The Abdus Salam
International Centre for Theoretical Physics

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Winter College on Fibre Optics, Fibre Lasers and Sensors

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Some Applications of Fibre Optic Sensors in Biomechanics

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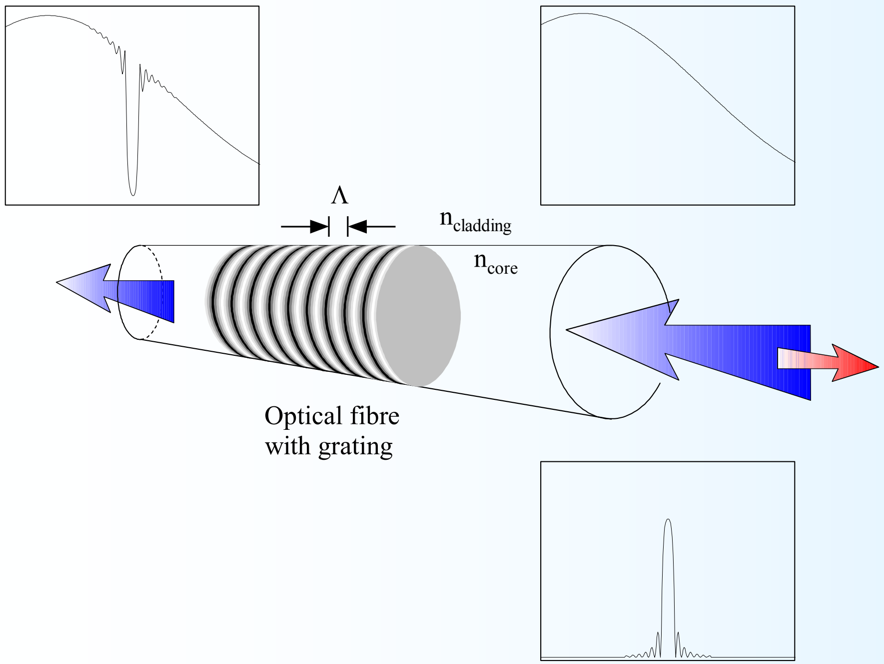
Outline

- FBG Applications in Bioengineering
- Electrically Assisted Ventilation
- Biomechanics after dental implants
- Orthodontic studies for corrective appliances
- Prosthesis biomechanics

Fibre Bragg Gratings



$\lambda_B = 2\ n\ \Lambda$

- Periodic modulation of refractive index in fibre's core
- Selective reflection filter in the optical domain
- Stable, strong, reliable, spectrally encoded, low cost device
- Sensitivity to physical agents
  - Bragg wavelength shift
  - Temperature (10 pm/C)
  - Strain (1 pm/C)
  - Frequency encoded, self calibrated sensor

Bragg Gratings in Bioengineering

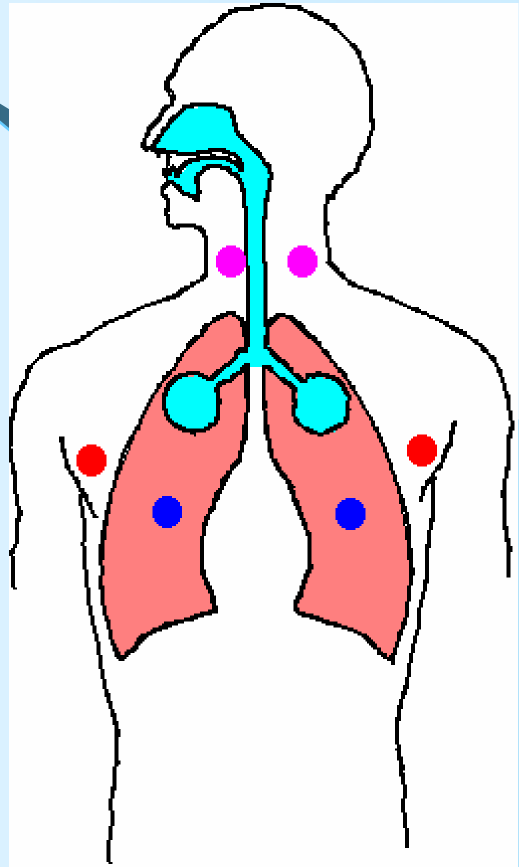
- Advantages
  - Reduced size & weight
  - Thin fibre (SMF) coupling
  - Low cost (sensor head)
  - Excellent SNR
  - Self referenced
  - Sensible to temperature or strain (& others)
  - Multiplexing
- Drawbacks
  - Requires current powered optical source
  - Frequency encoded signal
    - Expensive, cumbersome spectral analysis
      - Size of apparatus
      - Optical link
    - Spectral demodulation with filters (FBG)
      - Calibration and stability issues
      - RF accessed

FBG Applications in Biomedicine

- Monitoring of respiratory spectrum and electrically assisted ventilation triggering
- Orthopaedics studies
- Orthodontics applications
  - Control & surveillance of apnoea device
  - Studies of orthodontics materials, devices and procedures
- Studies of prosthesis devices and procedures
  - Better knowledge about integration
  - Optimised design of devices
  - Customized prosthesis

