Materials Science & Technology

Materials Science II - 2010, Ceramic Materials, Chapter 6, Part 5

Mechanical Properties of Ceramics

or

Mechanical Behavior of Brittle Materials

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What you already know and understand!

- Ceramic materials are susceptible to **thermal shock**,

  they fail if exposed to too fast temperature changes ($\Delta T/\Delta t$) and locally to too large temperature gradients ($\Delta T/\Delta x$).

- Small component = small $\sigma_{thermal}$ // Large component = large $\sigma_{thermal}$
- Low CTE, high K_{Ic}, and low E = high R_S (= 1st thermal shock parameter)
  2nd thermal shock parameter → constant heat transfer
  3rd thermal shock parameter → surface heated by constant rate
- **Slow Crack Growth** *(scg):* time dependent failure → limited life time
- **Crack velocity** is influence by humidity → brake up of bonds at crack tip
  e.g. in soda-lime glass by water (Si-O-Si- +H2O → -SiOH + -SiOH).
- SCG parameters can be measured in accordance to state of load
  (static, dynamic, cyclic, or a combination thereof).
- Correlation between largest failure relevant defect, failure strength and **lifetime**.
- Link between strength, probability of failure and lifetime:
  Strength-**P**robability-**T**ime diagram

Repetition learning targets part 4

- **Creep**: Boundary (diffusion) or lattice (dislocation) mechanism
- **Diffusional creep**:
  Free surfaces and grain boundaries work as source and assembly point for voids and atoms. Voids diffuse from surfaces under tension to surfaces under compression and matter flows in reverse direction.
- **Grain boundary sliding**:
  Structure elongates by shifting & twisting of grains
- **Stages of creep**:
  - primary
  - secondary (steady state)
  - tertiary
- Creep should be measured in **tension**
  and not in bending.
- **Stain rate** is increasing with
  - increasing load & temperature and
  - decreasing grain size.

Aim of chapter & Learning targets

part 1 Crack tip	1. Introduction	"Why mechanical testing …"	learning targets 1
	2. Stresses at a crack tip	"Higher than you'd assume …"	
	3. Griffith law	"Conditions for failure …"	
	4. K_I and K_{Ic}	"Stress intensity & critical stress intensity …"	
part 2 Strength	5. R-curve	"Improving toughness …"	learning targets 2
	6. Properties	"Knowing what you measure …"	
	7. Strength	"Just a value …"	
part 3 Statistics	8. Statistic	"Weibull, a name you'll never should forget …"	learning targets 3
	9. Proof testing	"Make it or …"	
	10. Fractography	"Reading fracture surfaces …"	
part 4 Time&Temp	11. Thermal shock	"Temperature, time and geometry …"	learning targets 4
	12. Slow crack growth	"After several years …"	
	13. SPT diagrams	"Combining strength, lifetime & statistics …"	
	14. Creep	"Temperature makes it move …"	
	15. Failure maps	"Finding your way …"	

part 5 - Case Study: Lifetime of All-Ceramic Dental Bridges

Acknowledgements

This lecture is based on / a compilation of

- A.R. Studart, F. Filser, P. Kocher, H. Lüthy, L.J. Gauckler
  dental materials 23 (2007) 115-123 and dental materials 23 (2007) 177-185
- A.R. Studart, F. Filser, P. Kocher, L.J. Gauckler
  dental materials 23 (2007) 106-114 and Biomaterials 28 (2007) 2695-2705
- I. Sailer, A. Fehér, F. Filser, L.J. Gauckler, H. Lüthy, Ch.H. F. Hämmerle
  The International Journal of Prosthodontics, 20 (2007) 151-156
- presentation *Lifetime of All-Ceramic Dental Bridges* @ ETH Materials Day 2005, F. Filser
- presentation *Load Bearing Capacity and Reliability of All-Ceramic Four-Unit Posterior Bridges* @ CICC-4 (2005), F. Filser
- lecture *Lifetime Prediction of Dental Ceramics under Cyclic Fatigue* @ ETHZ-MW-II-2007, F. Filser

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  M. Schumacher, O. Loeffel, C. Löscher
- Degudent, Dentsply Ceramco, Ivoclar and VITA Zahnfabrik for supporting those studies.

Outline

- Introduction
  - Dental bridges in time
  - Why ceramics
  - Mechanical short & longtime properties
  - Aim & Objectives of study
- Production process, various
- Experimental & Results
  - Mechanical short-time properties
  - Lifetime prediction
    - influence of water
    - subcritical crack growth & fatigue
- Lifetime diagrams
- Summary, Conclusion & Outlook

Dental bridges in time

Etruscan prosthesis

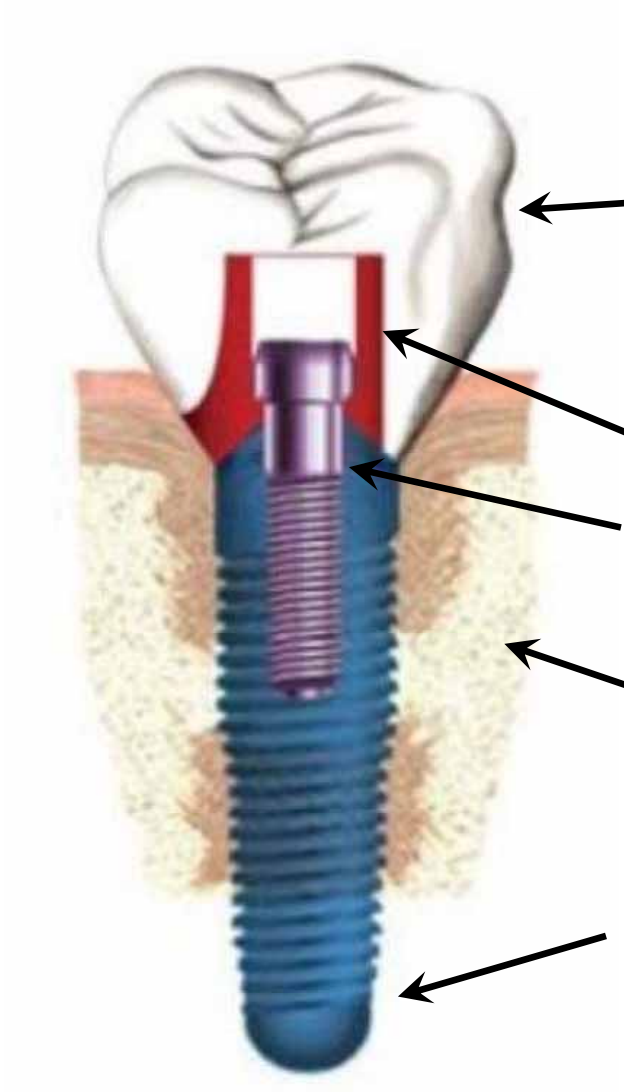
200 BC

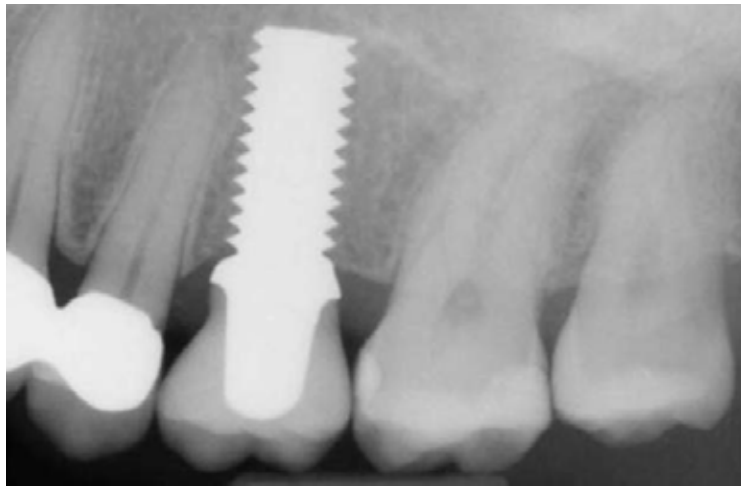
Metal-porcelain bridge

1960s

All-ceramic bridge

1999





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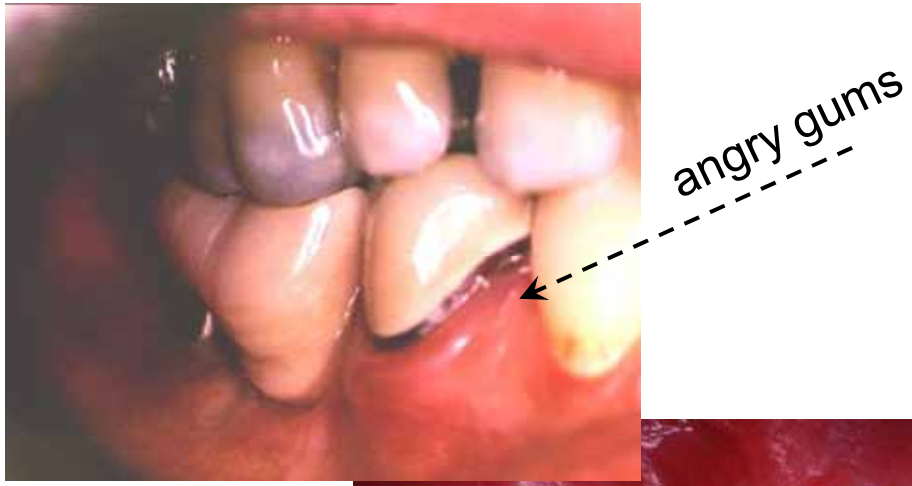


Metallic framework

Ceramic framework

- Chemically inert
- Low allergenic potential
- Pink esthetic of gums
  - Biocompatibility
  - Low deposition of plaque
- White esthetic of tooth
  - natural look
  - imitation of nature
  - translucent

Why ceramics ?

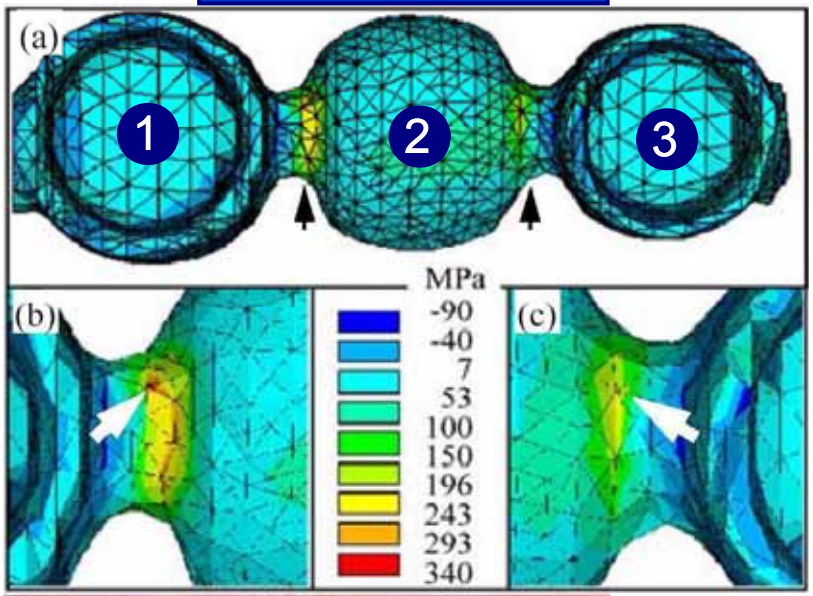
5-unit Bridge in the Molar Region after3 years in service (2002)

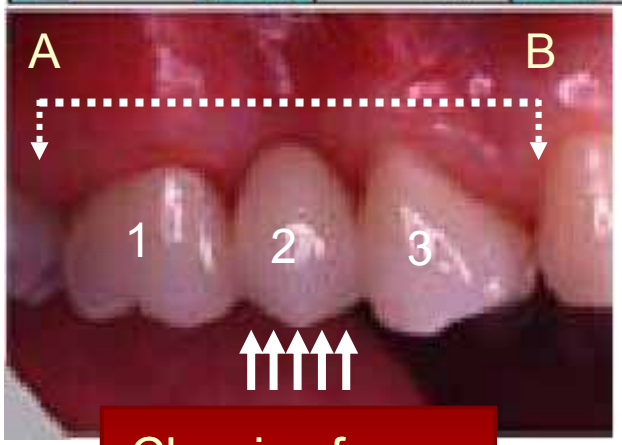
(Courtesyof A. Fehérand I. Sailer, University of Zurich)

Introduction

AB cross section

Filser et al.
PhD thesis
ETHZ (2001)

