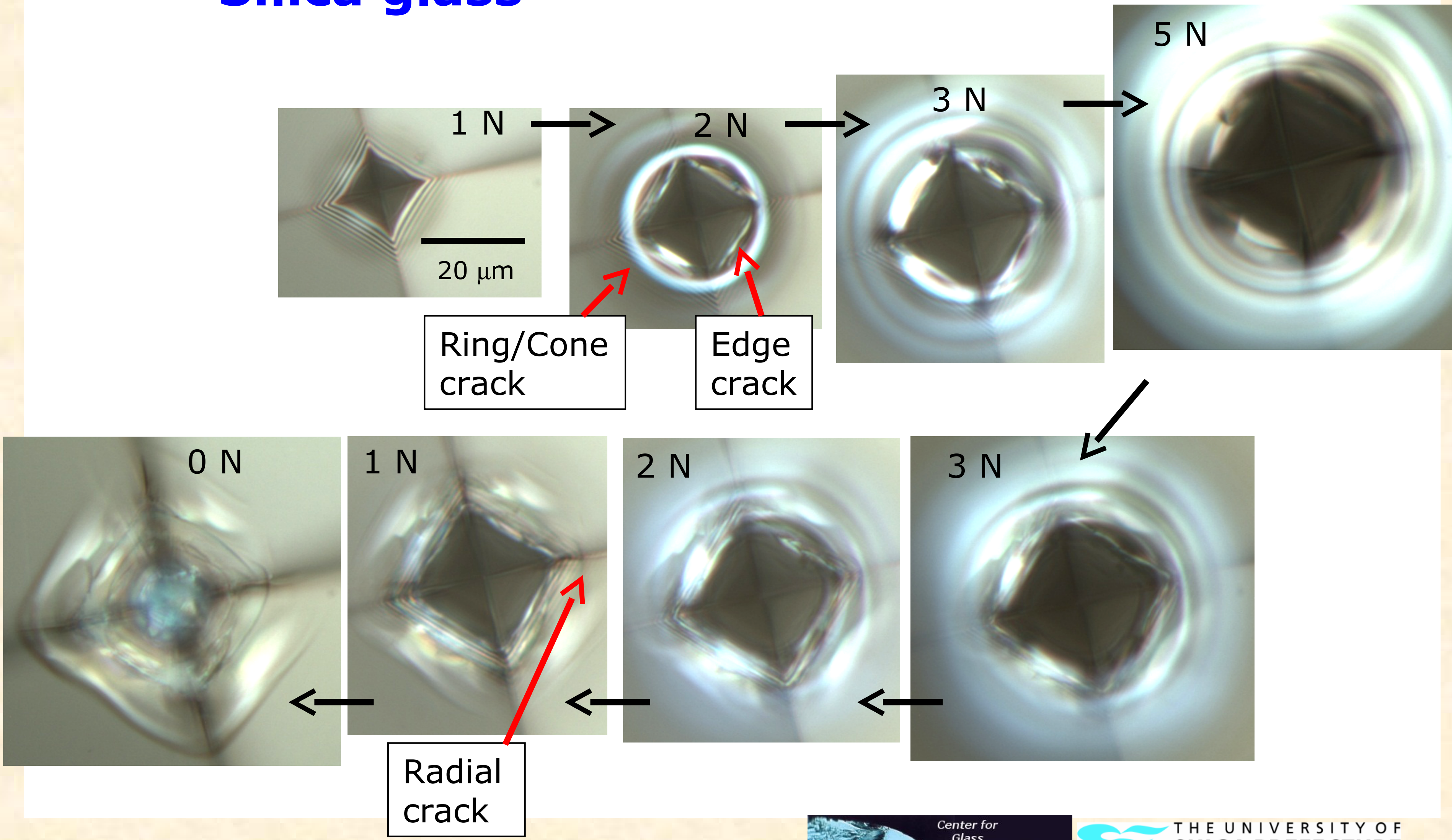
In-situ observation of Vickers indentation

Soda-lime glass



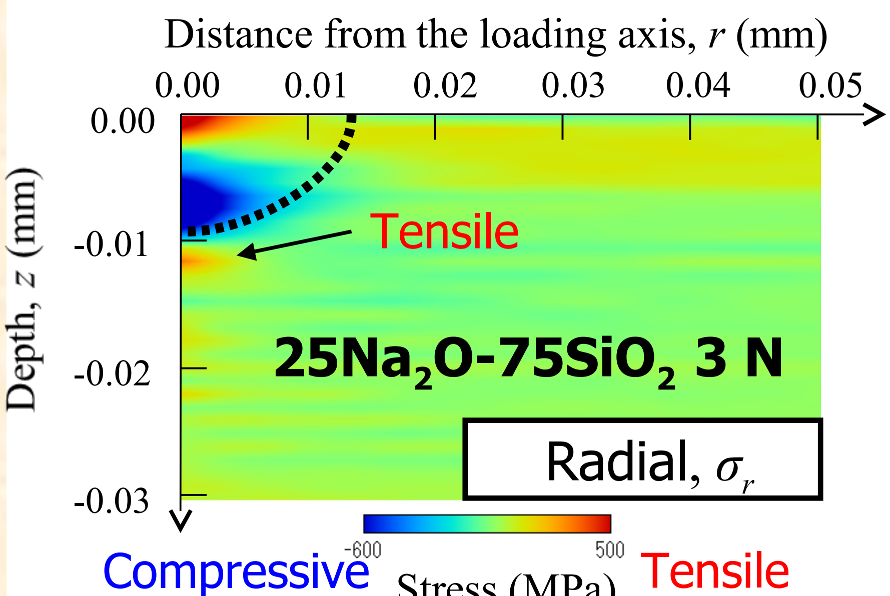
In-situ observation of Vickers indentation

Silica glass



Schematic model of stress state of SLS under Vickers

T. Wilantewicz, Ph.D thesis, Alfred Univ (2005)



Ball indentation

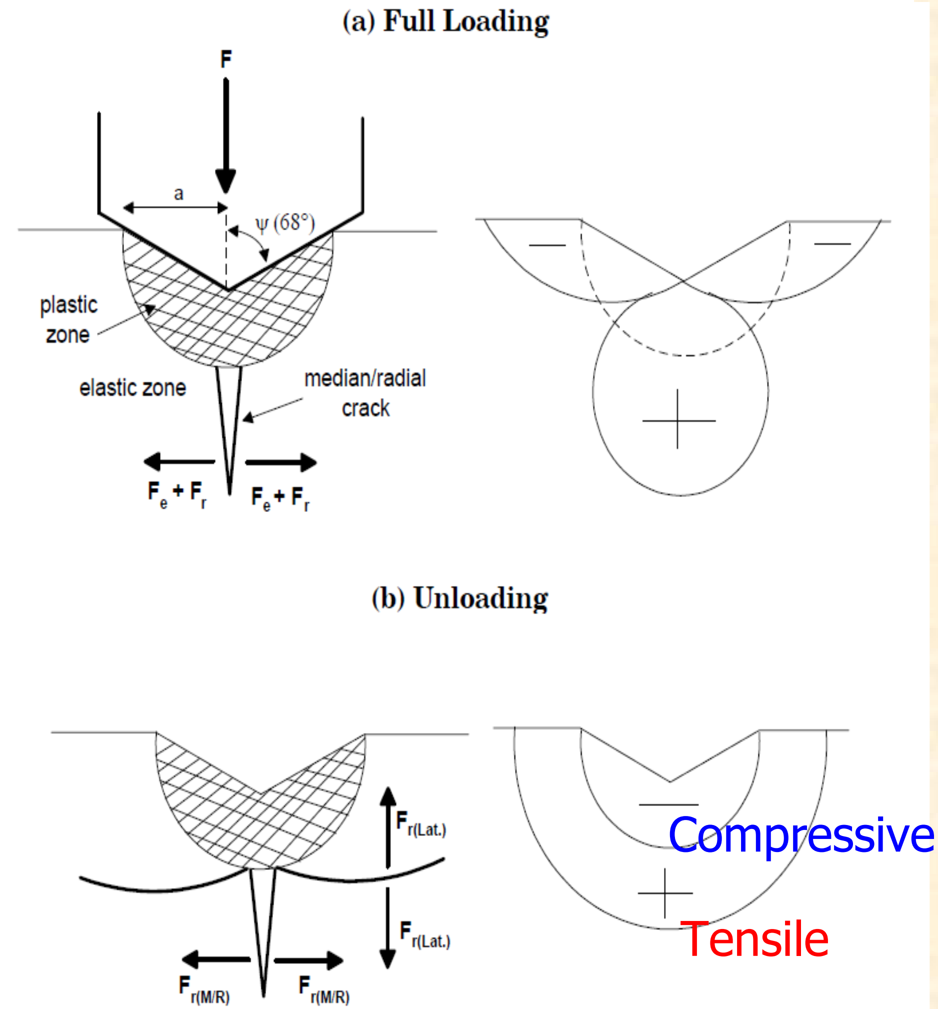
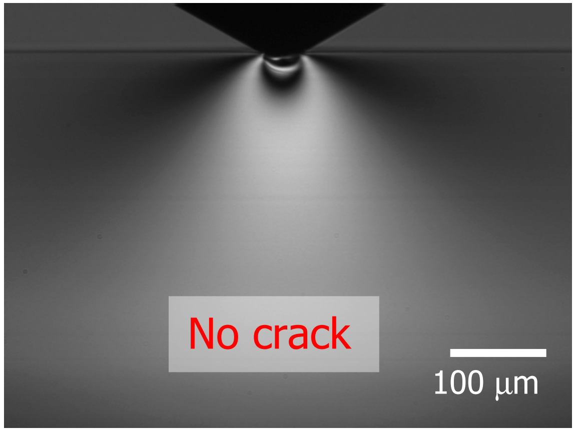