Electrically Assisted Ventilation FBG Trigger

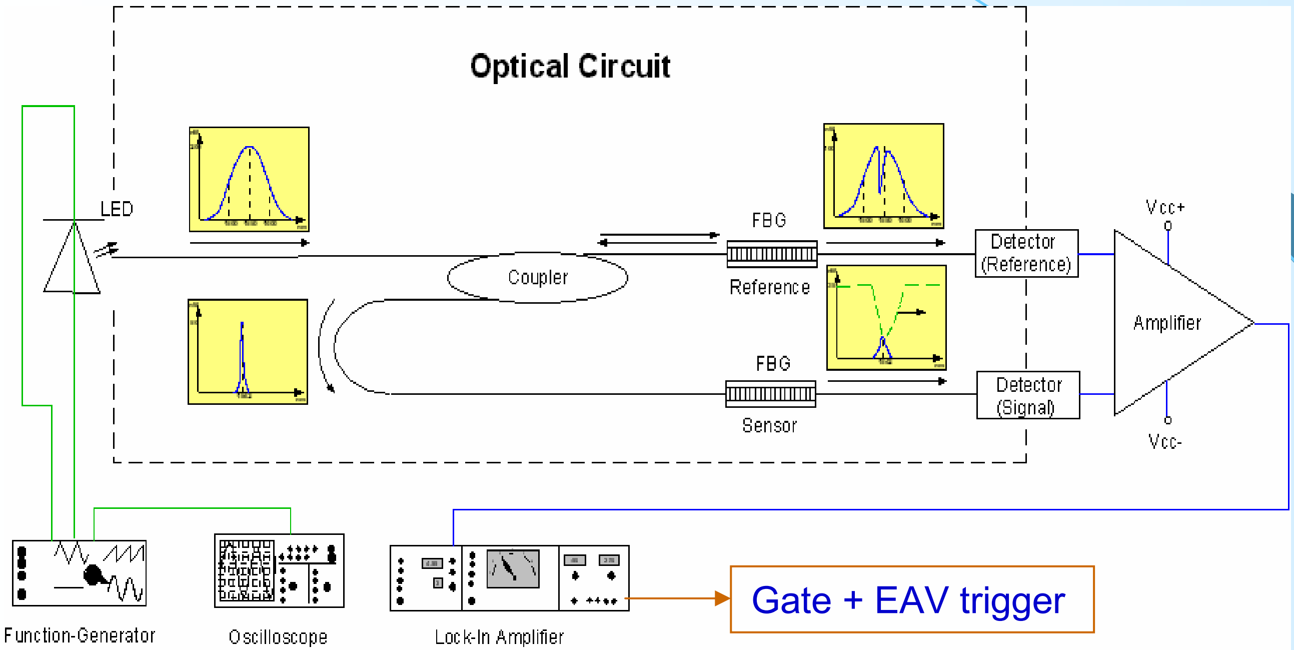
- ⇨ Burst of electrical pulses to stimulate respiratory nerves.
- ⇨ Inspiration induction (intrathorax negative pressure).
- ⇨ Accidents cause respiratory arrest, electrically assisted ventilation helps to resume normal process.
- ⇨ Electrical pulses applied on the patient's chest.
- ⇨ Short pulses (10 μs), 20-40 pps

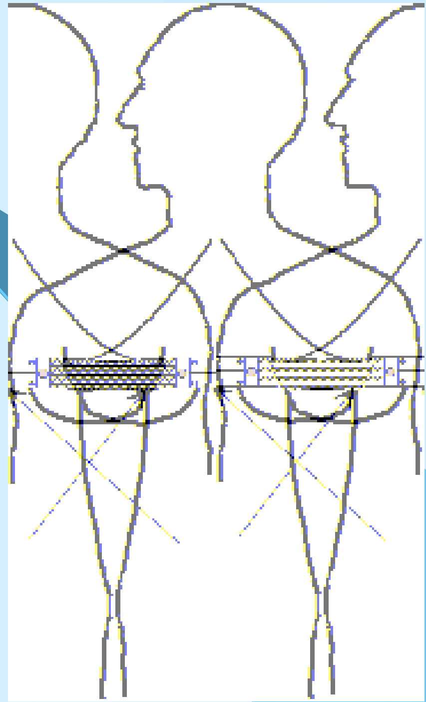


Aim of the Project

- ⇨ Fibre Optic Sensor to monitor the strain of the thorax
  - ✓ electromagnetic immunity
  - ✓ potential reduction in volume and weight
- ⇨ Monitoring the respiratory process.
- ⇨ Trigger for electrically assisted ventilation pulses.

Sensor



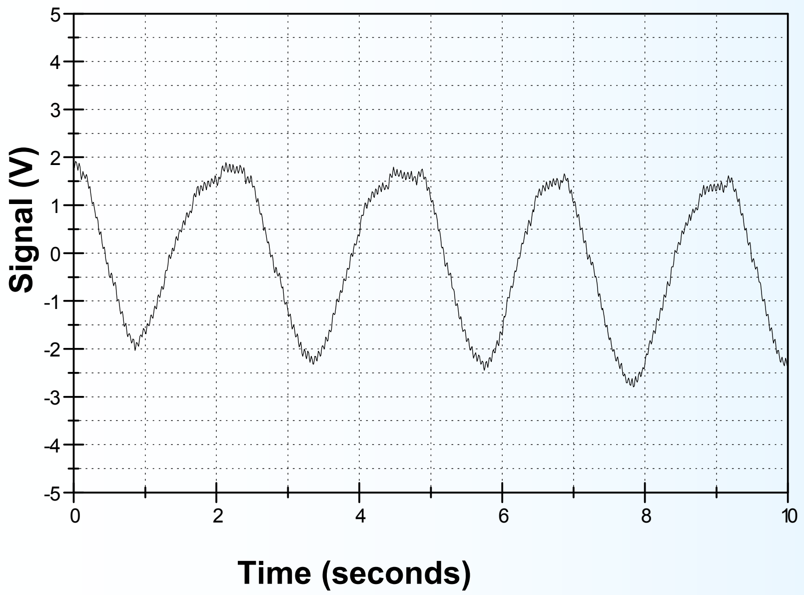


Schematics, fixed filter demodulation

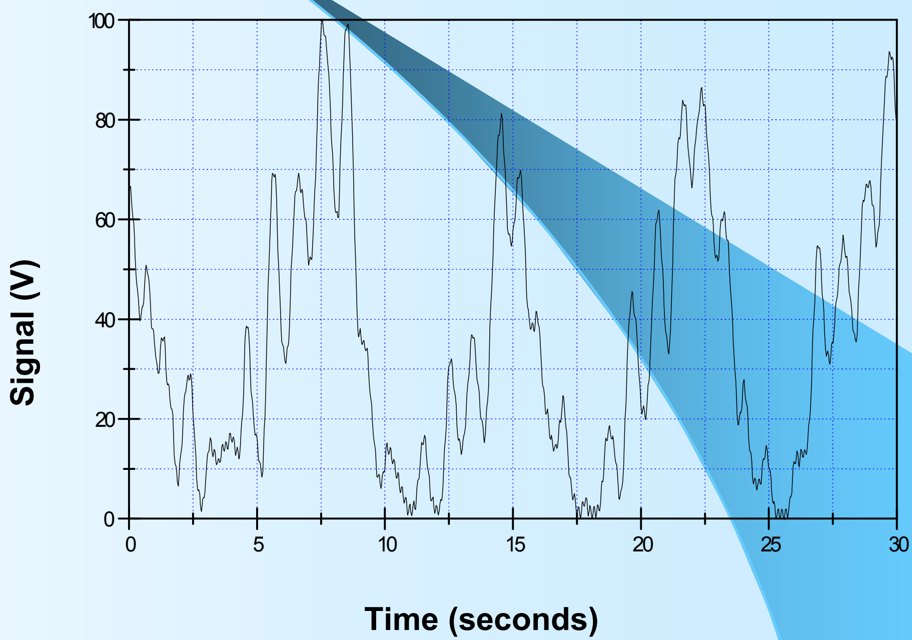
Can be used as an 'holster' type data logger for respiratory monitoring