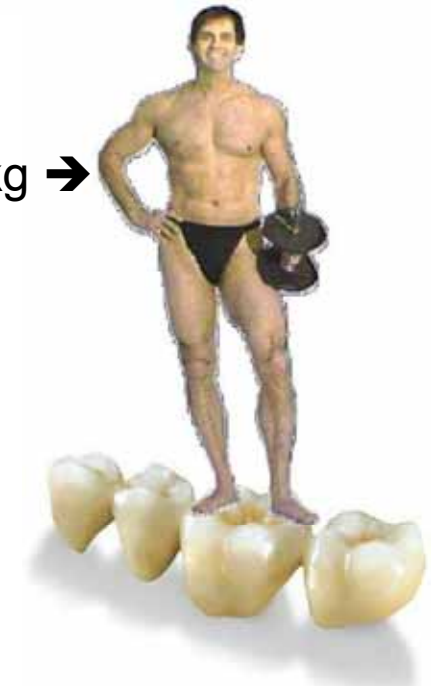




Chewing forces

typical failure situation

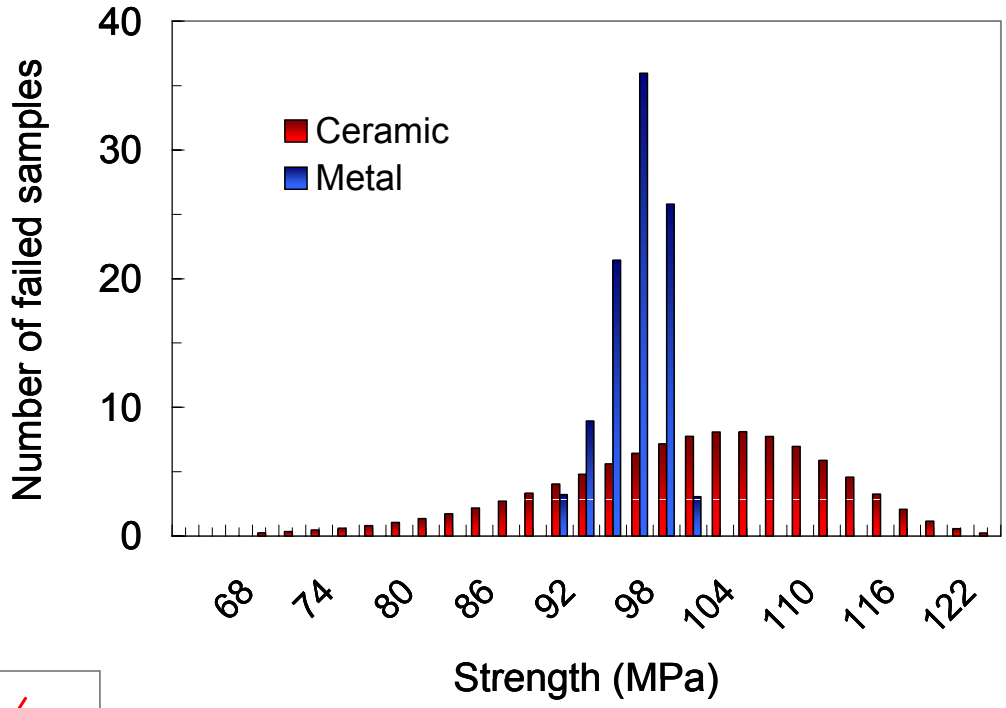
800 N = 80 kg ➔

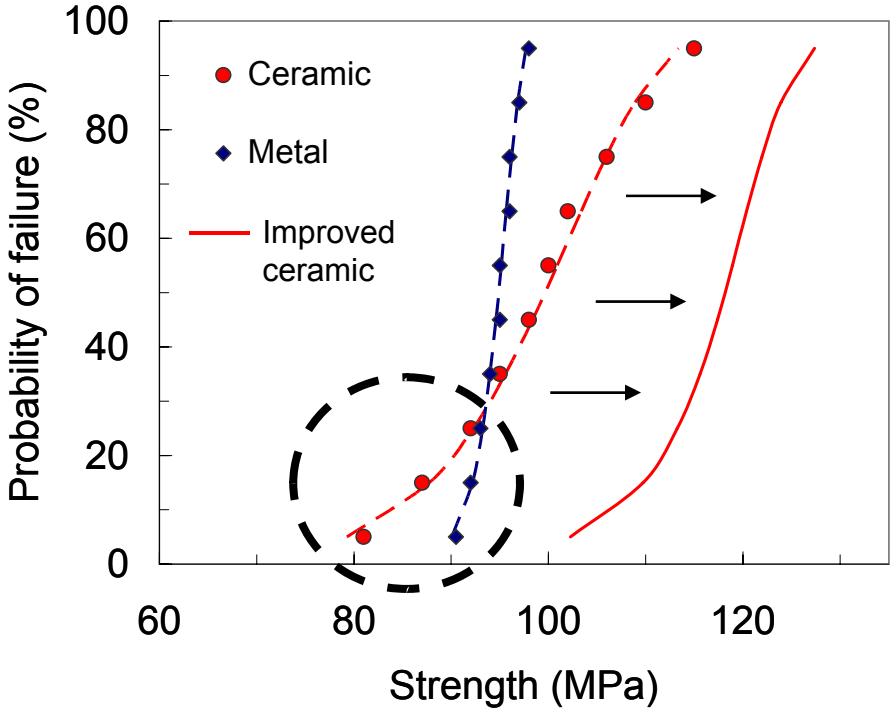


High-strength materials are required !

➔ The "failure load" was set to 800 N, 900 N or 250 N / teeth depending on the time in the long-time research project a specific part has been conducted.

Mechanical strength of ceramics and metals

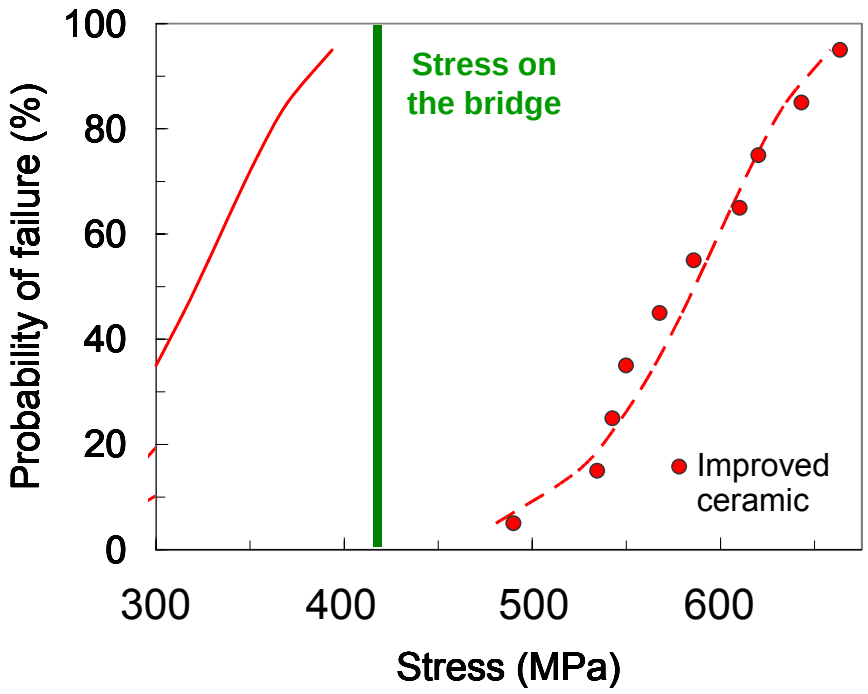


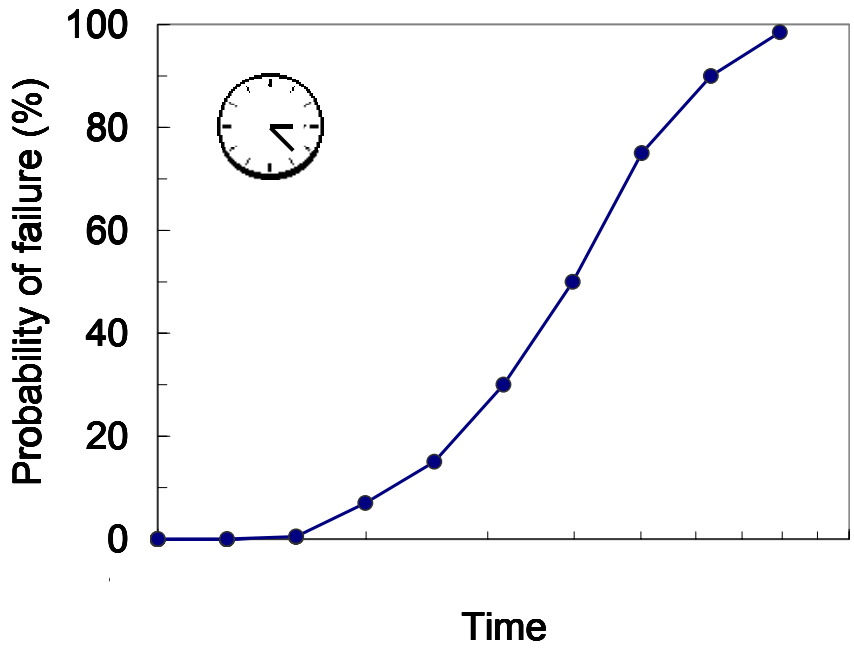


Strength of traditional ceramics had to be improved !

Fatigue and subcritical crack growth

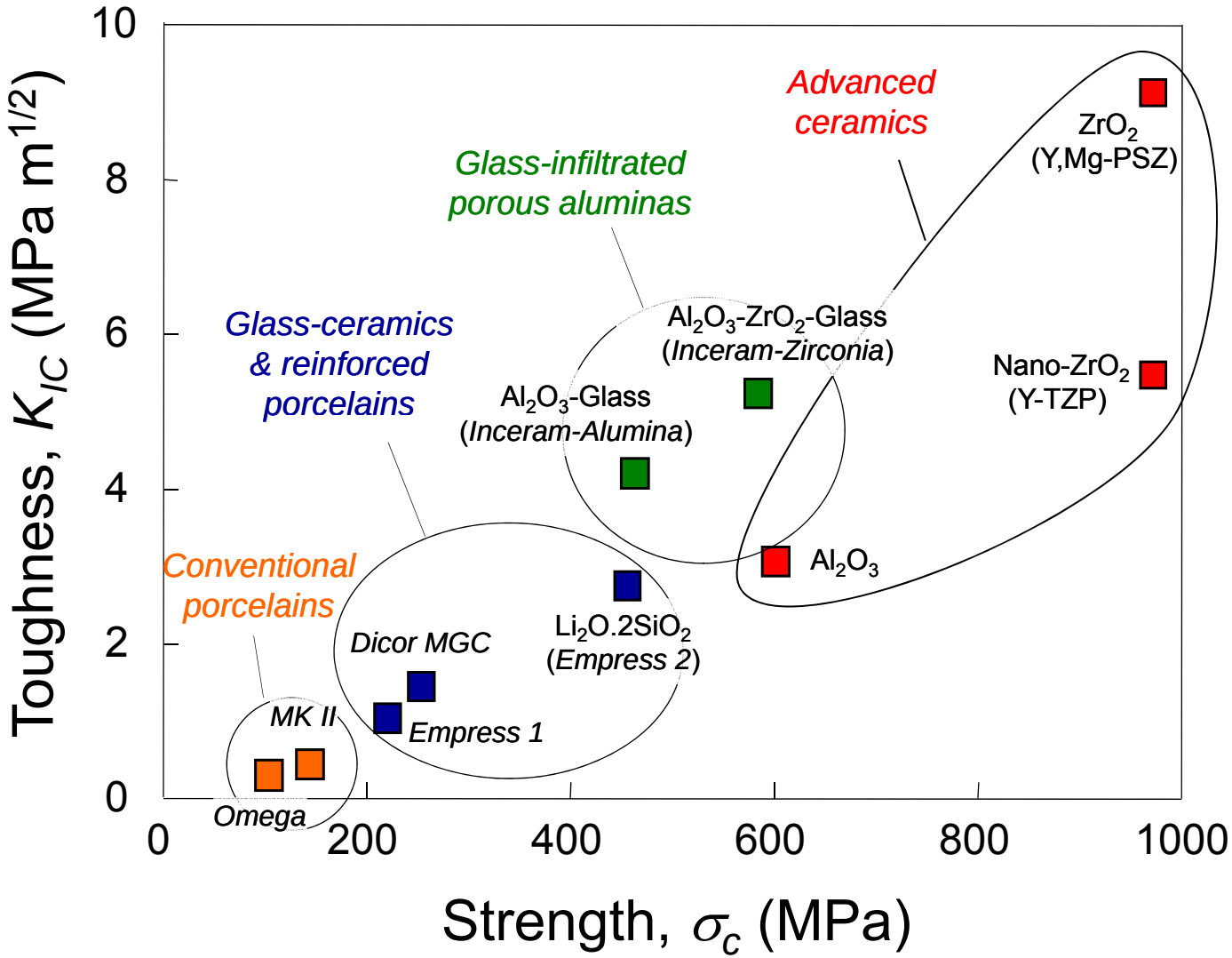
Mastication: *Cyclic stresses* + *Water*





Fatigue mechanisms decrease the strength over time !

New materials

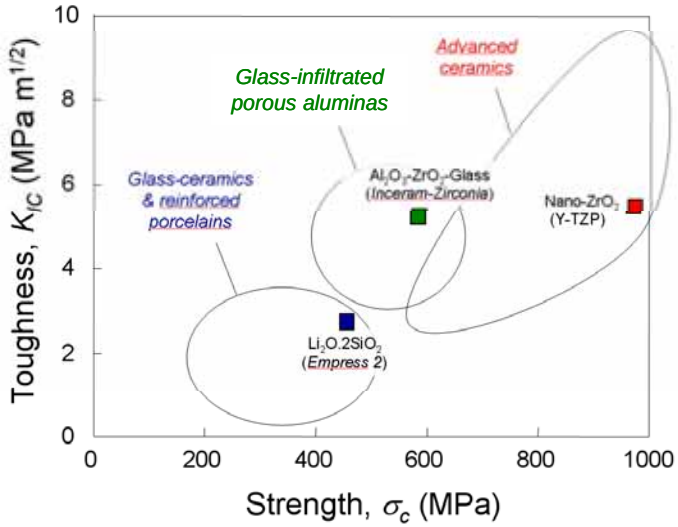


Aim & Ojectives

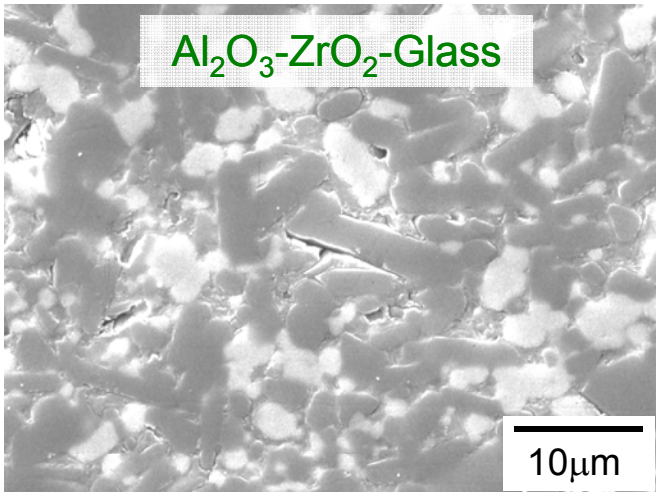
Systematically evaluate the lifetime under cyclic conditions for selected, representative dental ceramics.