Figure 1. Schematic illustrating the composite elastic-plastic field under full indenter loading (a) and after complete unloading (b). Negative signs designate compression, and positive signs tension. F_r is the wedge-opening force due to the residual stress field, and wedges open the lateral and median-radial (M/R) cracks, particularly on unloading. F_e is the elastic force which also wedges open median-radial cracks on loading. After Lawn et al.[20] Lawn, Evans, Marshall(1980)

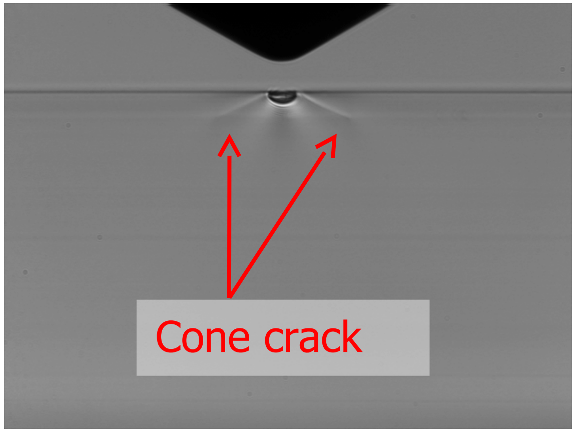
Ring/Cone crack after/during unloading

Silica, R=0.05 mm



8.0 N

Unloading



0 N

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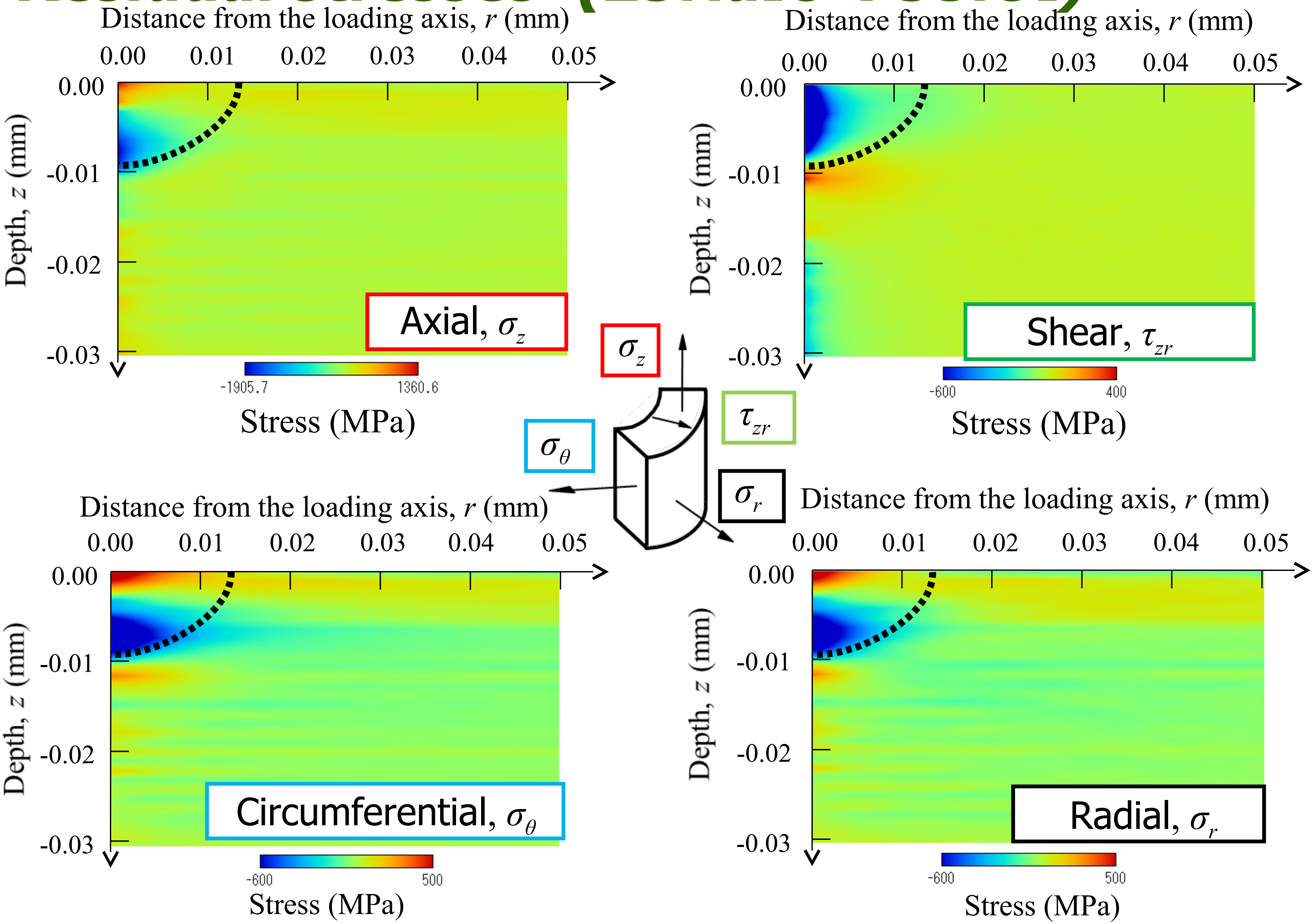
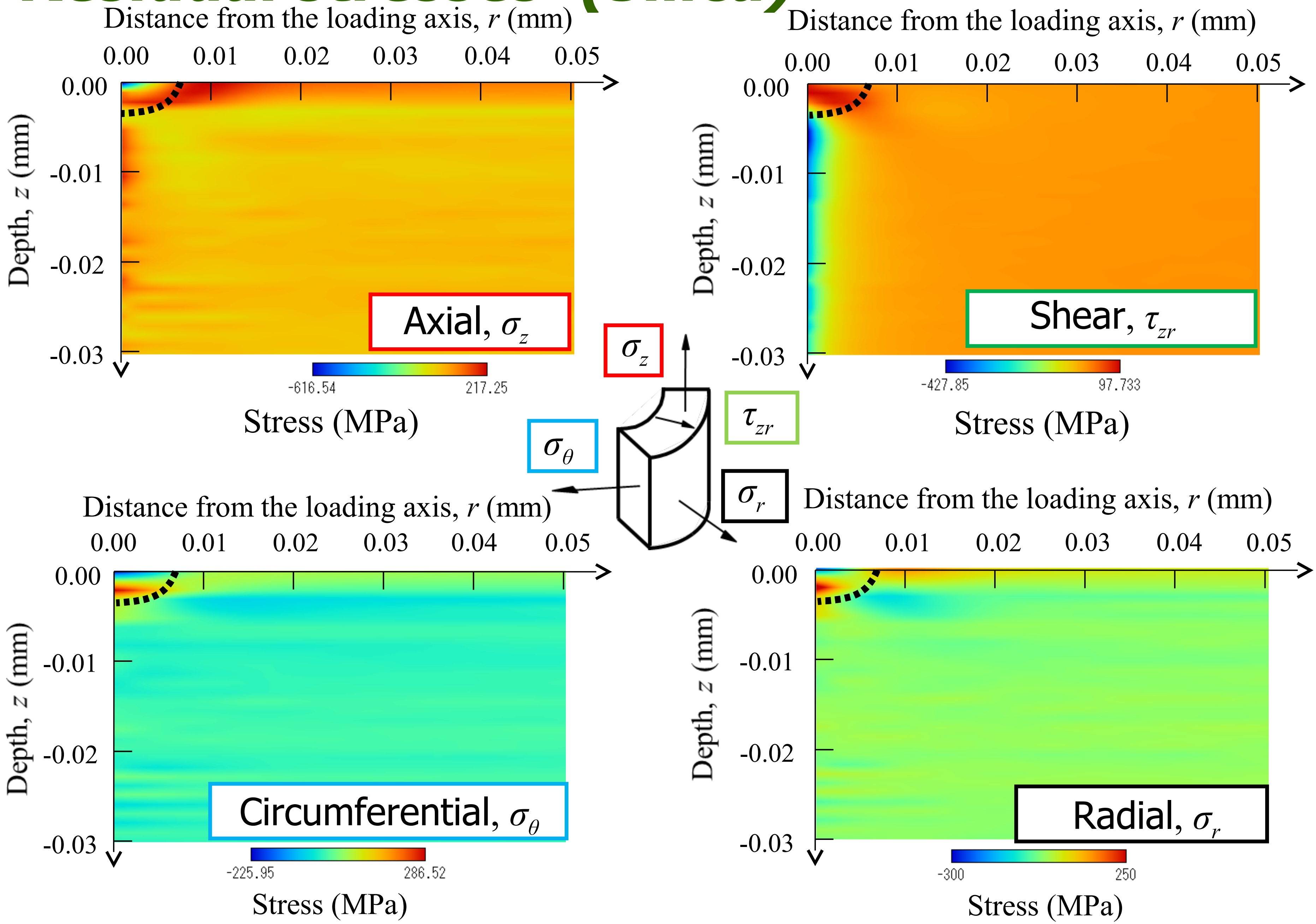
Residual stresses (25Na_2O-75SiO_2)