Sensor placement on patient's chest

Results



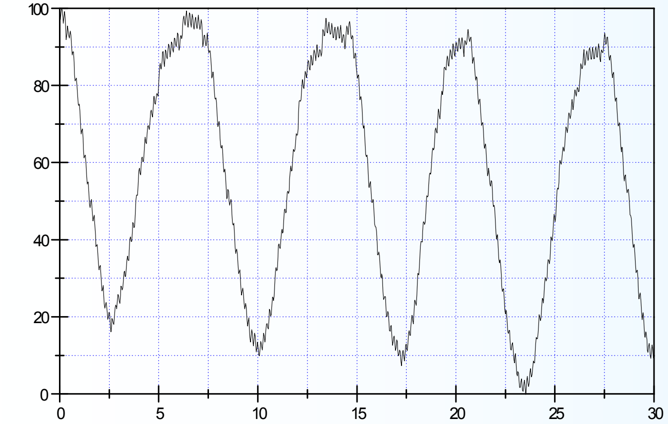
Normal Respiratory Signal
Rest Situation

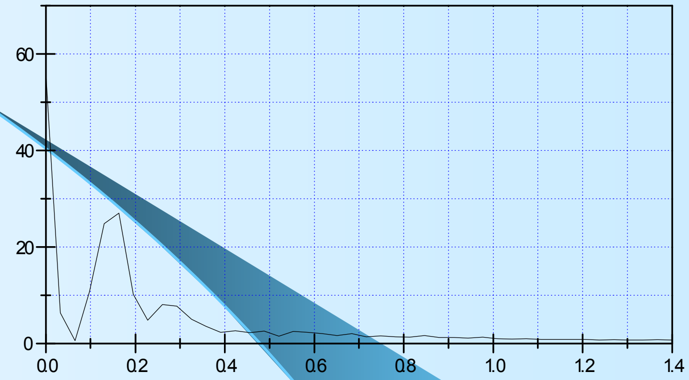


Signal when subject
turns the arm

G. Wehrle et al. Meas. Sci. Technol. 12, 805 (2001)

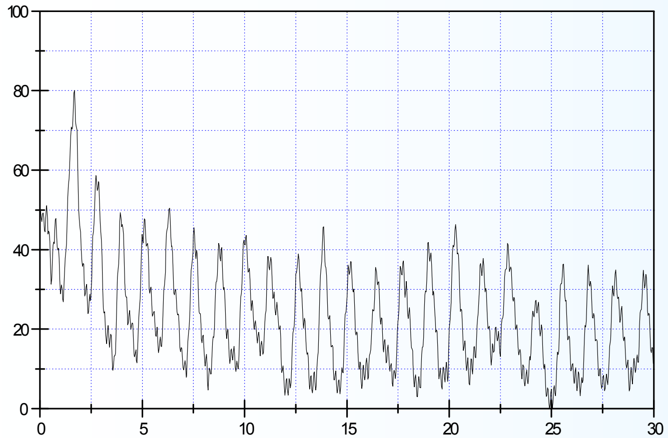
Results

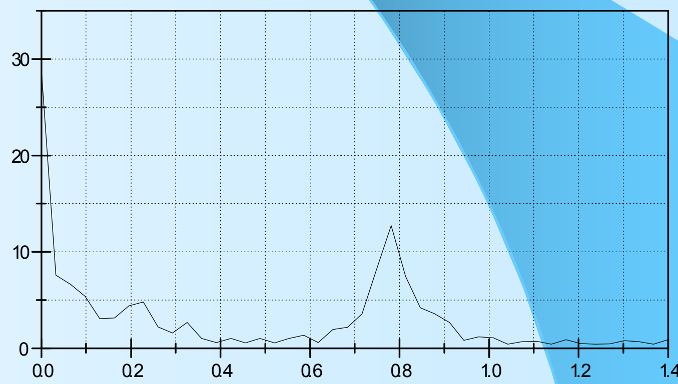




Rest Condition

Slow Breathing





Volume limitation (60 ml)

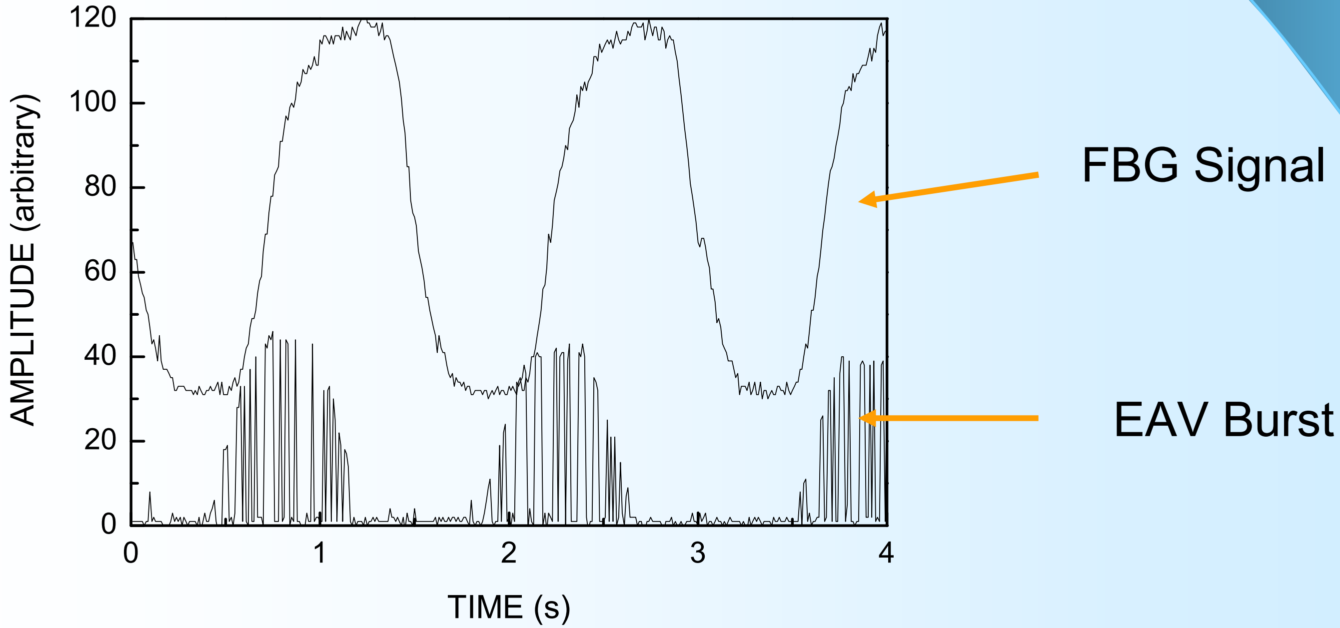
Increased respiratory frequency, can lead to arrest