With variables effect of water and effect of coating (porcelain)

Establish guidelines for materials selection, fabrication process and bridge design

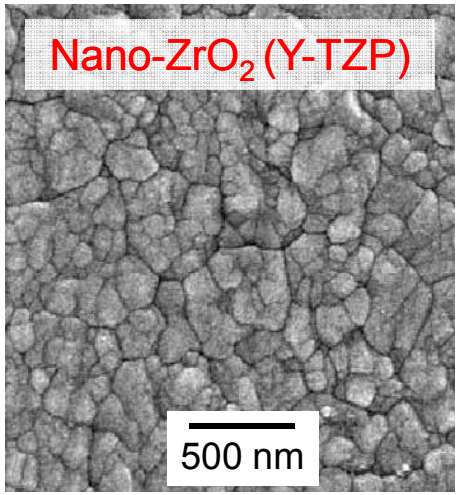


Framework:
Inceram Zirconia (VITA)



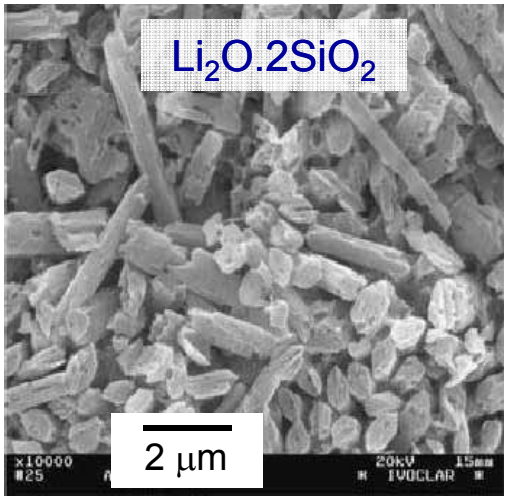
Veneer: Glass A

Framework:
Zirconia (Cercon, degudent)



Veneer: Glass Z

Framework:
LiSilicate (Ivoclar, Empress II)



Veneer: Apatite

Empress-2
Process

Pre-operative view shows the presence of extensive infiltrated composites.

Teeth are prepared.

The four waxed copings are sprued and then invested.

The frameworks after being pressed in the pressing furnace.

View of the finished frame-works on the master model.

The crowns and veneer are again placed on the master model.

IvoclarVivadent: “i, Vol. 7, Nr. 1, 2005

Empress-2
Process

Facial view of the four restorations.

Labial view of the four restorations.

Facial view of the four restorations following immediate operative placement

IvoclarVivadent: "i, Vol. 7, Nr. 1, 2005

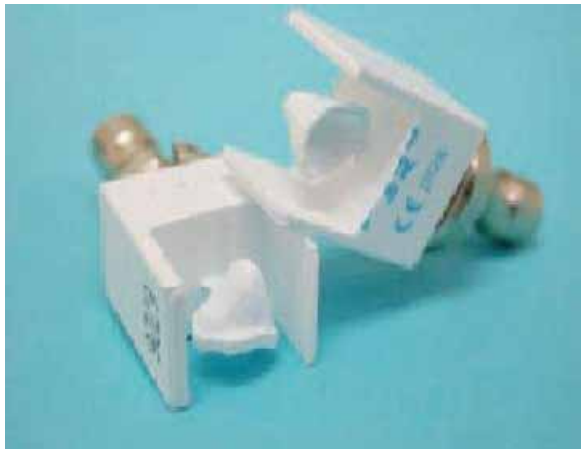
InCeram-Zirconia (Alumina)

Process

model made of gypsum

digitizing

grinding



crown caps after grinding

crown caps fitted on the gypsum model

glass infiltration

A. David, SpectrumInternational •IDS 2003, p. 5-7

InCeram-Zirconia (Alumina)

Process

infiltrating the porous alumina

overworking the excess infiltration glass

veneering the framework with VITADUR® ALPHA

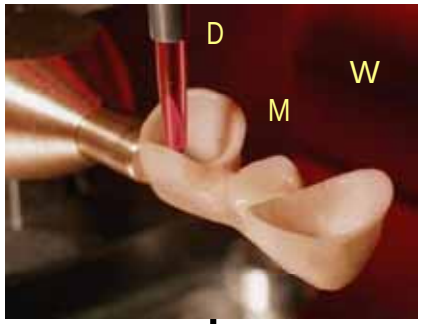
situation after cementation of the 3-unit bridge

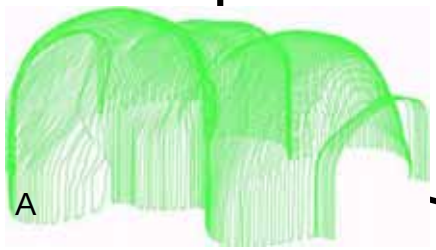
A. David, SpectrumInternational •IDS 2003, p. 5-7