Residual stresses (Silica)



Experimental

Sample 1: Soda-lime glass (Matsunami 0050)

Stress optical coefficient	2.7 TPa^{-1}
Poisson's ratio	0.20
Young's modulus	73 GPa

Sample 2: Silica glass

Stress optical coefficient	3.5 TPa^{-1}
Poisson's ratio	0.16
Young's modulus	72 GPa

Sample dimensions: 0.5 x 0.5 x 35 mm^3
Square fibers

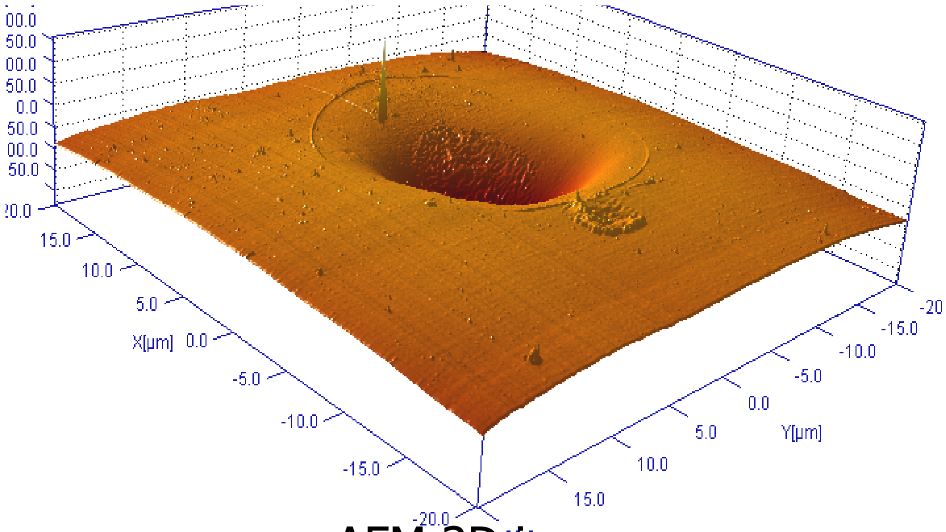
Indenter: Diamond ball indenter (R=0.05, 0.1 mm)

Why ball indentation ?

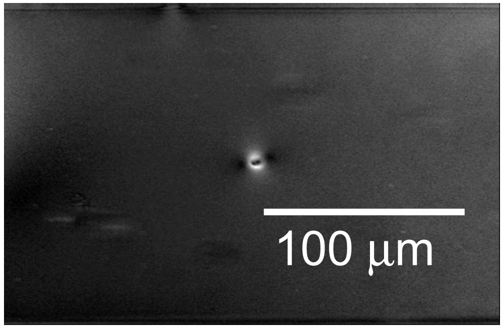
… The obtained stress field has an axial symmetry.

Residual indent (SLS)

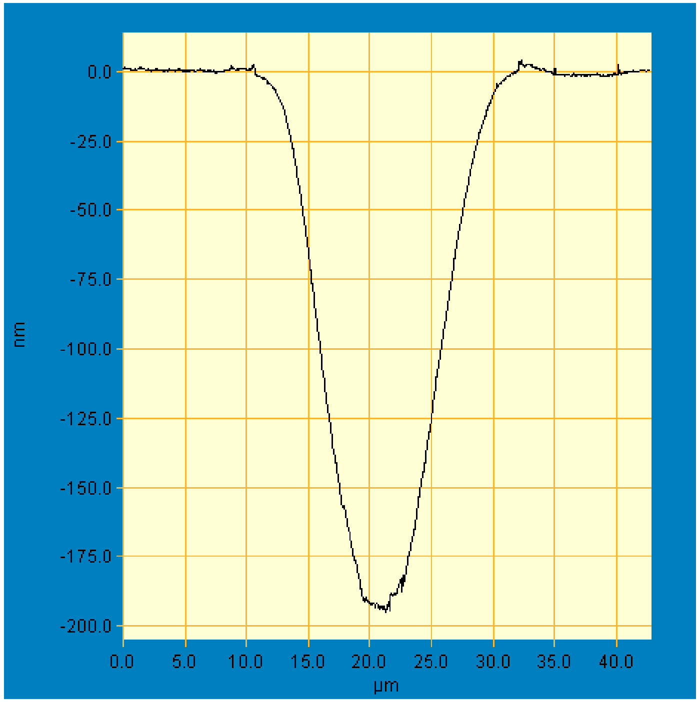
Soda-lime glass, 2.09 N, Indenter R=0.05 mm



AFM 3D image



Retardance (Top view)