Time (s)

Frequency (Hz)

EAV synchronization

Sensor output can be used to trigger the Electro-Assisted Ventilation Device

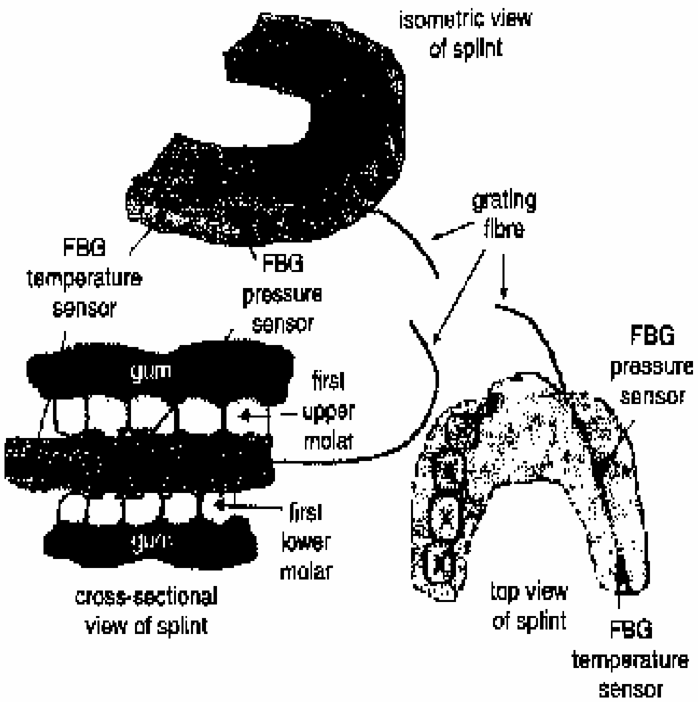


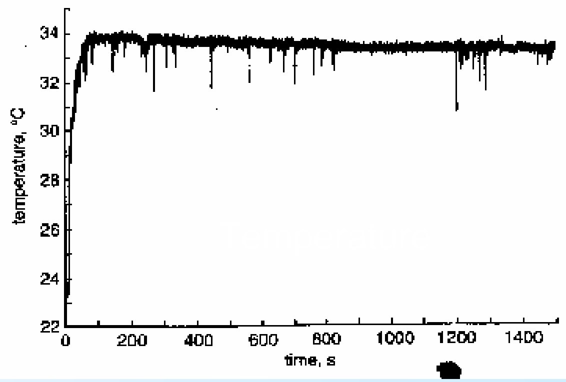
Compliance of dental splint for obstructive sleep apnoea

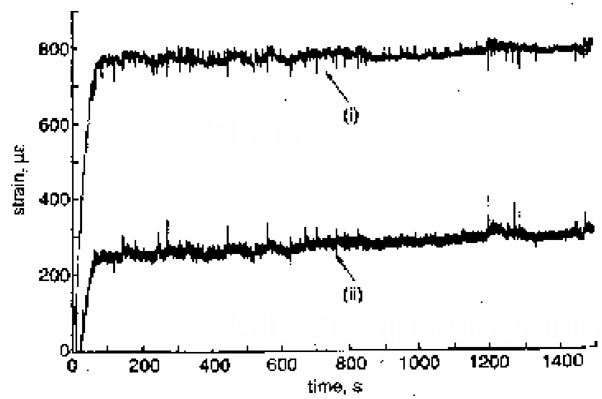
- Complete or partial collapse of the air passage, leading to absence (reduction) of nasal air flow
  - Snoring
  - Excessive daytime sleepiness
  - Nocturia several times at night
  - Un-refreshing sleep, daytime fatigue, poor memory
    - road traffic accidents, increased risk of vascular sequelae, obesity
- Pressure mask, dental splint, surgical treatment
  - Dental splint requires verification of compliance
    - Patients did not worn or had not worn it properly
    - Monitoring of splint use necessary
- Monitoring of temperature and force on splint
  - Unobtrusive sensors
  - Single, embedded fibre optic strand with multiplexed FBG sensors for temperature and strain

S.C. Tjin et al., Med & Biolog Eng & Comput, 39 (182-184) 2001

Compliance of Splint for Apnoea







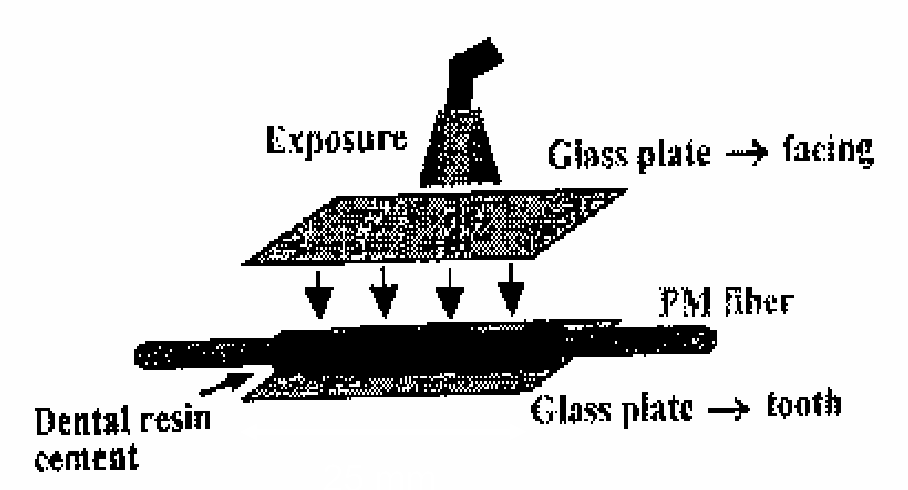
0.1 C
Minimum gum
contact

0.5 N
1st MOLAR

Stress build-up in Dental Cements

- Repair, correction and replacement of teeth
  - Aesthetical
  - Close imitation of outperforming of nature
  - Well being of patients and beauty of smiles
- New dental porcelain materials (1980+)
  - Precision fabricated, fully crystalline shell structure, bonded by composite resin to a prepared tooth
  - Progress in porcelain properties
  - bonding with resin cement is a critical issue
    - Polymerisation includes volume shrinkage > stresses > pain, cold and heat-sensitivity, micro-cracks
    - Partial or total loss of all-ceramic facing