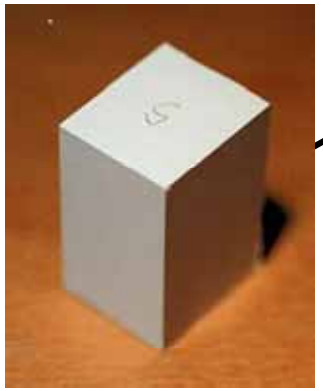
cercon smart ceramics

Process

of Machining in the Soft Sintered State







C

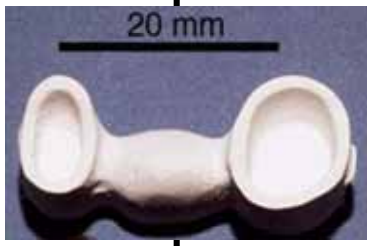
Cercon® (Degudent) system

M

F

S

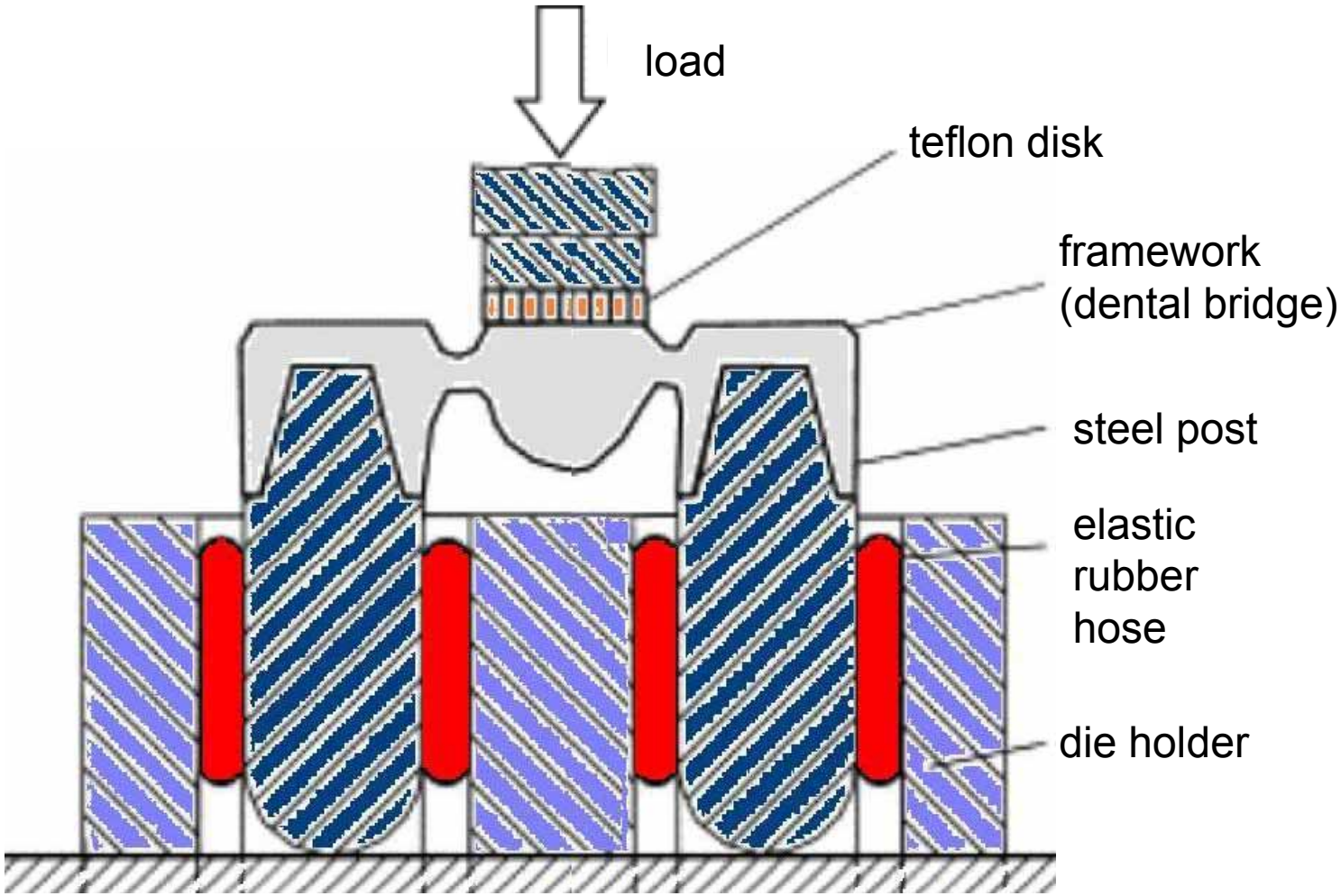
A



F. Filser et al., ETH Hochschulverlag, ISBN 3-7281-2635-7, 1998, p. 165-189

Load Bearing Experimental Setup

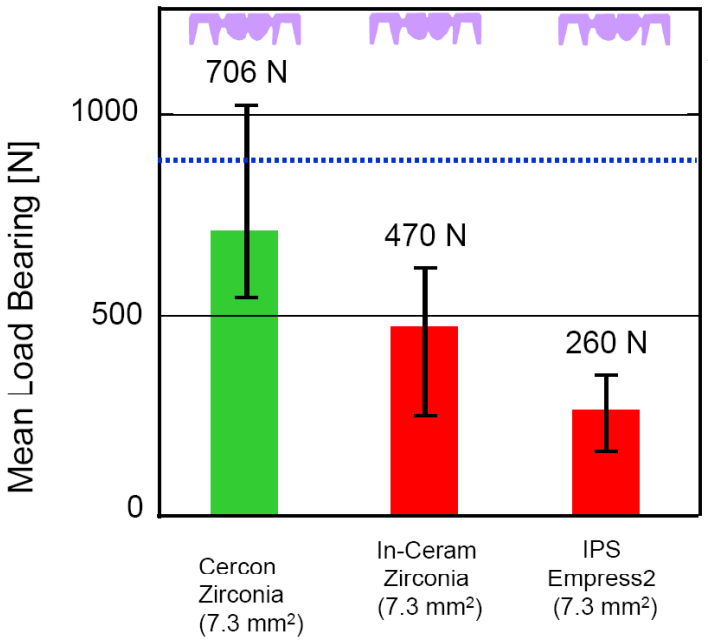
e.g. 3-unit bridges

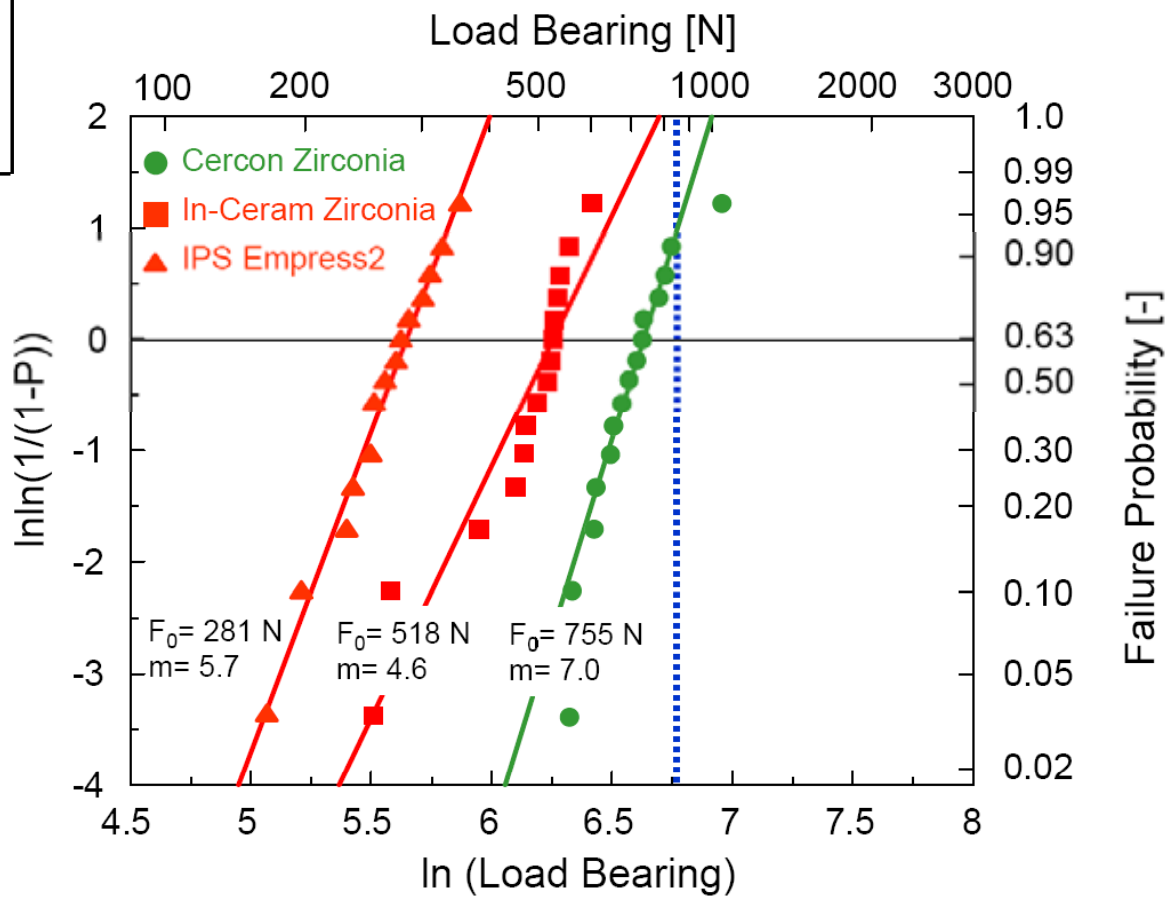


adapted from
H. Lüthy et al., Dental Materials, 21 (2005) p930

Strength

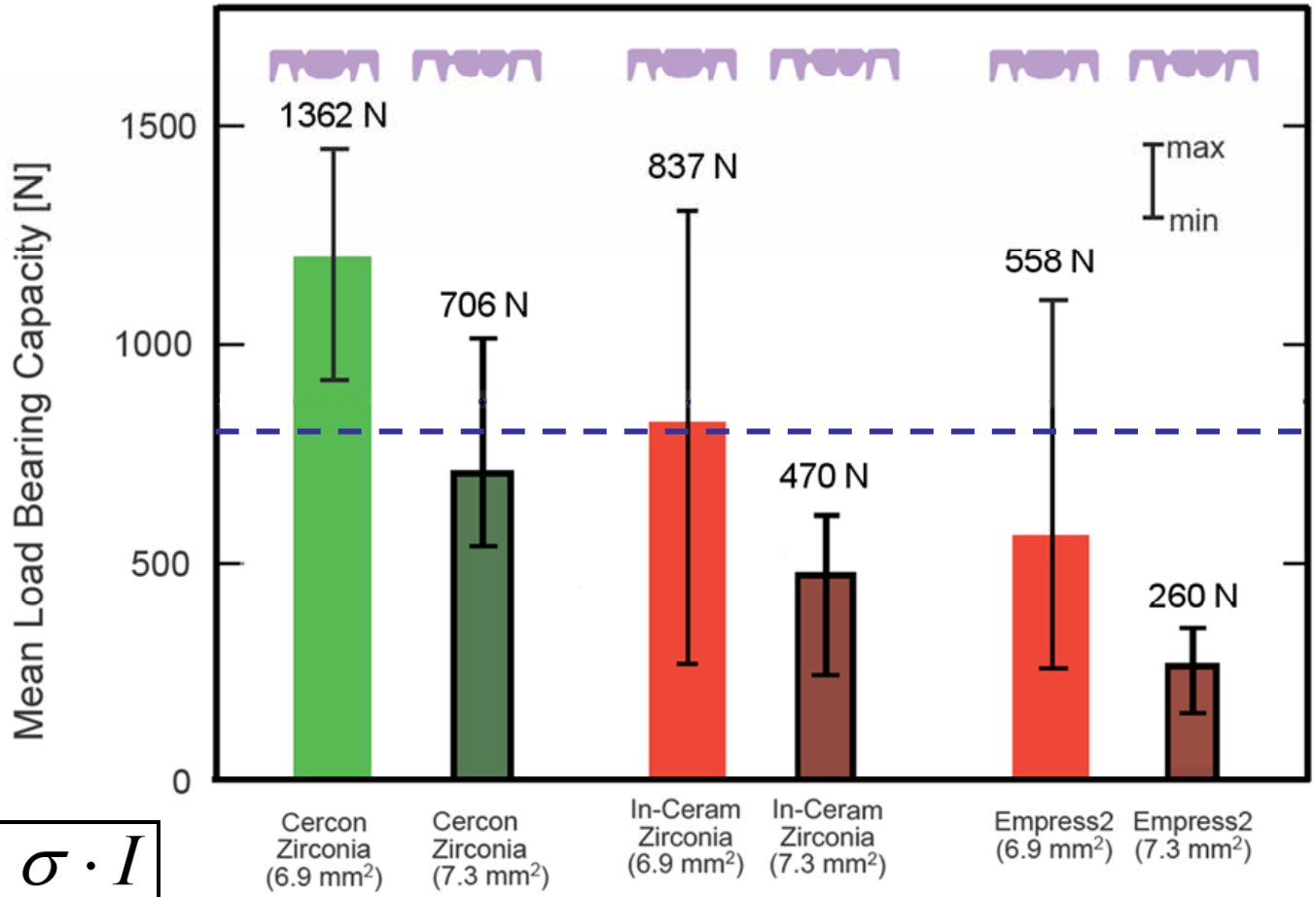
Load Bearing Capacity and Reliability of 4-Unit Frameworks





H. Lüthy et al.
Dental Materials, 21 (2005) p930

Mean Load Bearing Capacity of 3- and 4-unit Frameworks



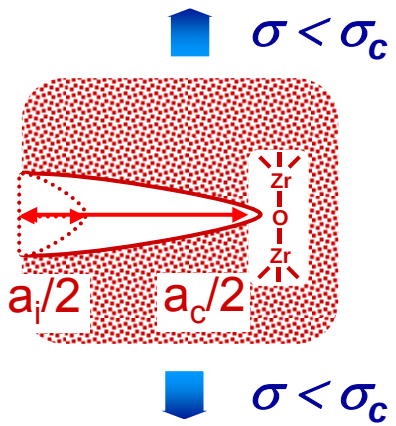
$$F = \frac{\sigma \cdot I}{l \cdot e}$$

First conclusions

- Cercon Zirconia is the superior material
- in-vitro load bearing capacity and reliability of Cercon Zirconia 3-unit bridges are superior
- 7 mm^2 connector area is sufficient for 3-unit Cercon bridges
- 7 mm^2 connector area is NOT sufficient for Cercon 4-unit bridges
- 4-unit bridges need larger connector areas, or less span width or stronger materials

And what about lifetime ?

Subcritical crack growth

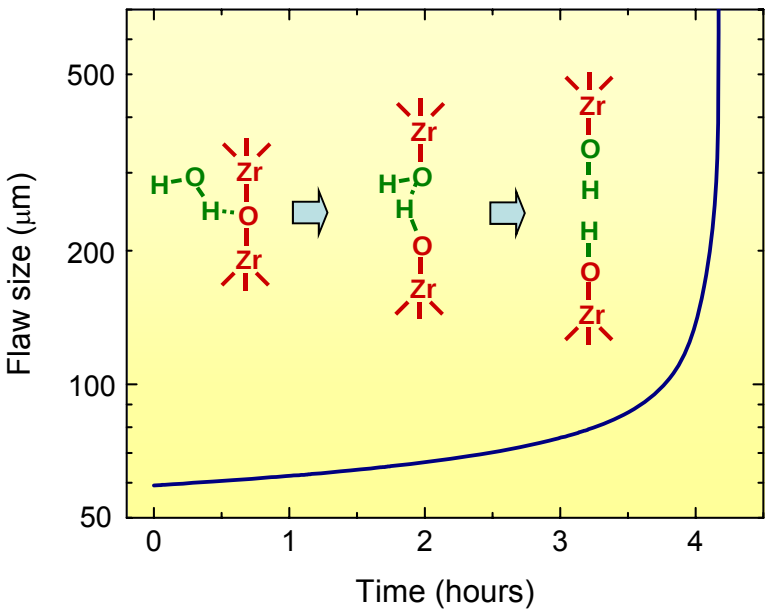


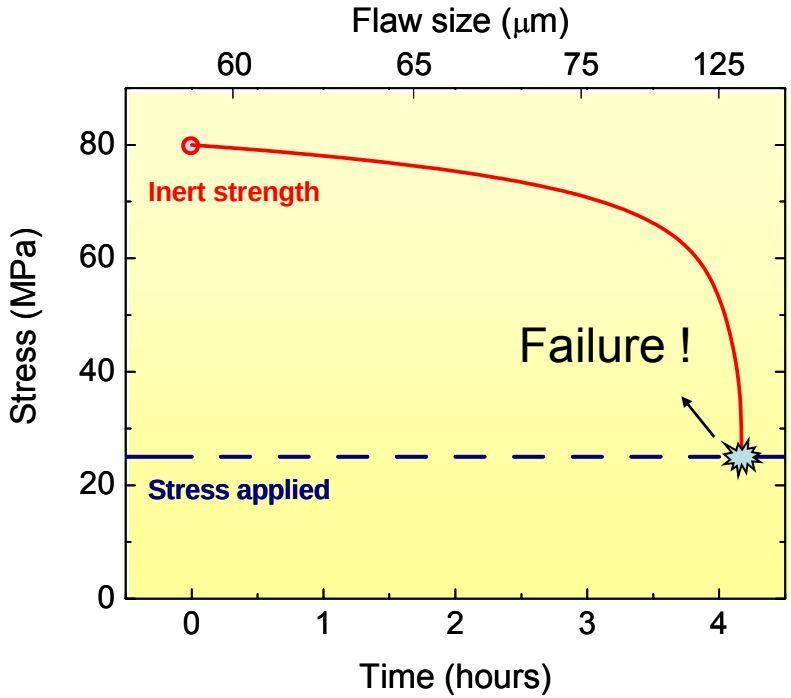
$$\sigma_c = \frac{K_{IC}}{Y\sqrt{a_c}}$$

Griffith's law

How fast does the crack propagate under subcritical conditions ?

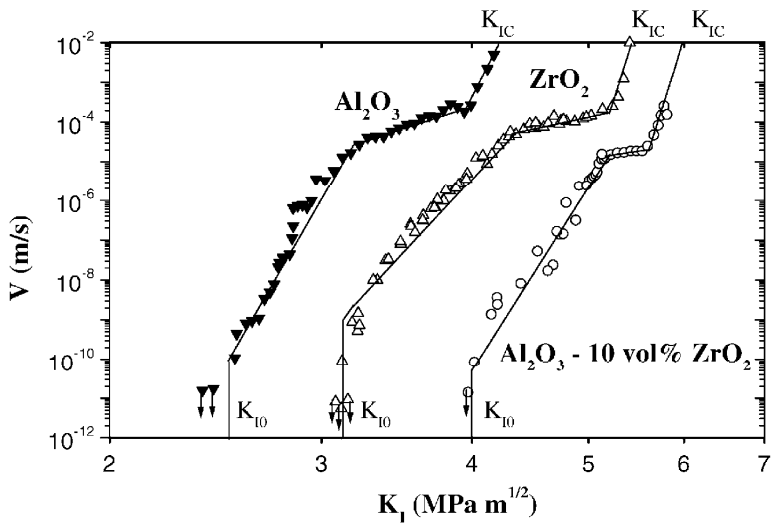
$$v = f(K_I) \ ?$$



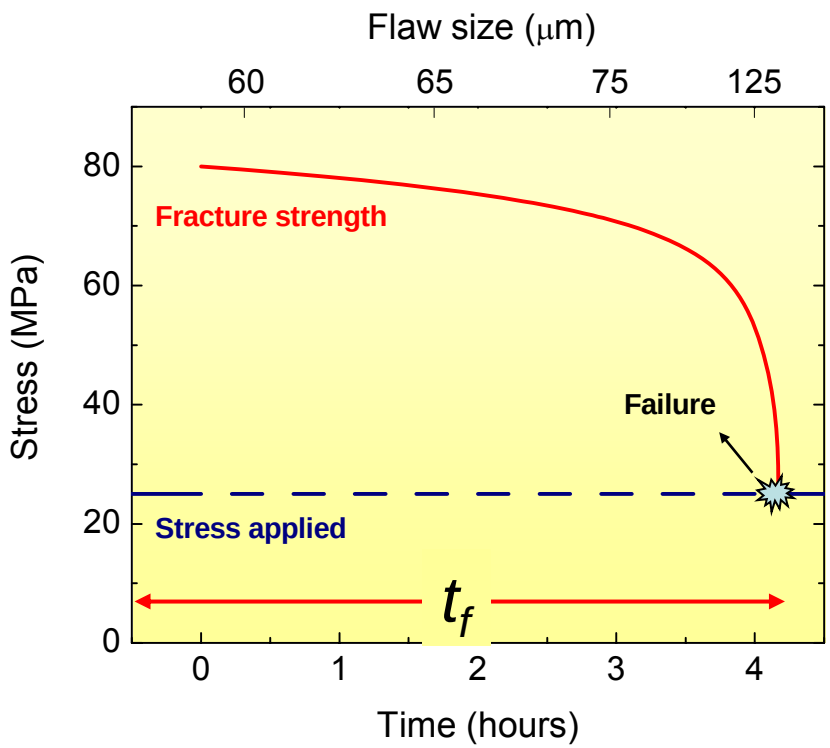


Lifetime prediction

$$v = f(K_I) \ ?$$



De Aza et al., Biomaterials 23, 937 (2002)



$$v = A.K_I^{\,n}$$ Empirical relation

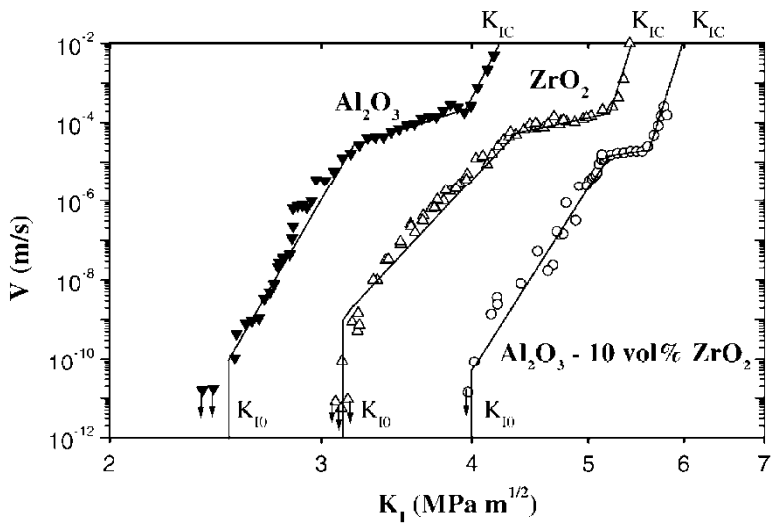
$$\sigma_c = \frac{K_{IC}}{Y\sqrt{a_c}}$$ Griffith's law

$$t_f = \left(\frac{2}{AY^2(n-2)}K_{IC}^{2-n}\right)\sigma_c^{n-2}\sigma^{-n} = B\sigma_c^{n-2}\sigma^{-n}$$

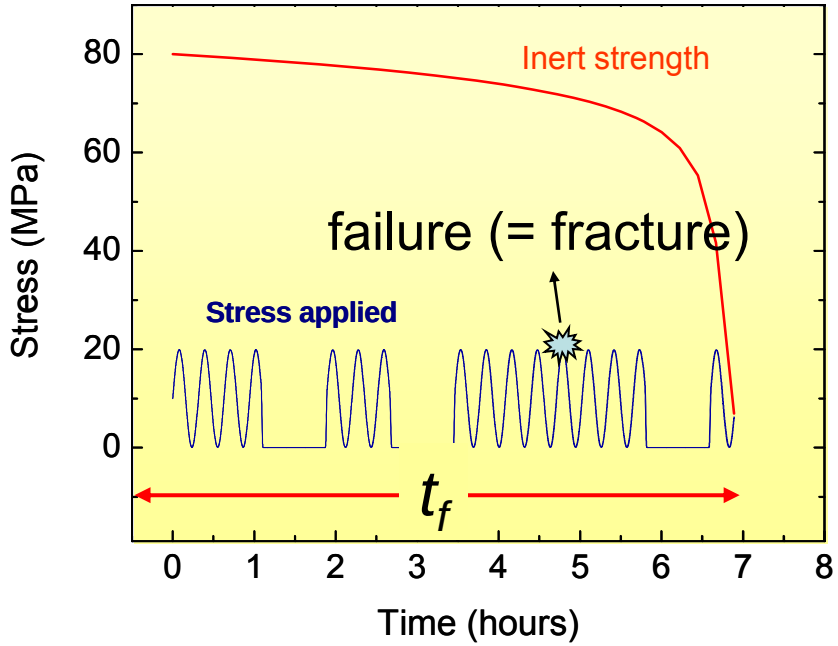
For constant stress σ!