AFM cross-section
Max. depth ~0.2 μm
Diameter ~ 22 μm

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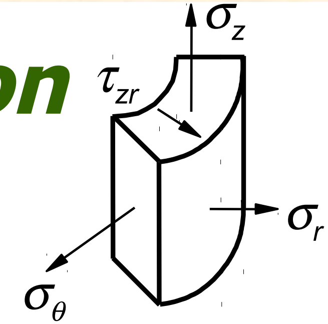
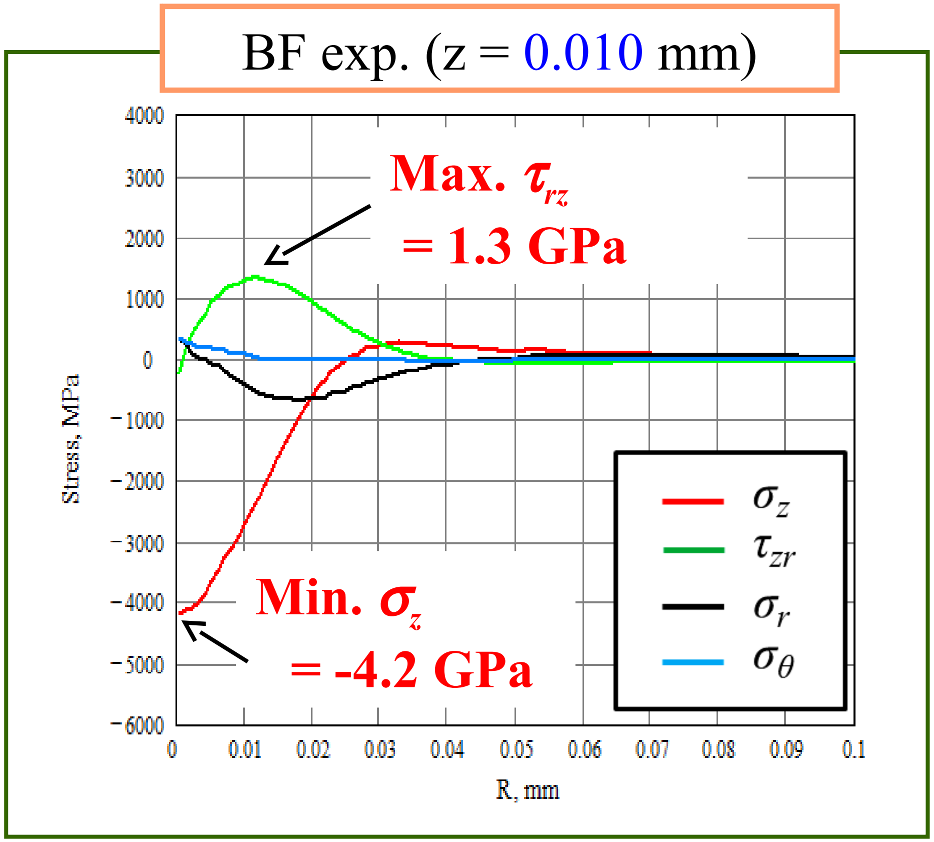
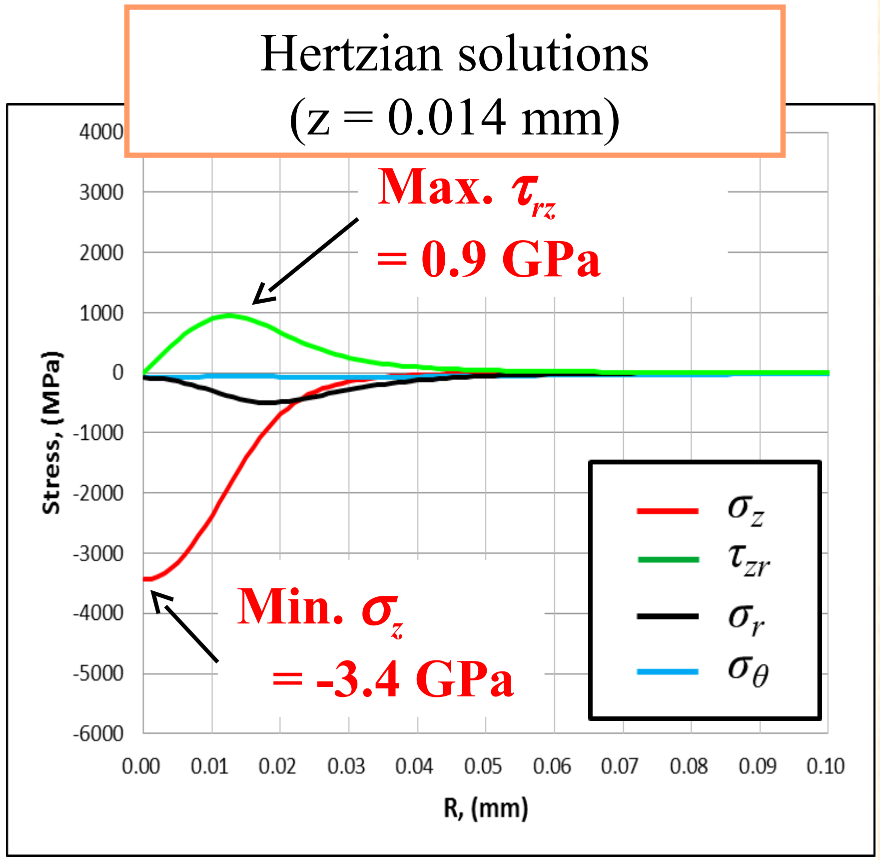
Comparison with analytical solution