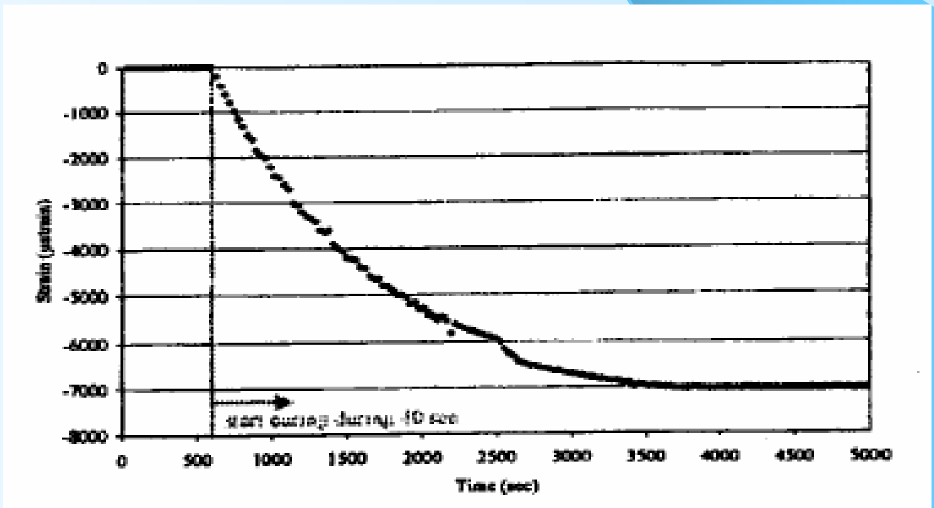
Strain on dental resin cement



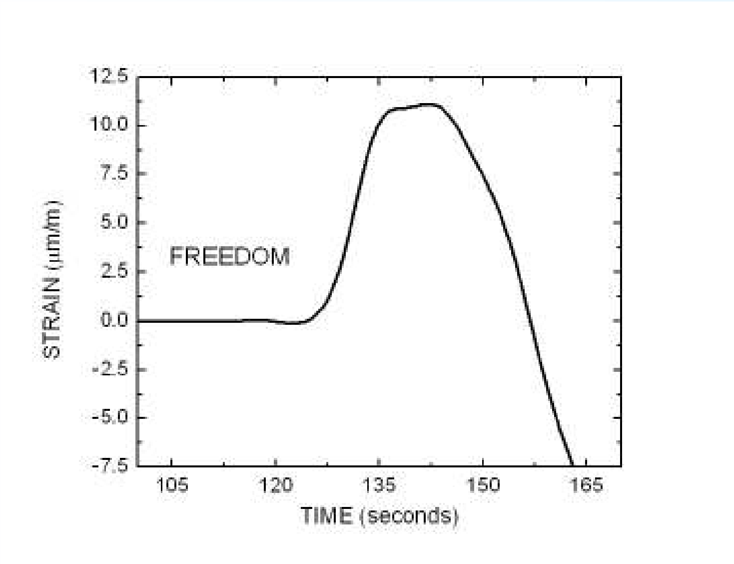
- Stress build-up during VIS induced curing of resin
- HiBi FBG sensors fully characterised
    - Longitudinal strain
    - Temperature
    - Hydrostatic pressure
    - Transversal forces
- Laboratory essays (ASE + Pol. Controller + Birr axes orientation, 470nm curing source)

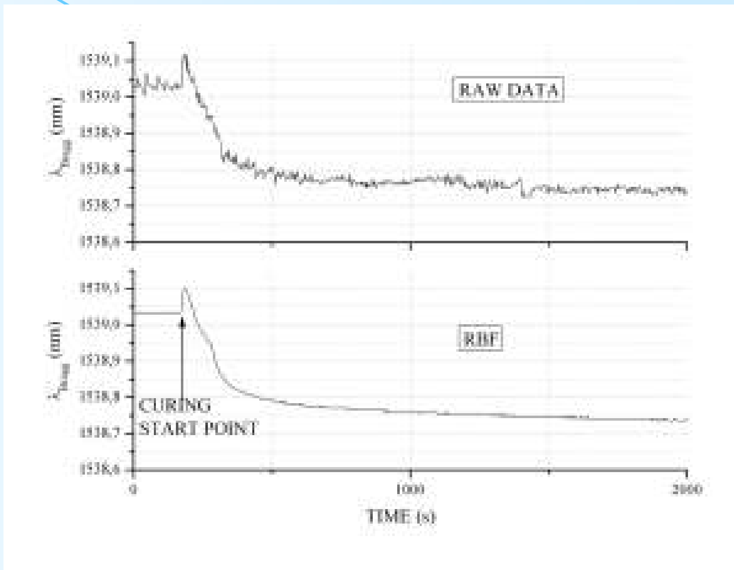
- 40 s curing, after 600 s (typical dentist procedure)
- wavelength decrease and stabilises after ~1 hour
- longitudinal shrinkage of 0.7% (0.3% - 0.9%)
- polarization bands separation: 0.5nm > 2.2nm
    - Transversal force of 270N
    - Non negligible transversal strain