Lifetime prediction

$$v = f(K_I) \ ?$$



De Aza et al., Biomaterials 23, 937 (2002)



$$v = A.K_I^{\,n}$$ Empirical relation

$$t_f = B\sigma_c^{n-2}\sigma^{-n}$$ *Constant stress σ*

$$\sigma_c = \frac{K_{IC}}{Y\sqrt{a_c}}$$ Griffith's law

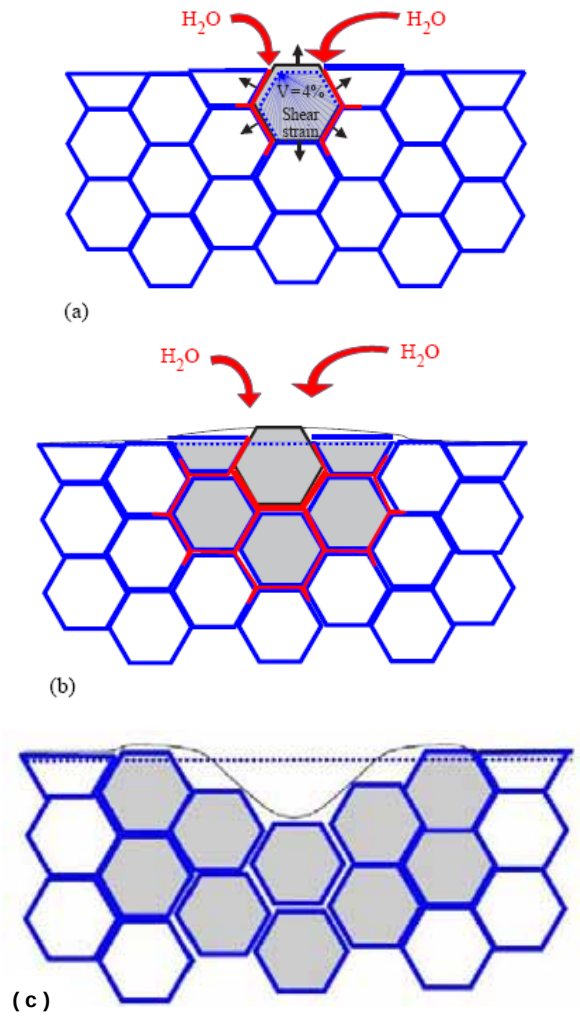
$$t_f = \frac{1}{h(n,\sigma_m/\sigma_a)} B\sigma_c^{n-2}\sigma_a^{-n}$$ *Any given stress variation*

Theory Lifetime

Scheme of the ageing process

a) Nucleation on a particular grain at the surface, leading to microcracking and stresses to the neighbours
b) Growth of the transformed zone, leading to extensive microcracking and surface roughening.
c) Grain pull-out induced by wear

Chevalier, Leading Opinion: What future for zirconia as a biomaterial? Biomaterials 27 (2006) 535–543

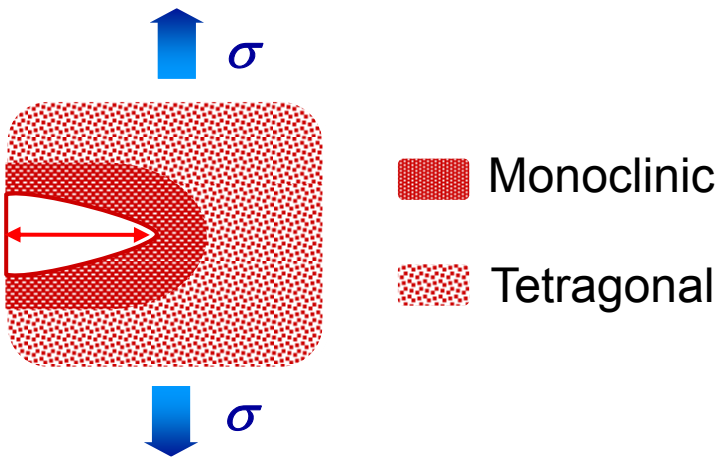


water induced

t → m

transformation

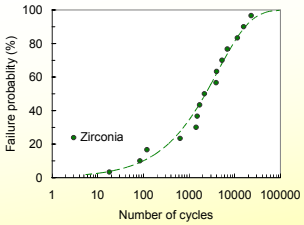
(degradation of strength)



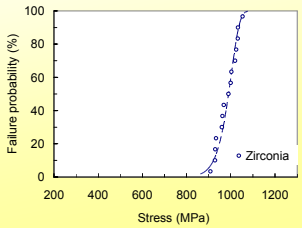
Experimental Approach

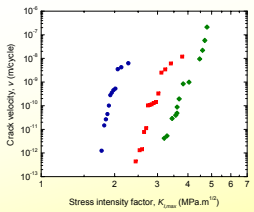
Sample preparation

Set-up fatigue machine



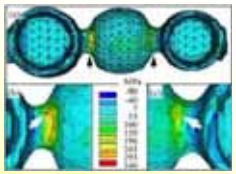
Strength and lifetime measurements





Subcritical crack growth curves

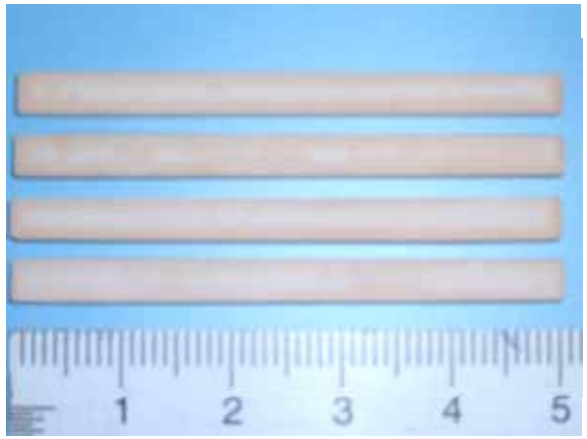
Stresses on posterior bridges



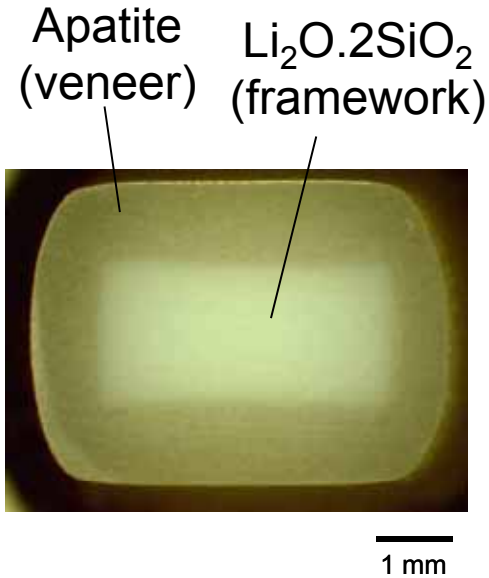
Lifetime diagrams

Sample preparation

Framework



Framework + veneer

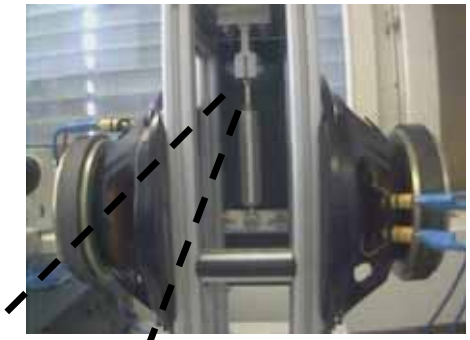


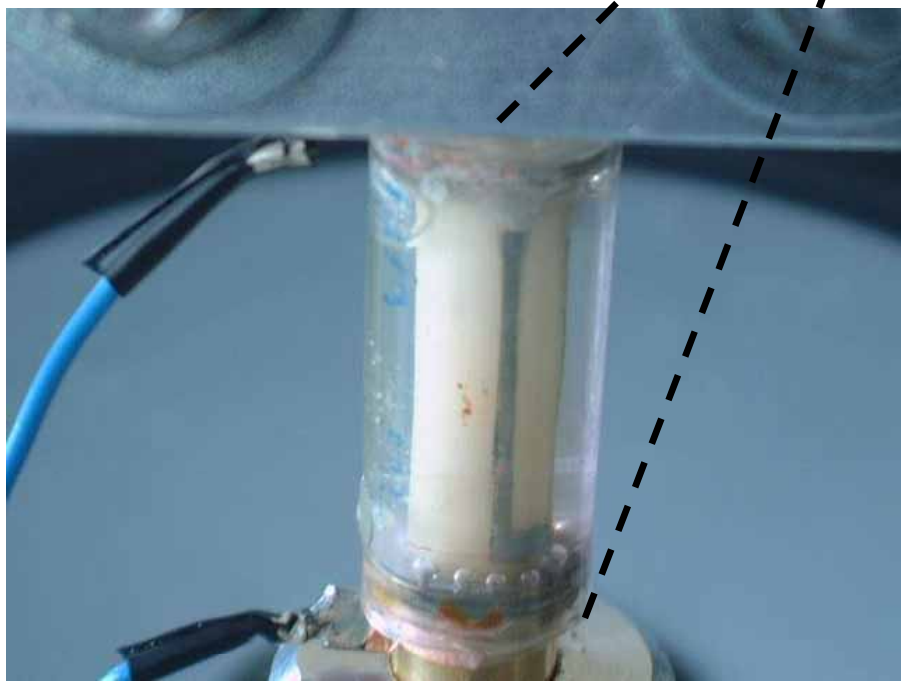
inert strength + lifetime in water
X
coated + uncoated
X
3 materials + TZP rods
=
240 samples (effective 232)