Soda-lime, R = 0.1 mm, Load = 3.0 N

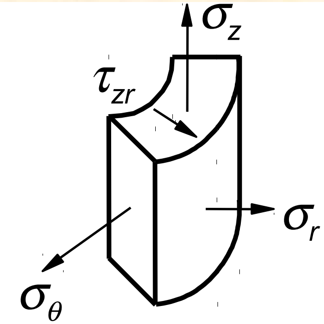
Deeper under the indenter

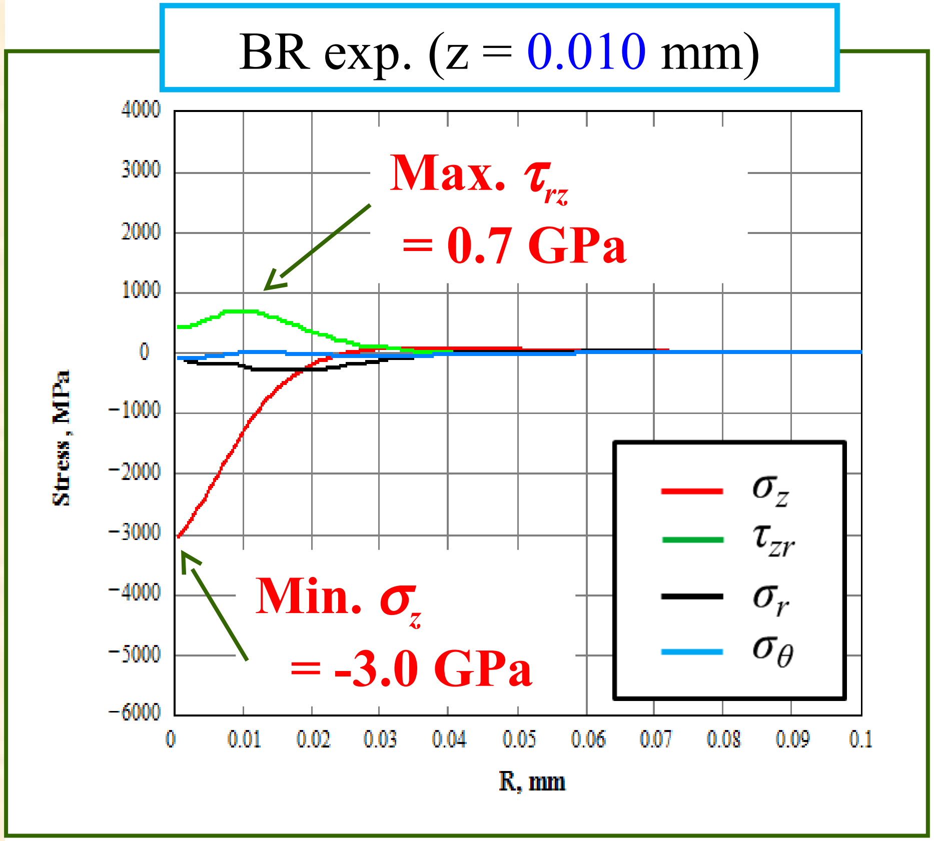


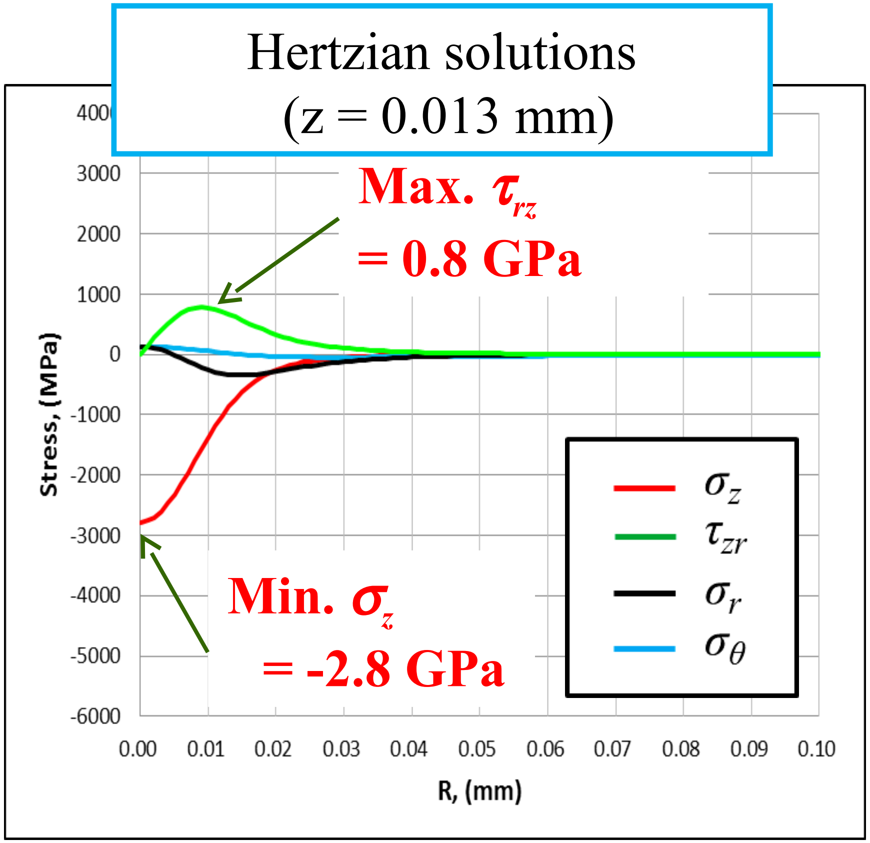


Elastic stresses (Silica)

Silica, R = 0.05 mm, Load = 1.5 N

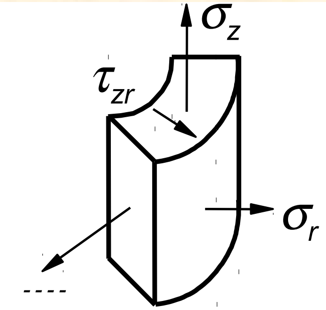


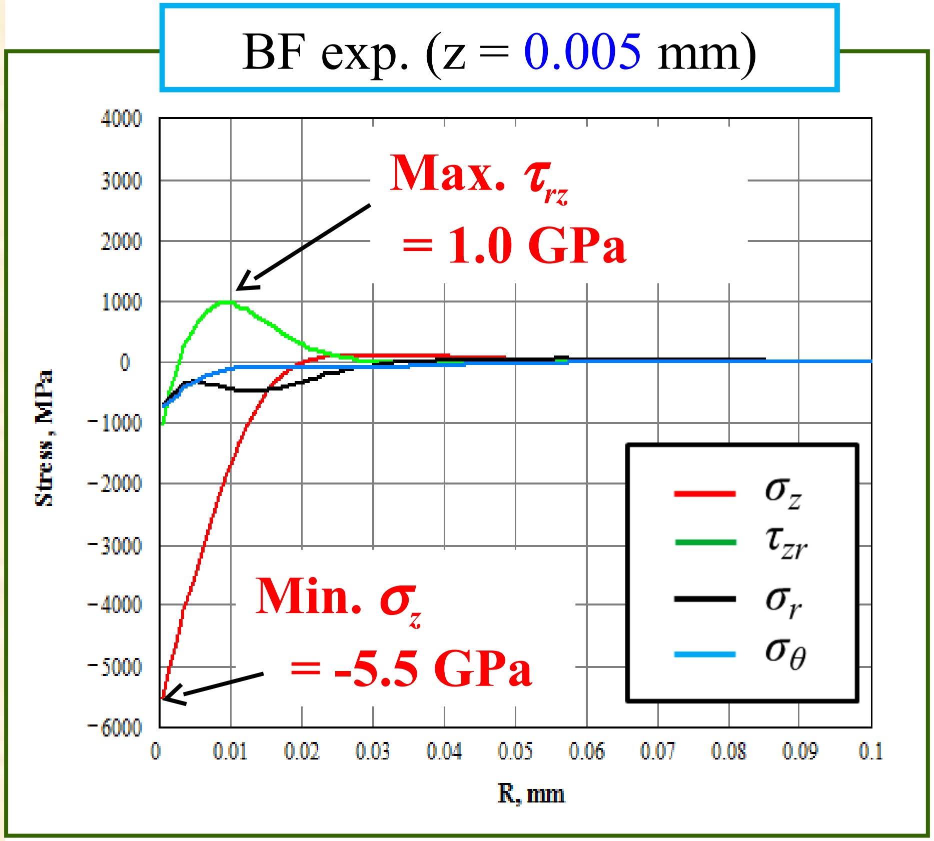


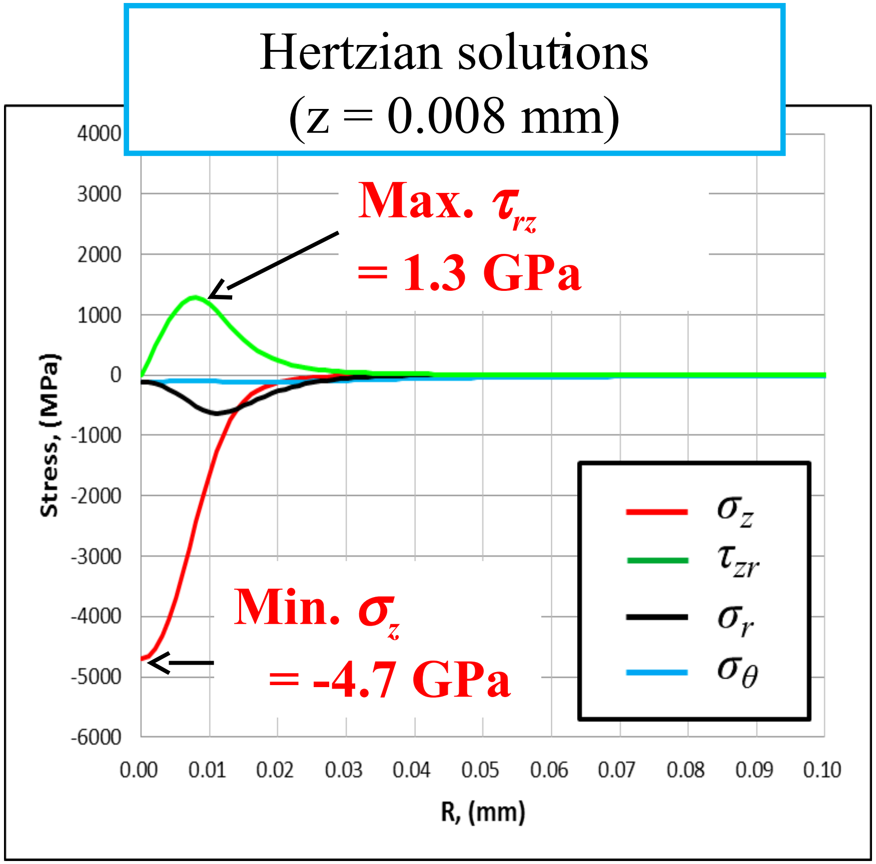


Elastic stresses (Silica)