H. Ottevaere et al., Proc. OFS-16, Nara, 2003



Recent Results

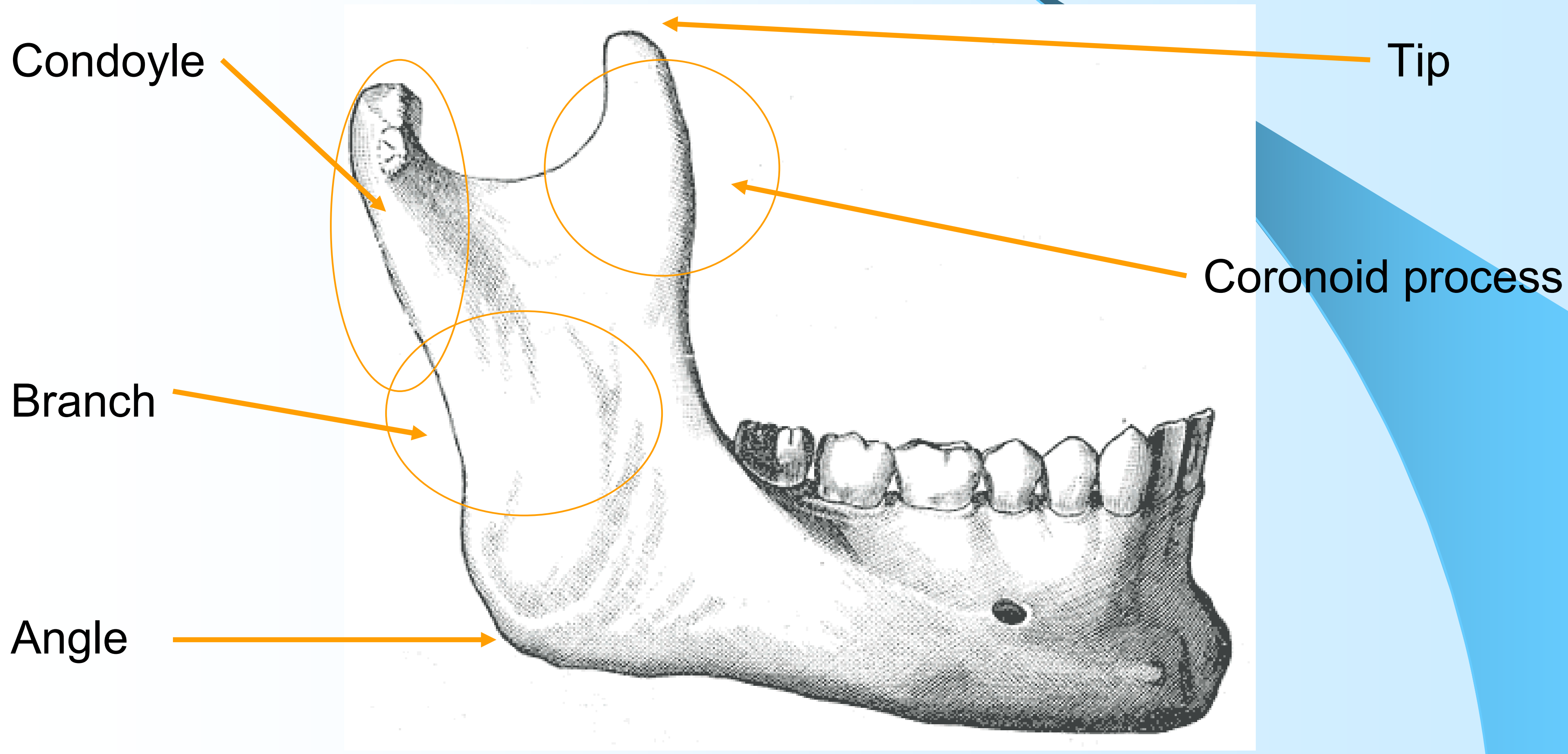




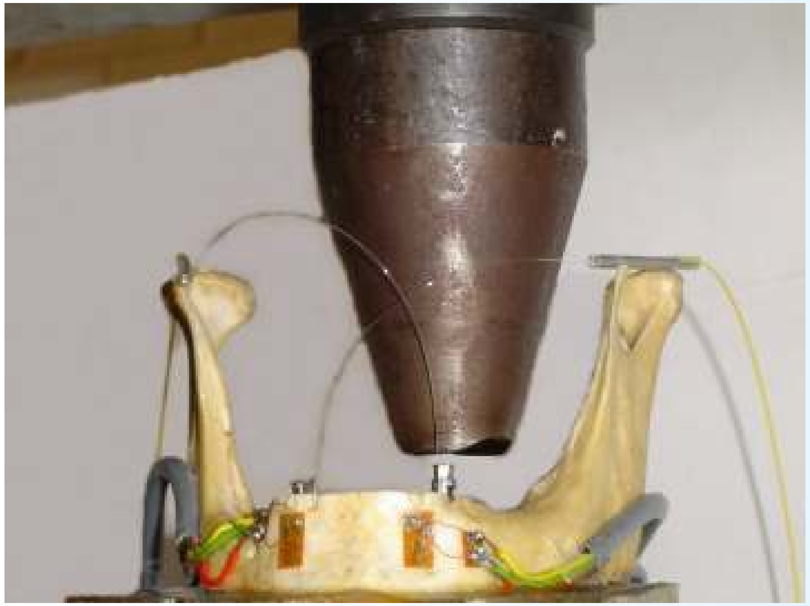
- Initial expansion due to exothermal process
- Shrinkage data for several resins
- Dental gypsum also studied (different brands)
  - New information about effective age of materials

M.S. Milczewski et al. Meas. Sci. Technol. 17, 1152 (2006)

FBG studies with mandible bone



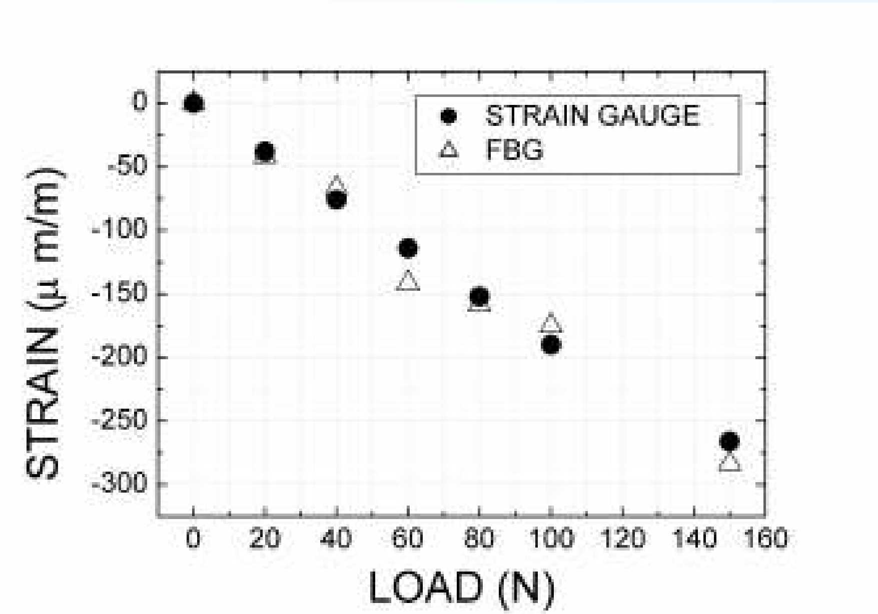
Load transfer from implants to bone structure



- Cadaver's mandible
  - Already dry
- Static strain
  - Bone response to applied load on implant
  - Several load positions
  - Comparison with model (FEM and polymeric plaster)