Experimental

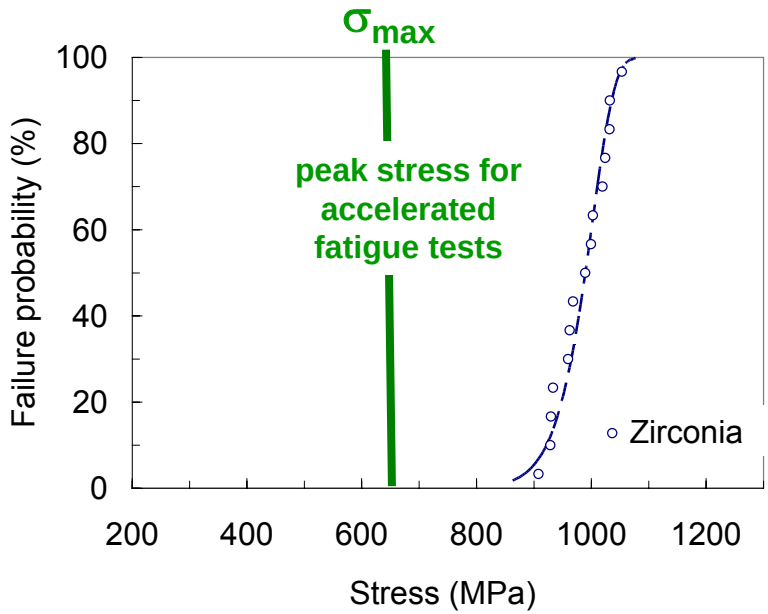
Detection of sample breakage

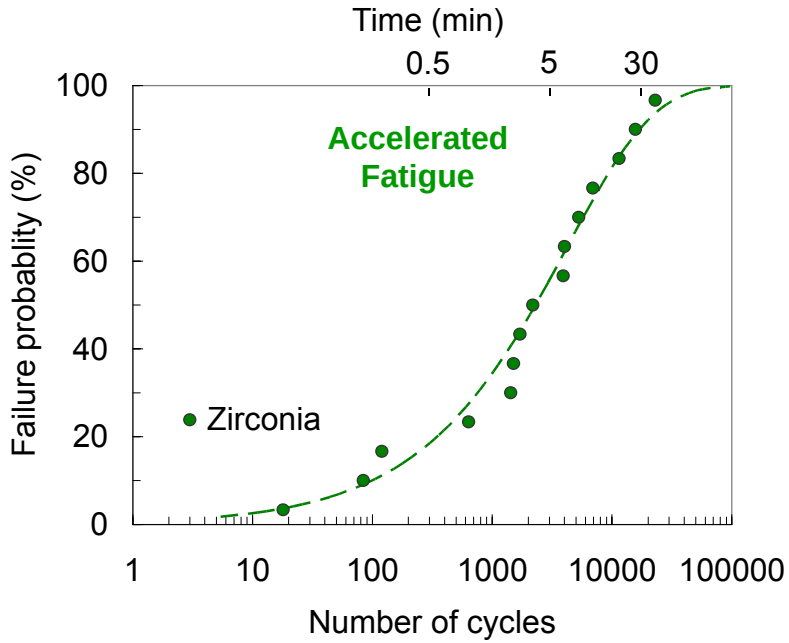
Aqueous environment



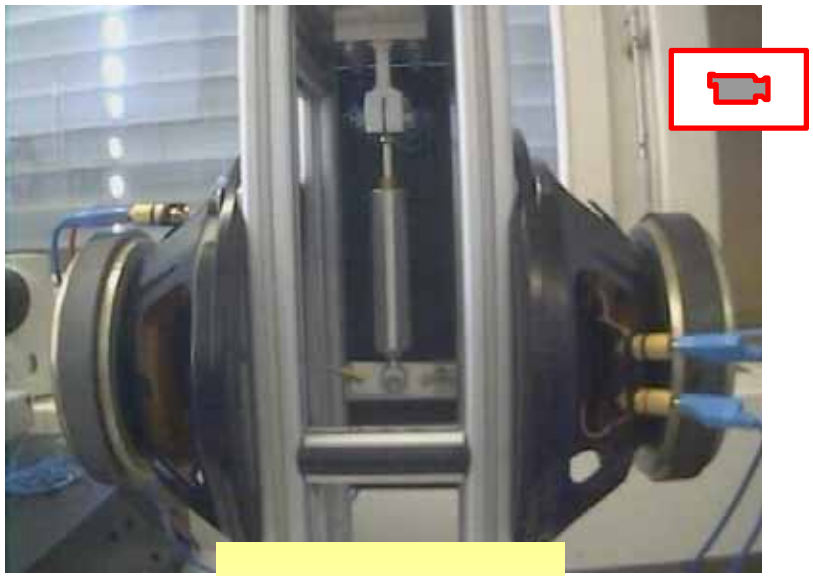


Experimental



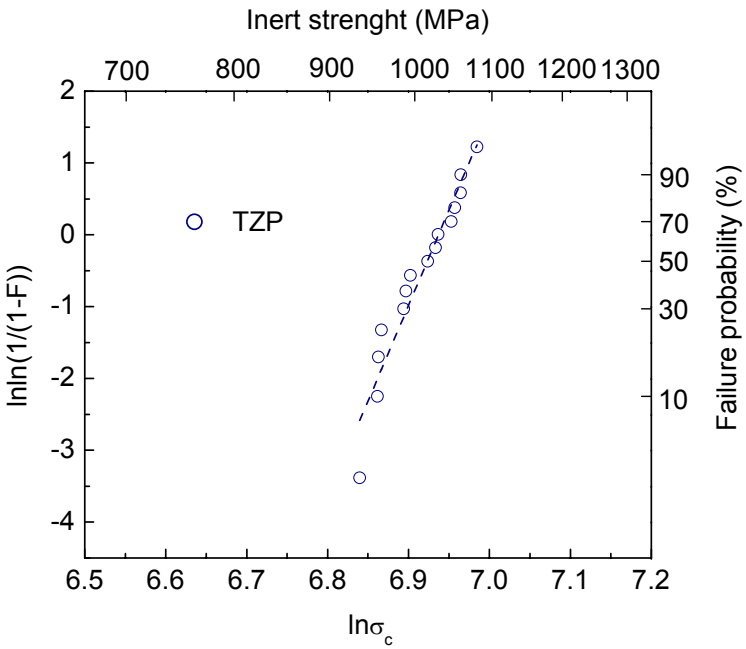


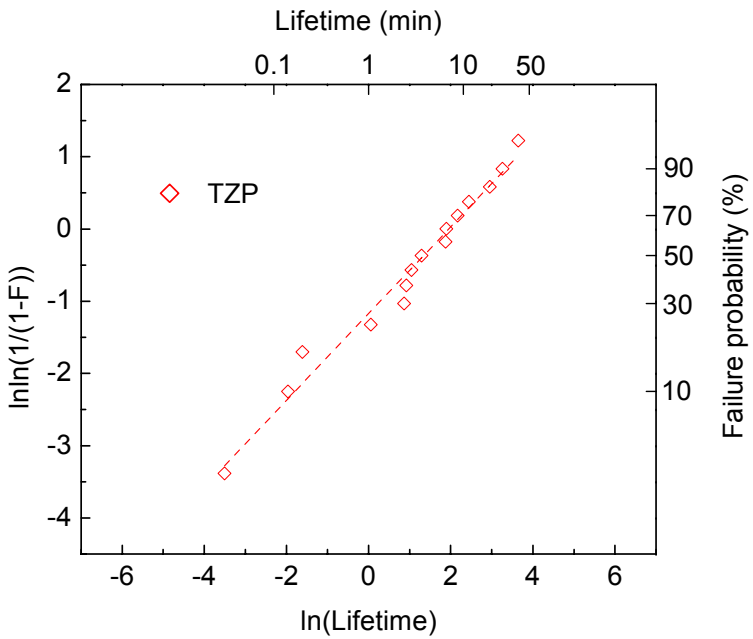
Mechanical strength

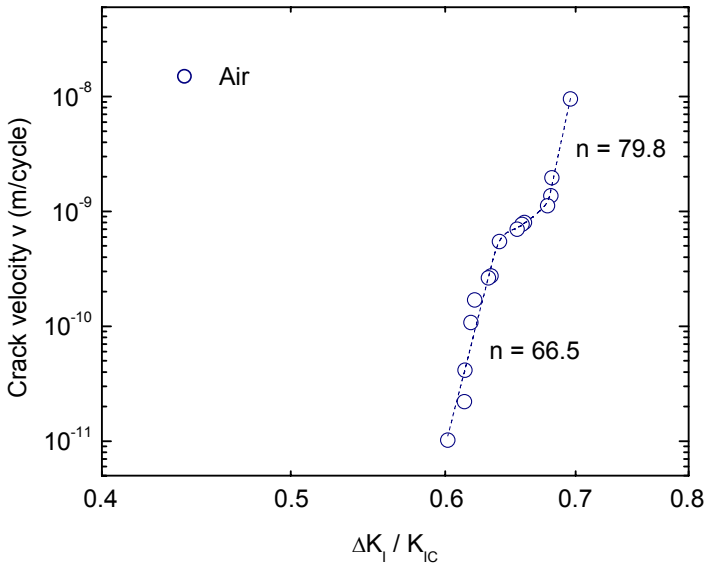


Fatigue

Determination of SCG behavior e.g. TZP



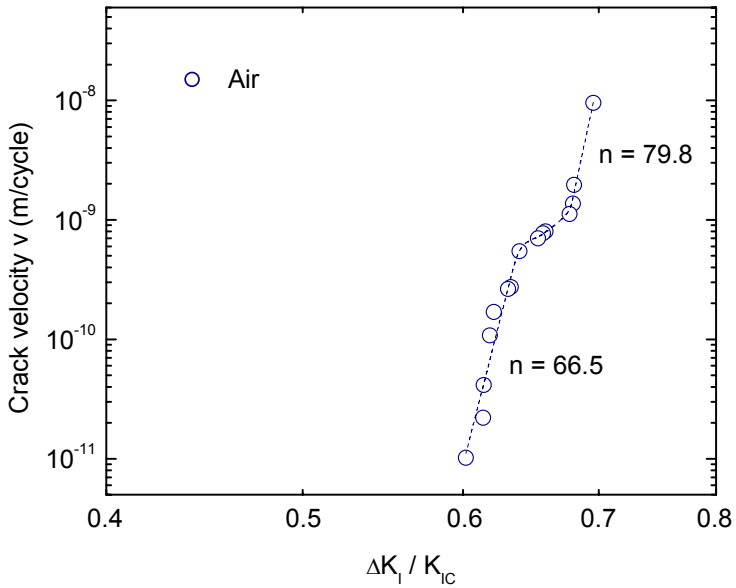


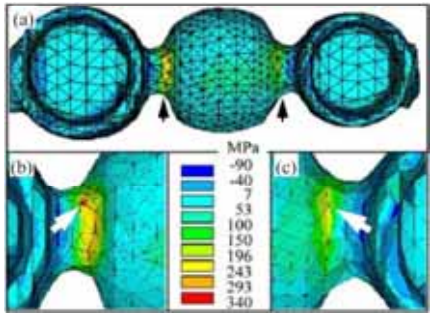


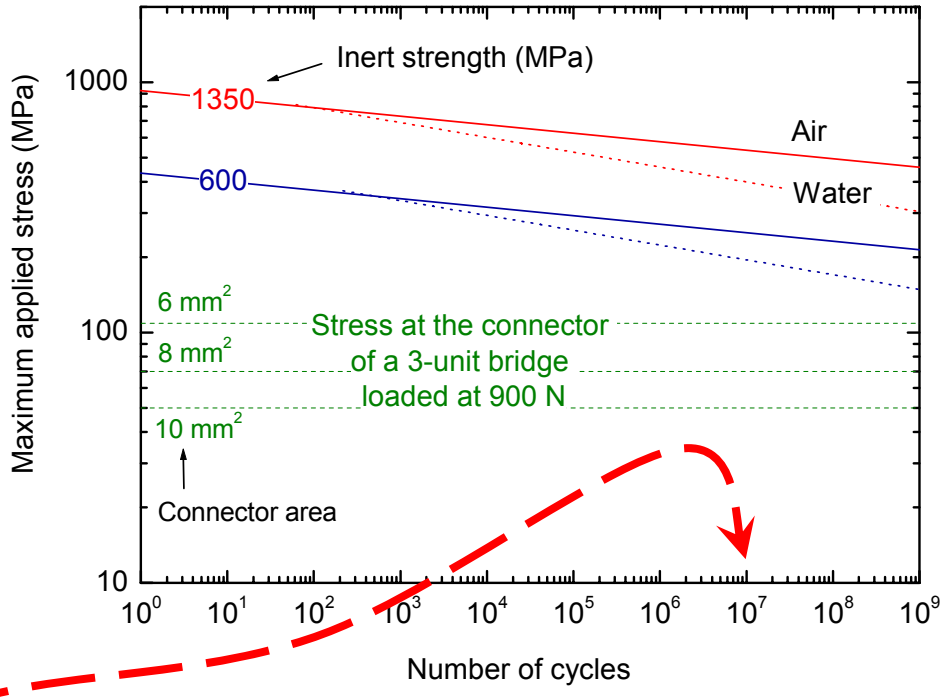
Describes the properties of the material !