Silica, R = 0.05 mm, Load = 1.5 N

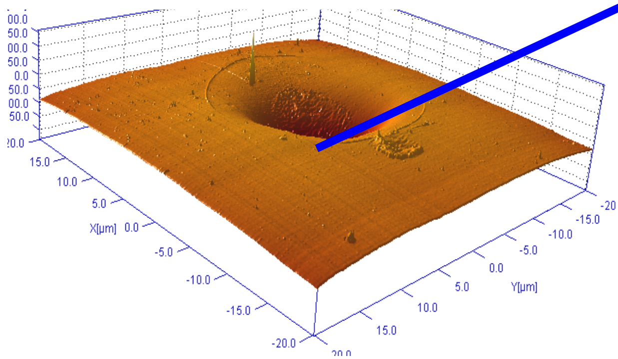




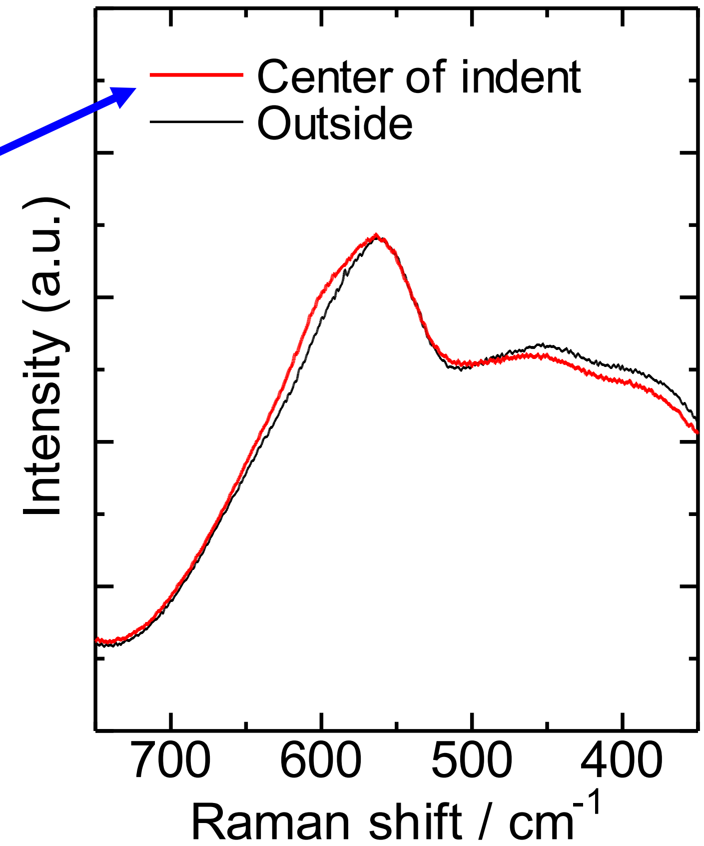


Residual indent (SLS)

Soda-lime glass, 2.09N, Indenter R=0.05mm



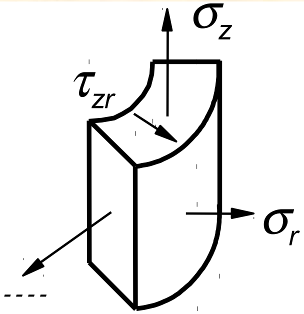
AFM 3D image



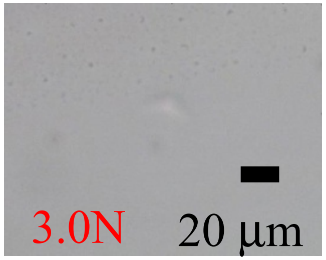
Raman spectra before and after indentation

Retardation images (Silica)