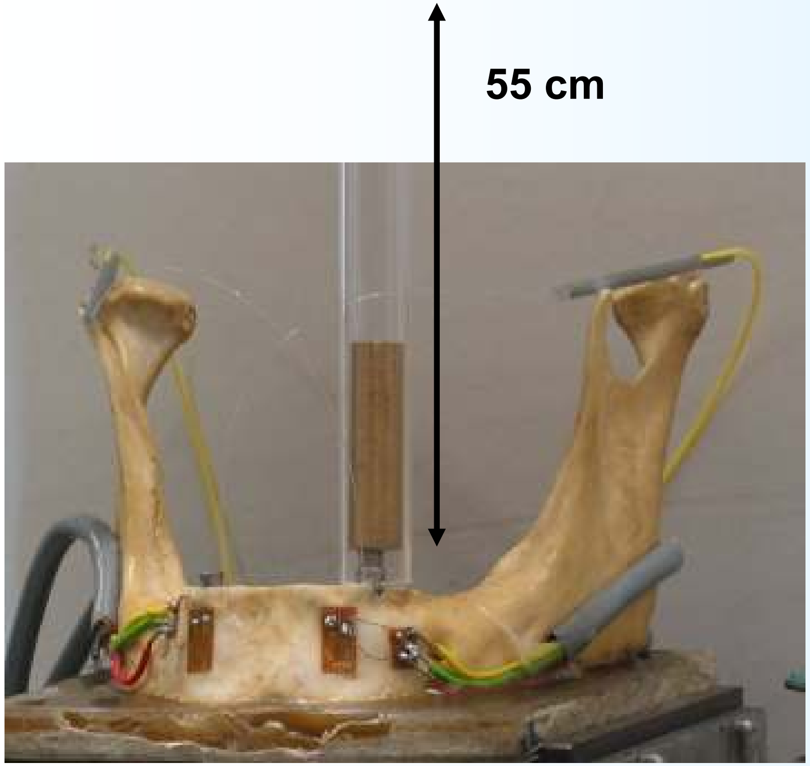
L. Carvalho et al. J. Strain Anal. Eng. Design 41, 411 (2006)

Comparison with standard strain gauge



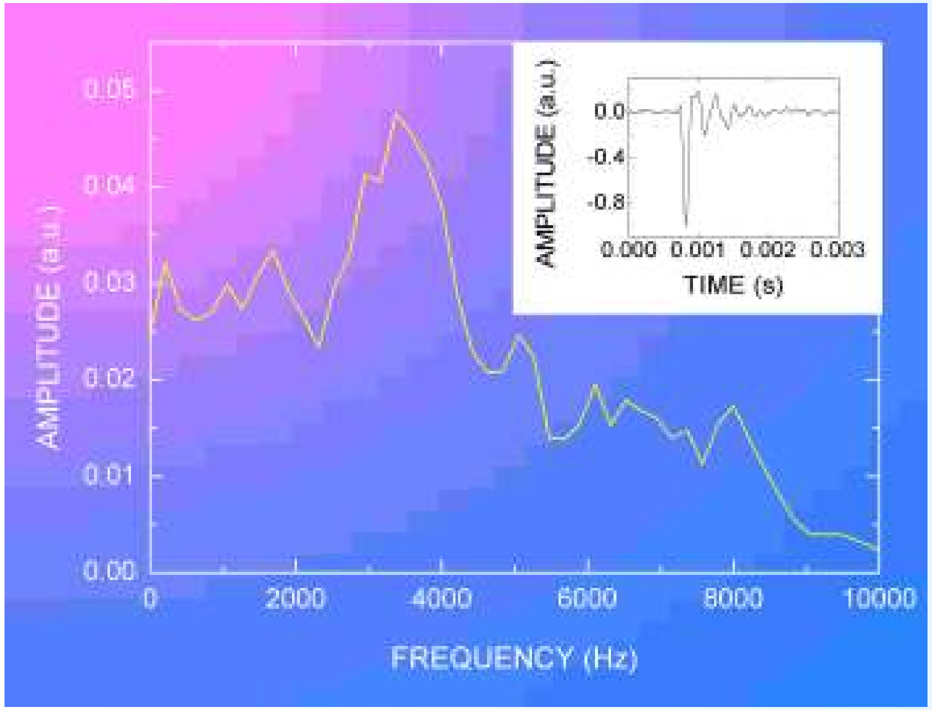
- Good agreement
  - Mandible has been previously measured with resistive strain gauges
- FBG has smaller size
  - Local strain with better spatial resolution
  - Reduced cabling in case of several sensors

Dynamic Studies



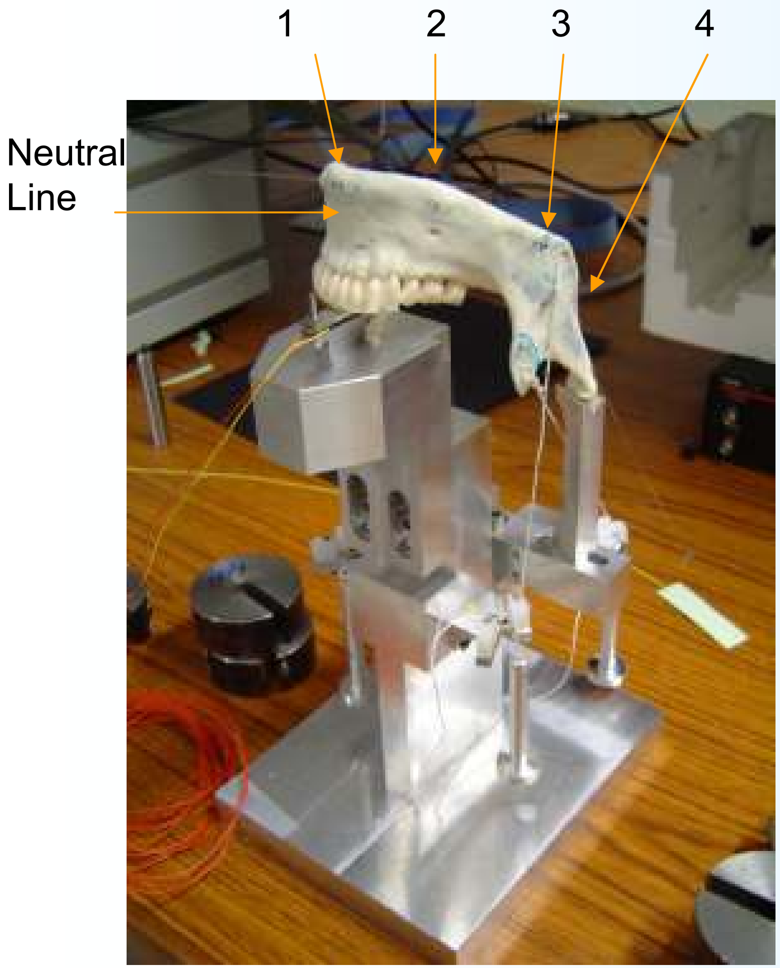
- Strain evolution after impact
  - Approximation for masticatory process
  - Difference between teeth - bone and implant - bone integration (damping buffer effect)
- Permits to develop better implant designs
  - New materials
  - Mechanical design
  - Fixing procedure
  - Prosthesis attachment