Results

Lifetime prediction of dental materials





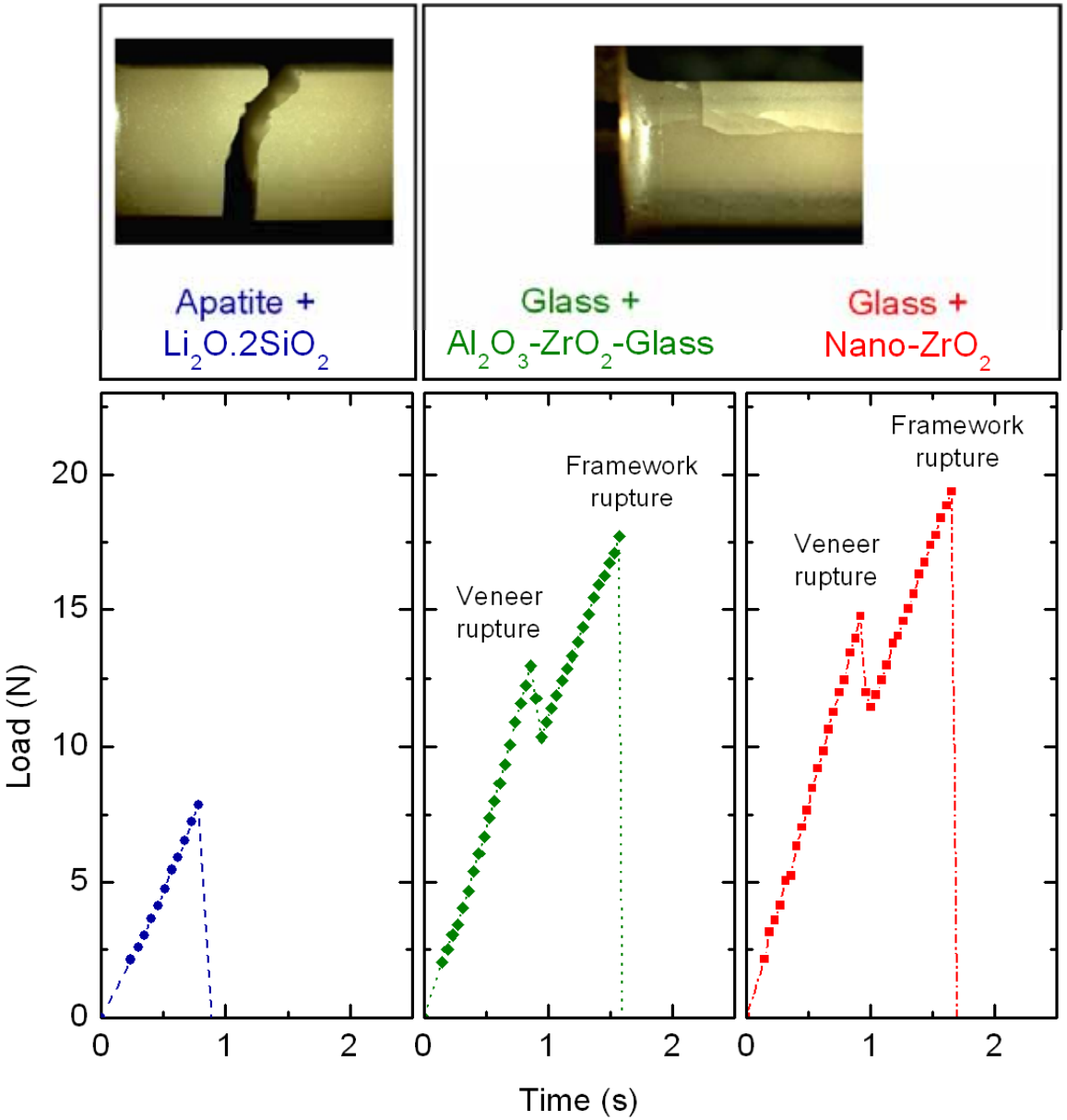


Materials‘ properties

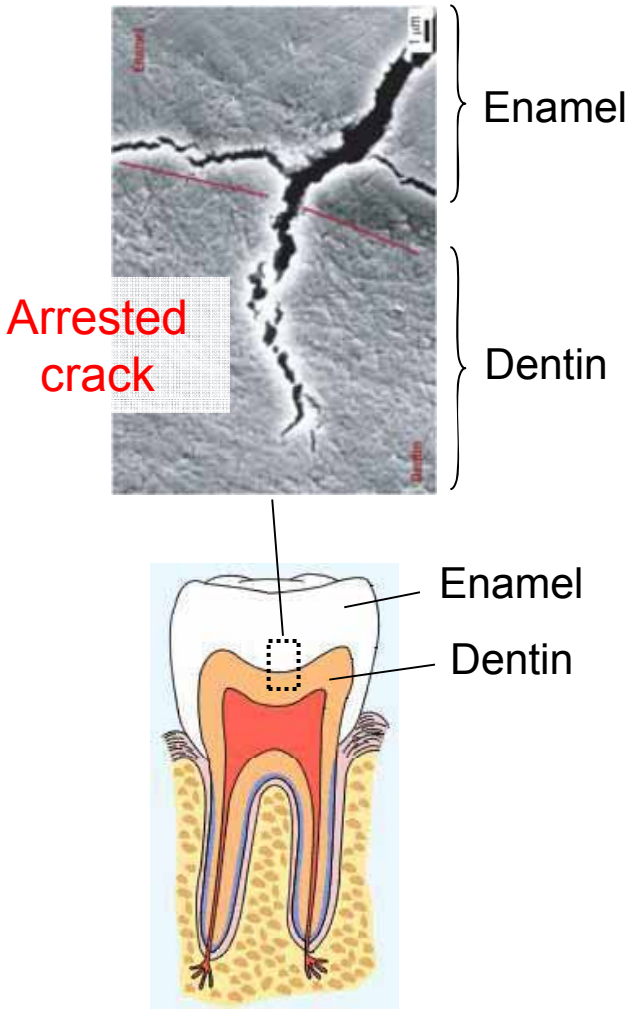
20 years with
1’400 cycles/day

Predict lifetime for any bridge !

Fracture mode



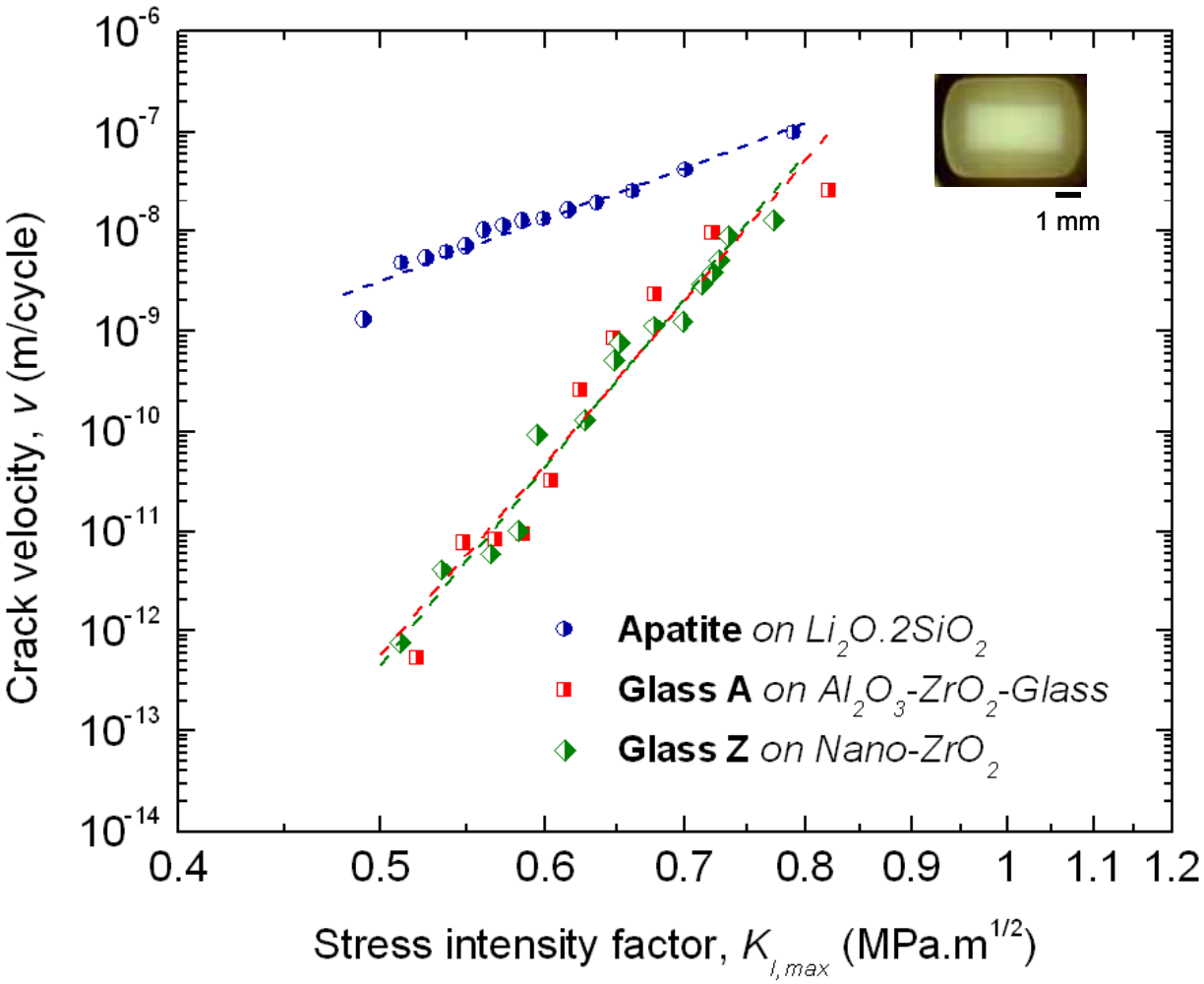
Imbeni et al,
Nature Materials, 4, 229 (2005)