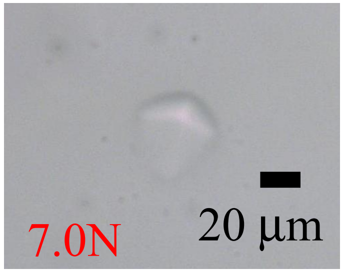
$R = 0.05$



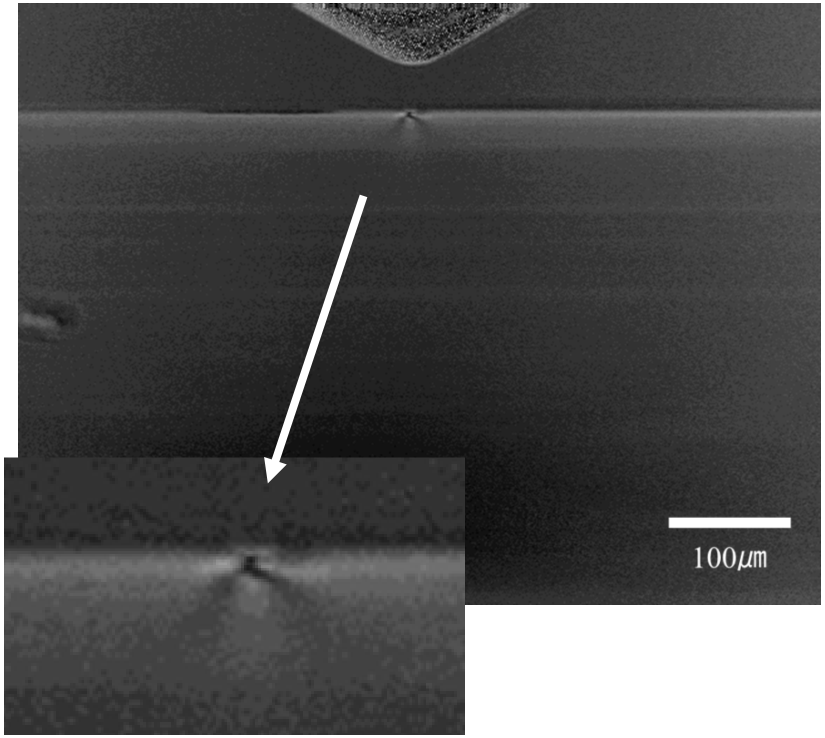
Load dependence

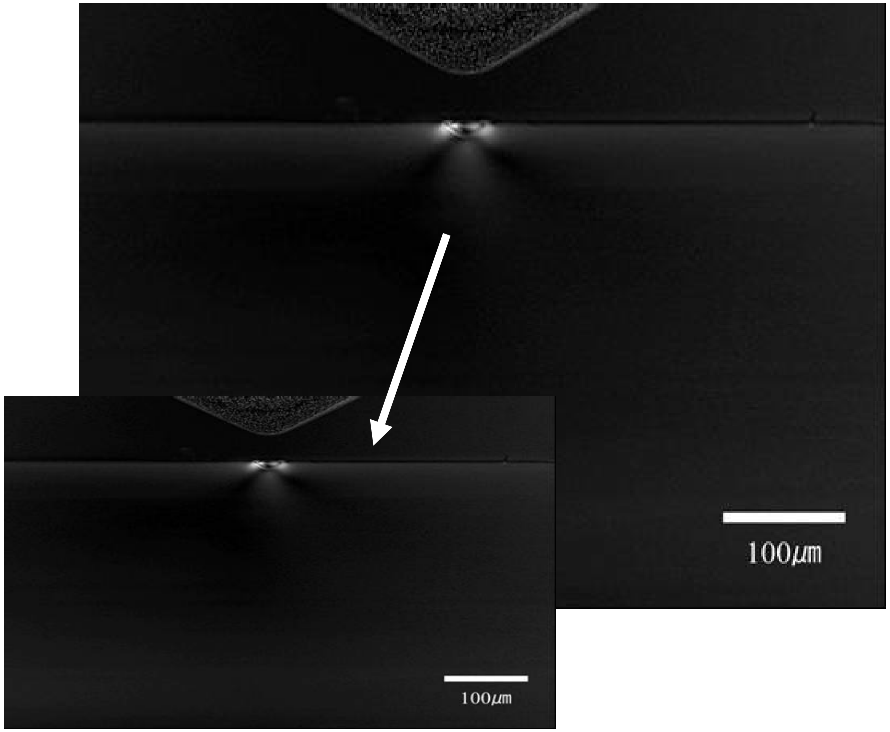


Load: **3.0 N**



Load: **7.0 N**

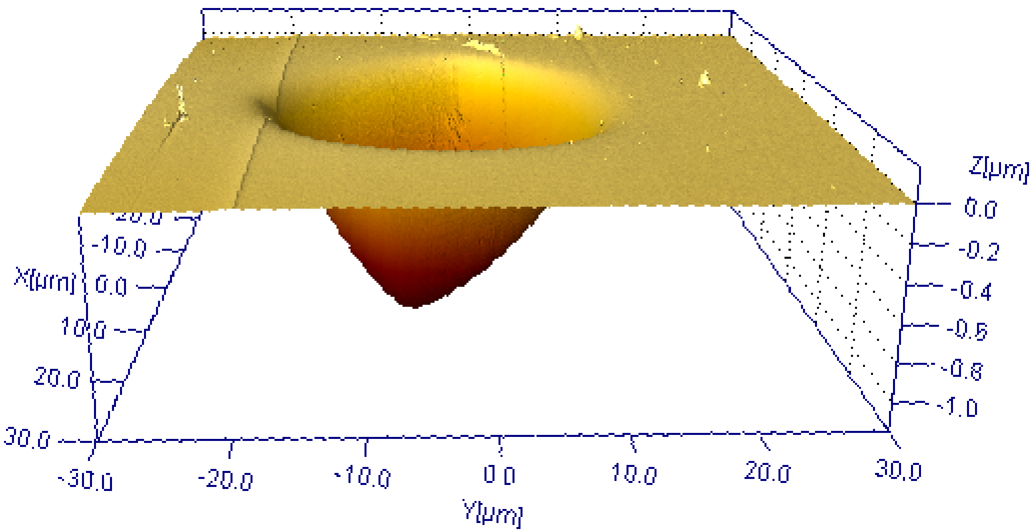


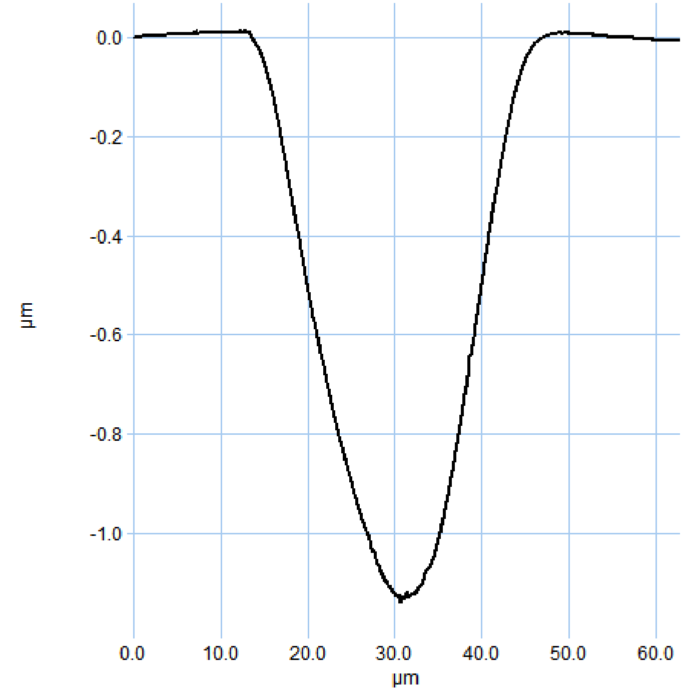


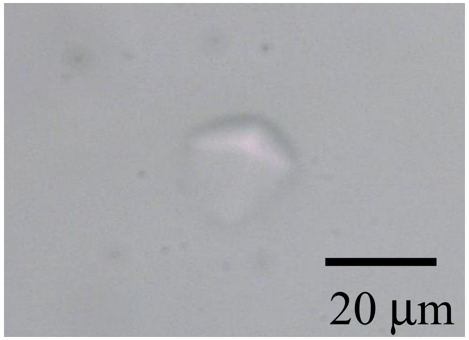
Black hole ?

Residual indent (Silica)

Silica glass, 7.0 N, Indenter R=0.05mm

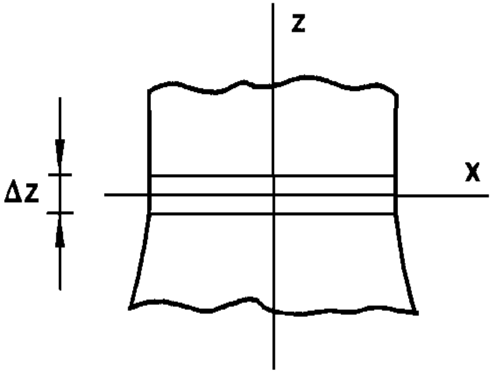


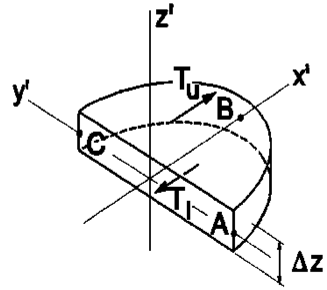


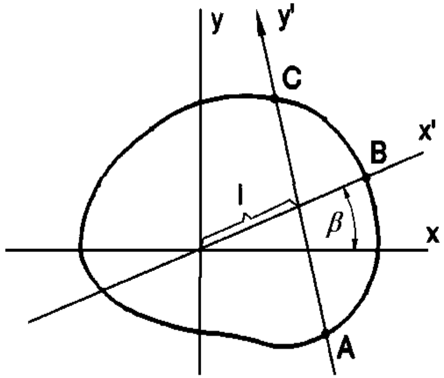


Determination of stress distribution

Determination of axial stress distribution







Experimental BF parameters, V_1 and V_2

$$\begin{cases} V_1 = \Delta\cos 2\varphi = C\int(\sigma_{z'} - \sigma_{x'})dy', \\ V_2 = \Delta\sin 2\varphi = 2C\int \tau_{x'z'}dy'. \end{cases}$$

$$\Delta z\int_A^C \sigma_{x'}\, dy' = T_u - T_l,$$

$$T_u = \frac{1}{2C}\int_l^B V_2 dx', \qquad T_l = \frac{1}{2C}\int_l^B V_2 dx',$$

$$\int_A^C \sigma_{x'}\, dy' = \frac{1}{2C\Delta z}\left(\int_l^B V_2' dx' - \int_l^B V_2 dx'\right).$$

σ_z is obtained from V_2 (main section) and V_2' (auxiliary section)

$$\int_A^C \sigma_{z'}\, dy' = \frac{V_1}{C} + \frac{1}{2C\Delta z}\left(\int_l^B V_2' dx' - \int_l^B V_2 dx'\right).$$

Determination of stress distribution

Determination of radial stress distribution

Equilibrium eq.

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} + \frac{\partial \tau_{rz}}{\partial z} = 0,$$

Written
in a discrete form

$$\sigma_{r,i} = \sigma_{r,i-1} - \left(\frac{\sigma_{r,i-1} - \sigma_{\theta,i-1}}{r_{i-1}} + \frac{\Delta \tau_{rz,i-1}}{\Delta z} \right) \Delta r.$$

Determination of stress distribution

Determination of circumferential stress distribution

Compatibility equation:

$$\frac{\partial \varepsilon_\theta}{\partial r} - \frac{\varepsilon_r - \varepsilon_\theta}{r} = 0$$

Hooke's law:

$$\varepsilon_r = \frac{1}{E}[\sigma_r - \mu(\sigma_\theta + \sigma_z)],$$

$$\varepsilon_\theta = \frac{1}{E}[\sigma_\theta - \mu(\sigma_r + \sigma_z)]$$

$$\frac{\partial \sigma_\theta}{\partial r} - \mu \frac{\partial}{\partial r}(\sigma_r + \sigma_z) - \frac{1}{r}(1+\mu)(\sigma_r - \sigma_\theta) = 0$$

$$\frac{\Delta \sigma_\theta}{\Delta r} - \mu \frac{\Delta(\sigma_r + \sigma_z)}{\Delta r} - \frac{1}{r}(1+\mu)(\sigma_r - \sigma_z)$$

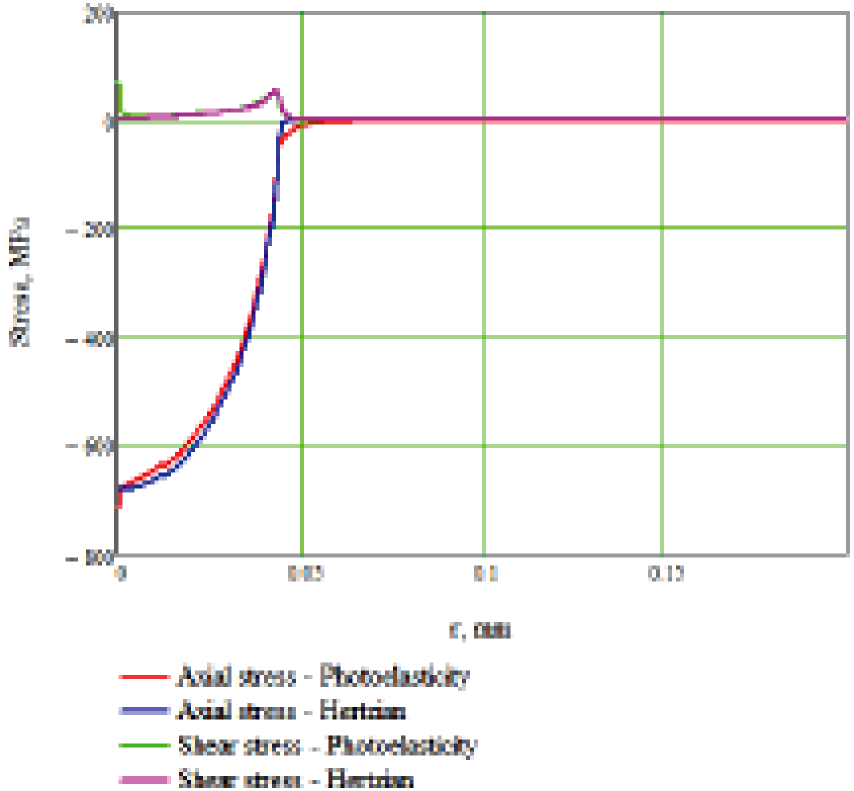
$$\sigma_{\theta,i} = \sigma_{\theta,i-1} + \mu(\sigma_{r,i} - \sigma_{r,i-1} + \sigma_{z,i} - \sigma_{z,i-1}) + \frac{\Delta r}{r_i}(1+\mu)(\sigma_{r,i-1} - \sigma_{\theta,i-1})$$

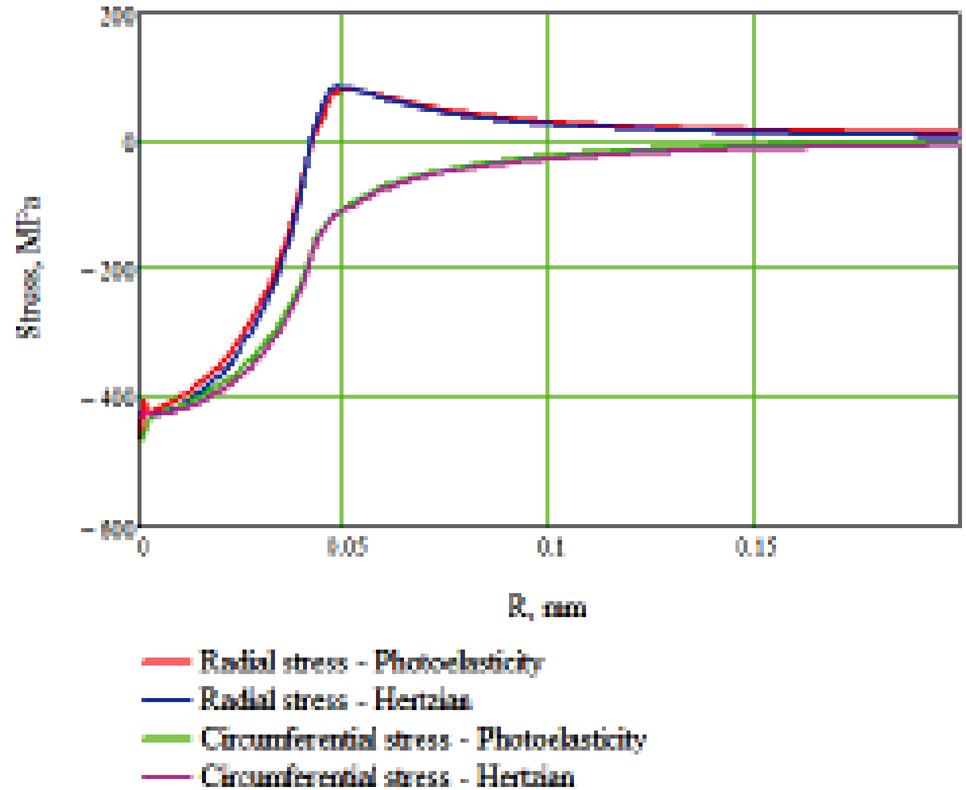
Important constraint: in the centre of solid specimen $\sigma_r = \sigma_\theta$.

σ_θ and σ_r ⟵ τ_{rz} and σ_z

Comparison of BF with Hertzian stresses

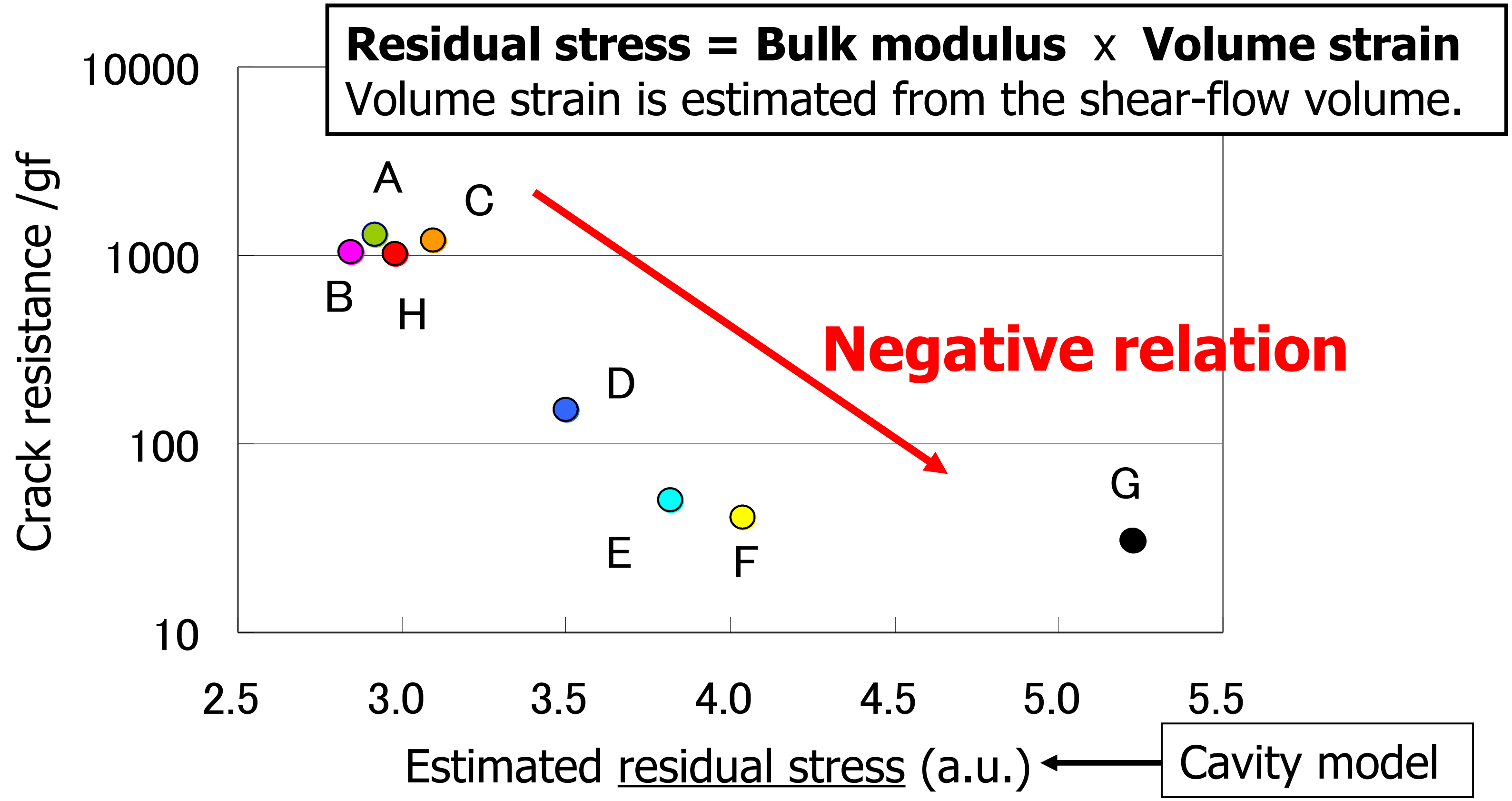
Hertzian stresses → Photoelastic data → Photoelastic stresses





Poisson's ratio of glass: 0.22
Young's modulus of glass: 71.7 GPa
Poisson's ratio of indenter: 0.4
Young's modulus of indenter: 100 GPa
Radius of indenter: 2.0 mm
Load: 2.7 N
Z-coordinate: -0.001 mm

Relation between crack resistance and residual stress



Y. Kato *et al.*, *J. Non-Cryst. Solids* **356**(2010)1768.

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THE UNIVERSITY OF SHIGA PREFECTURE