Results

Fatigue and subcritical crack growth

Veneer



$$10Ca^{2+} + 6PO_4^{3-} + 2OH^{-}$$

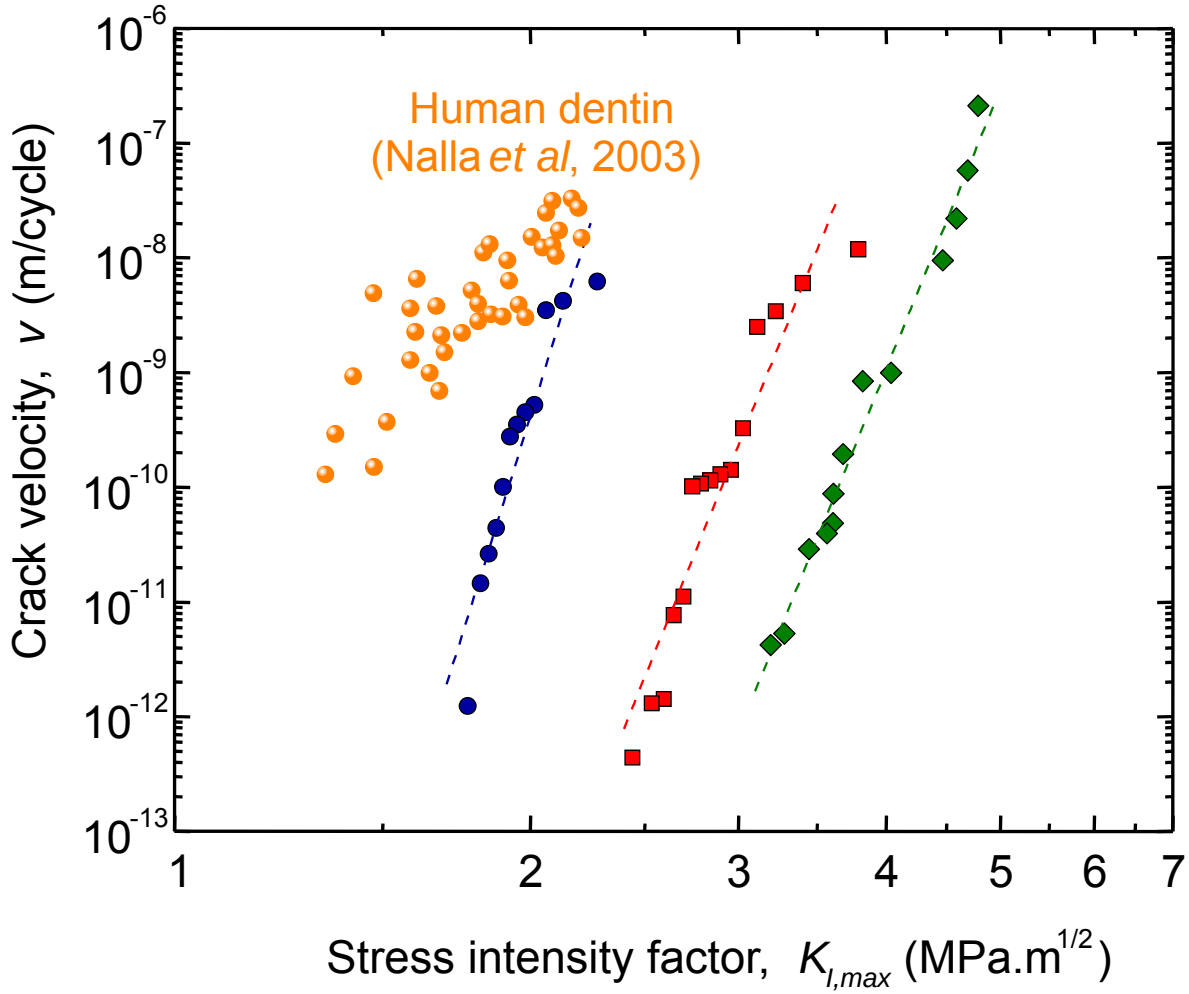
$$\rightleftharpoons$$

$$Ca_{10}(PO_4)_6(OH)_2$$

Enamel: Apatite

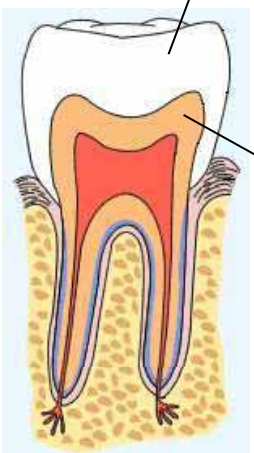
Fatigue and subcritical crack growth

Framework



- $Li_2O.2SiO_2$
- Al_2O_3-ZrO_2-Glass
- Nano-ZrO_2

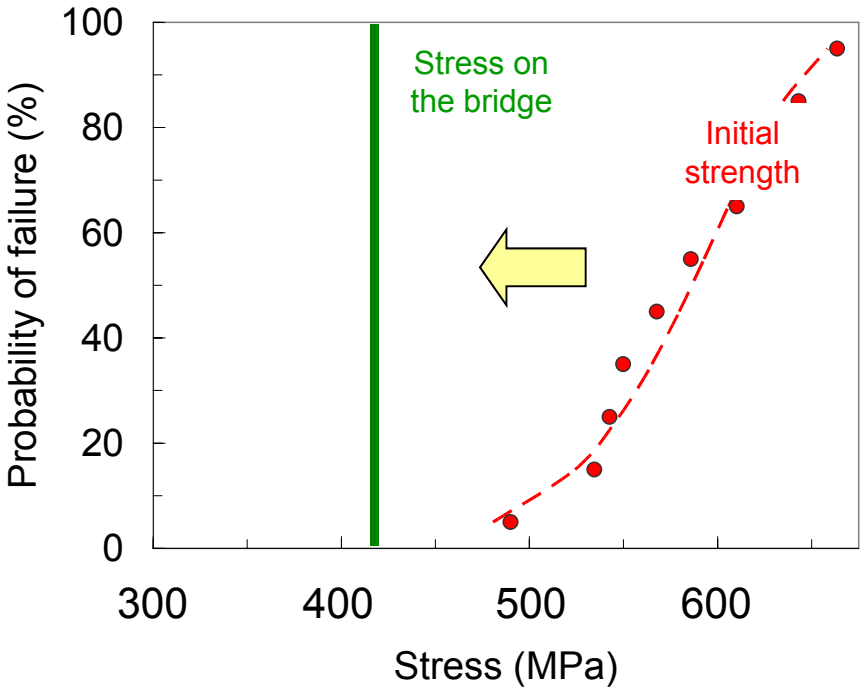
Enamel: Apatite

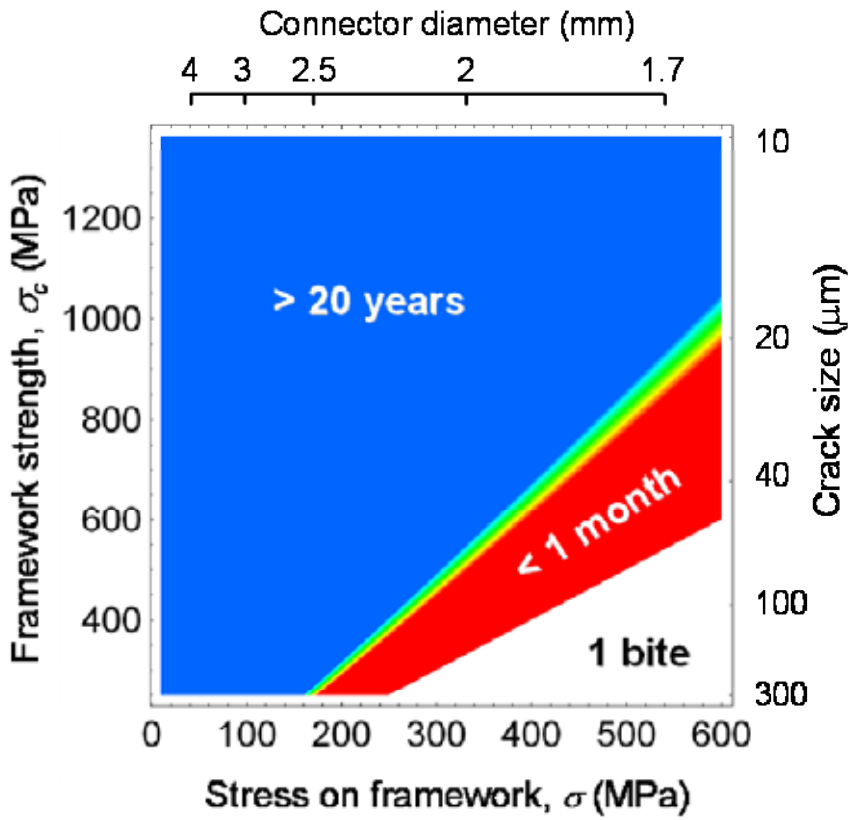


Dentin:
~ 75 % Apatite
+ 25 % collagen

Lifetime diagram

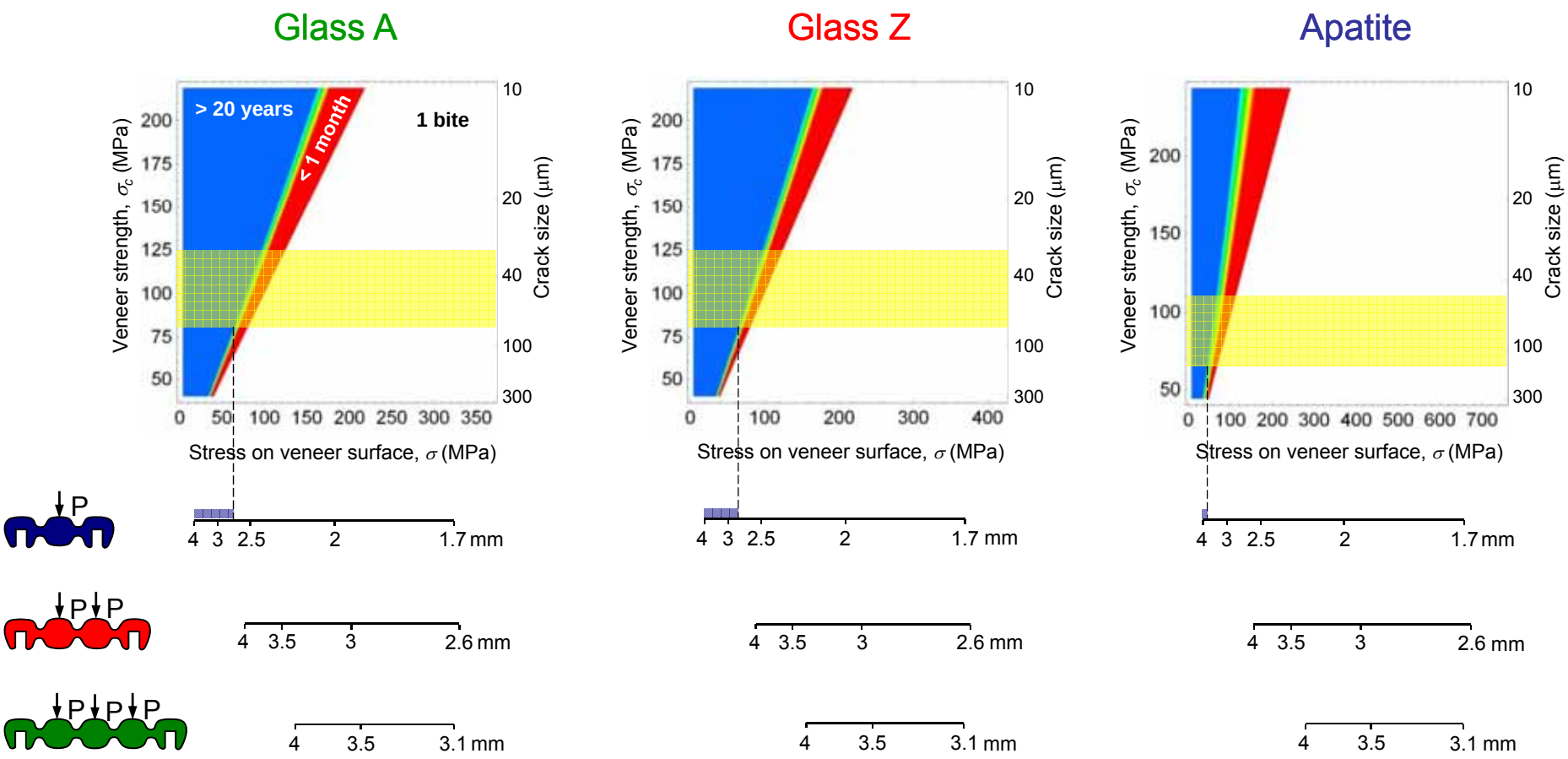
20 years with
1'400 cycles/day and
$Load_{max}$ = 130 N





Nano-ZrO_2

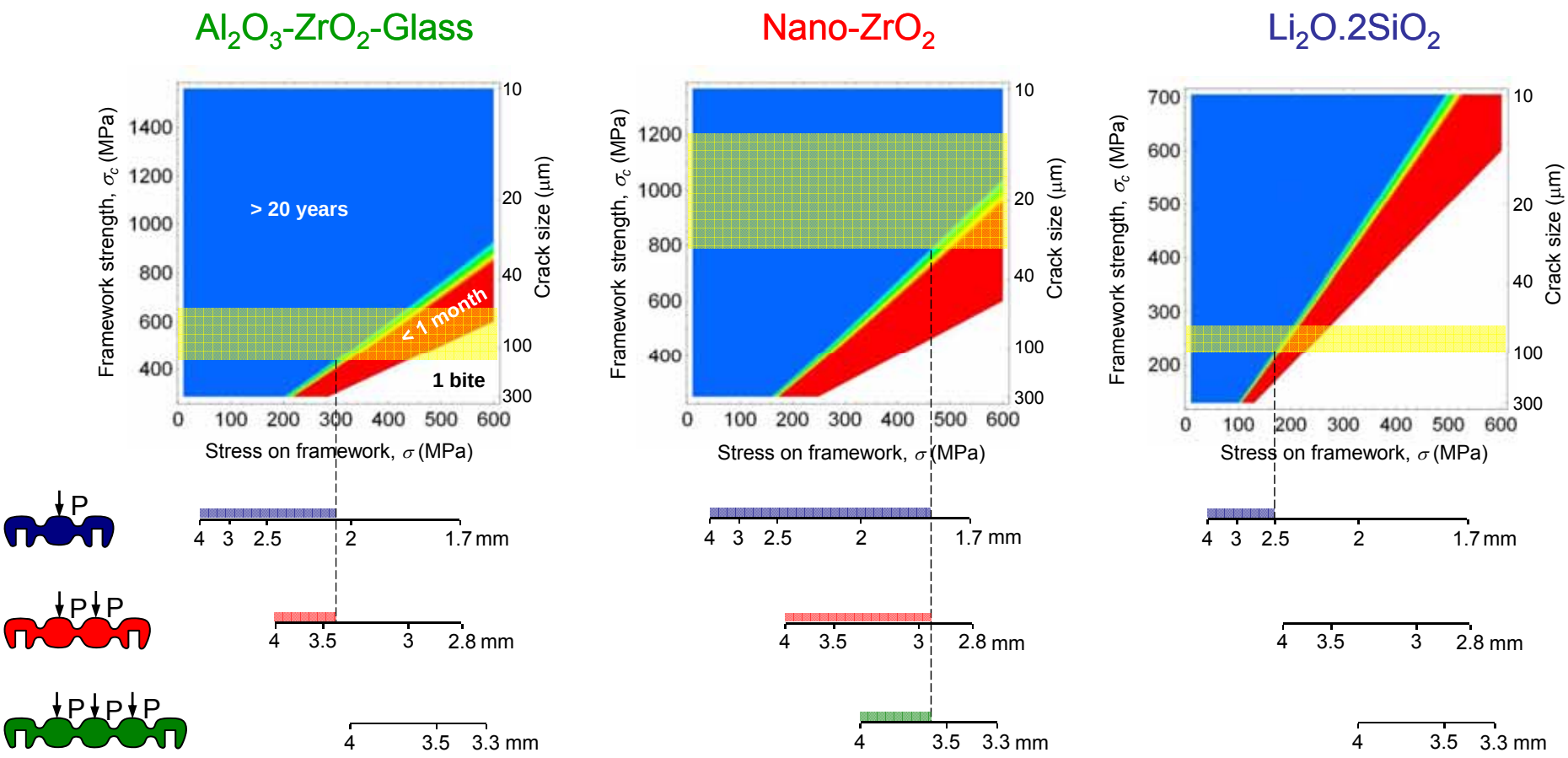
Lifetime diagram : **Veneer**



1400 cycles/day

$Load_{max}$ = 130 N

Lifetime diagram : **Framework**

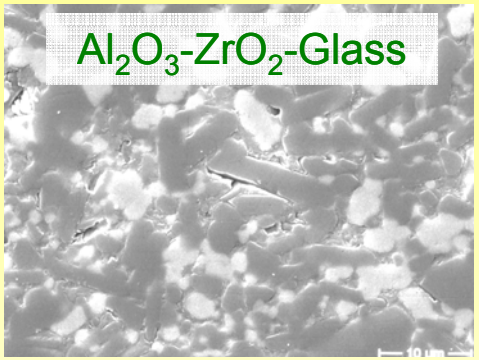


1400 cycles/day

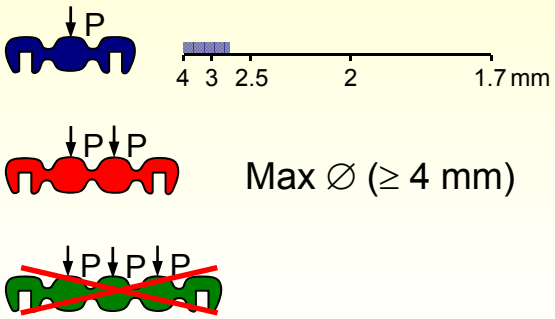
$Load_{max}$ = 130 N

Summary

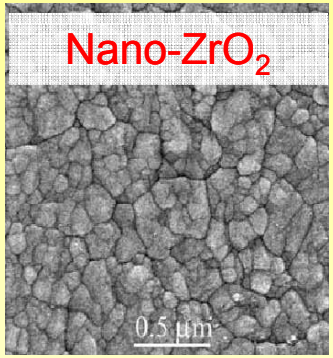
Framework:



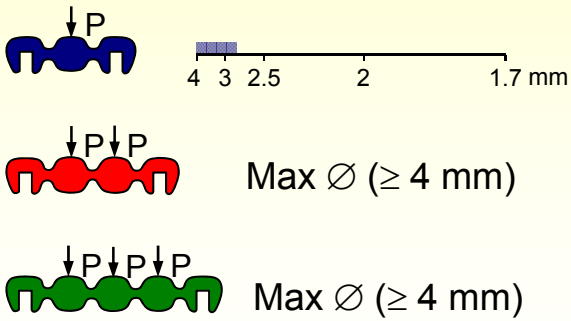
Veneer: Glass A



Framework:

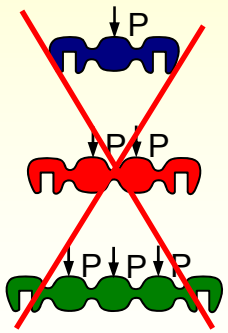


Veneer: Glass Z



Framework:

Veneer: Apatite



1400 cycles/day

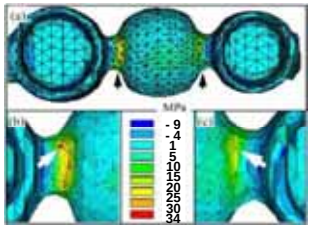
$Load_{max}$ = 130 N

Veneer and not framework dictates what's feasible …..

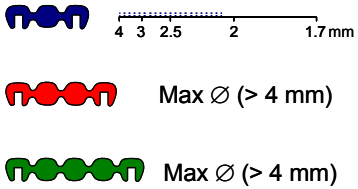
Courtesy: University of Zürich, Center for Dental & Oral Medicine

Conclusions

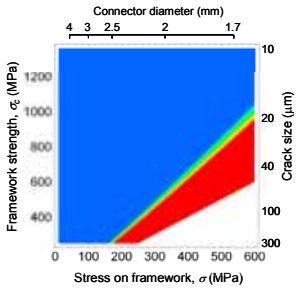
Nano-ZrO_2 ceramics and ZrO_2-based ceramic composites can withstand the high stresses applied on posterior bridges during mastication



Long-term failure due to fatigue and subcritical crack growth can be avoided through proper bridge design



Lifetime diagrams are suitable tools for the selection of new materials and fabrication technologies for dental restorations



Apatite-based materials should be avoided in the connector region of posterior bridges due to the pronounced subcritical crack growth

$$Ca_{10}(PO_4)_6(OH)_2$$
$$\rightleftarrows$$
$$10Ca^{2+} + 6PO_4^{3-} + 2OH^-$$

Outlook

Etruscian prosthesis	Metal-porcelain bridge	All-ceramic bridge
200 BC	1960s	2005

Ceramic high strength, non veneer bridge ?

Natural tooth genesis mediated by stem cells ?

20yy

2zzz

different materials -
strength not anymore the issue -
treatment methods shifting -

- wishful
- 1st steps successful
- lots of challenges ahead

Summary:
What you know and understand, now!

This you should have learned!

- ✓ Hook's law …
- ✓ Stress …
- ✓ Griffith's law … ★
- ✓ Weibull statistic … ★
- ✓ Influence of surface, volume, microstructure … ★
- ✓ R-curve …
- ✓ Environment …
- ✓ Sub-critical crack growth …
- ✓ Static & dynamic fatigue …
- ✓ Proof-testing …
- ✓ Deformation & failure @ elevated temperatures …
- ✓ Thermal shock …

★ ***Those relations, laws & equations you known by heart, now!***