Dynamic response of mandible



- Natural frequency peak at 3.3 kHz
- Rigid fixing after osseo-integration
- Absence of damping due to lack of the viscous-elastic tissue
- Excellent SNR (better than strain gauge)

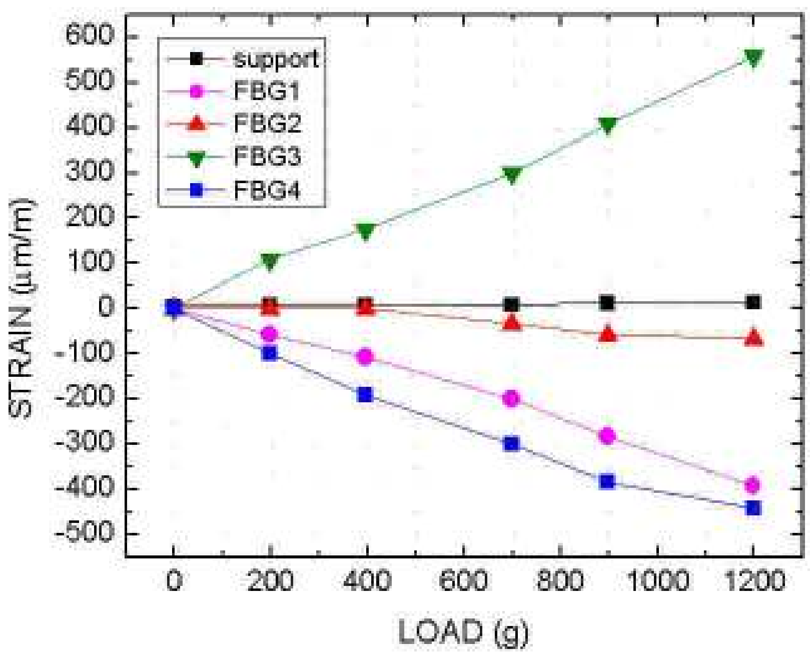
Model Mandible



- Polymeric model with known characteristics close to those of bone
- Several FBG sensors close to 'neutral' line and to the inferior limit of bone
  - Incisive (FBG1)
  - Canine (FBG2)
  - Mandible angle (FBG3)
  - Along mandible's branch (FBG4)
- Load applied in condition similar to that of muscles
  - Masseter {Coronoid process tip} (9.81 N)
  - Temporal {Branch} (4.96 N)

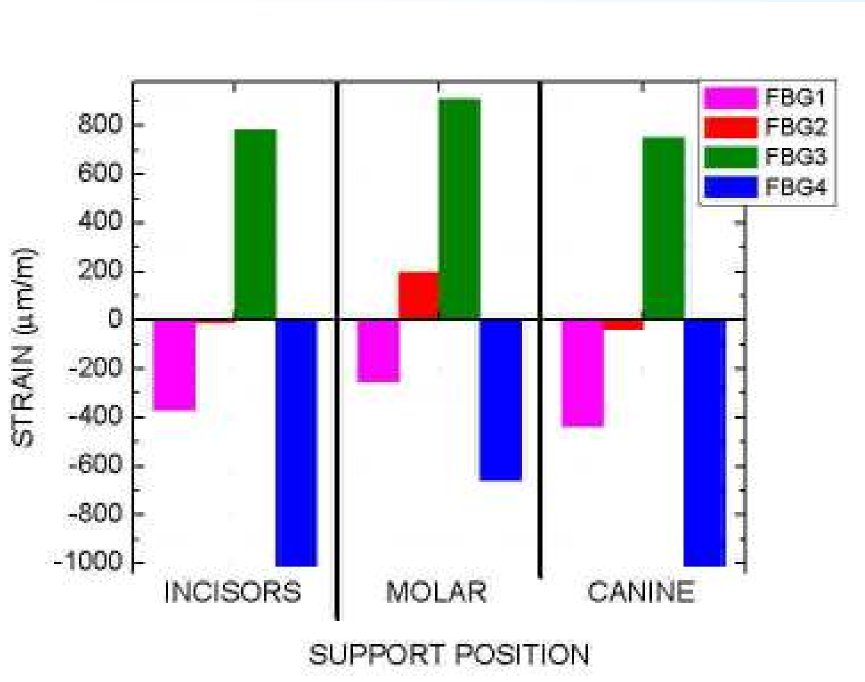
J.C.C. Silva et al. Proc. SPIE (OFS 17) 5855, 102 (2006)

Results – 4 FBG Sensors



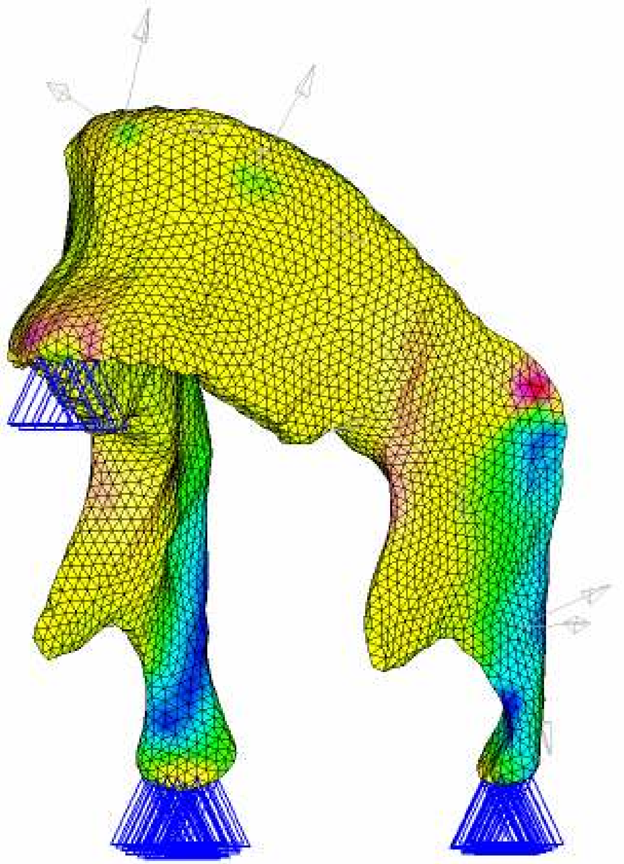
- Linear increase in strain vs. applied load (incisive position)
- Maximum strain on back of mandible (retro-molar region, mandible branch)
- Traction (mandible's angle) /compression effects due to load

Bone response to load position



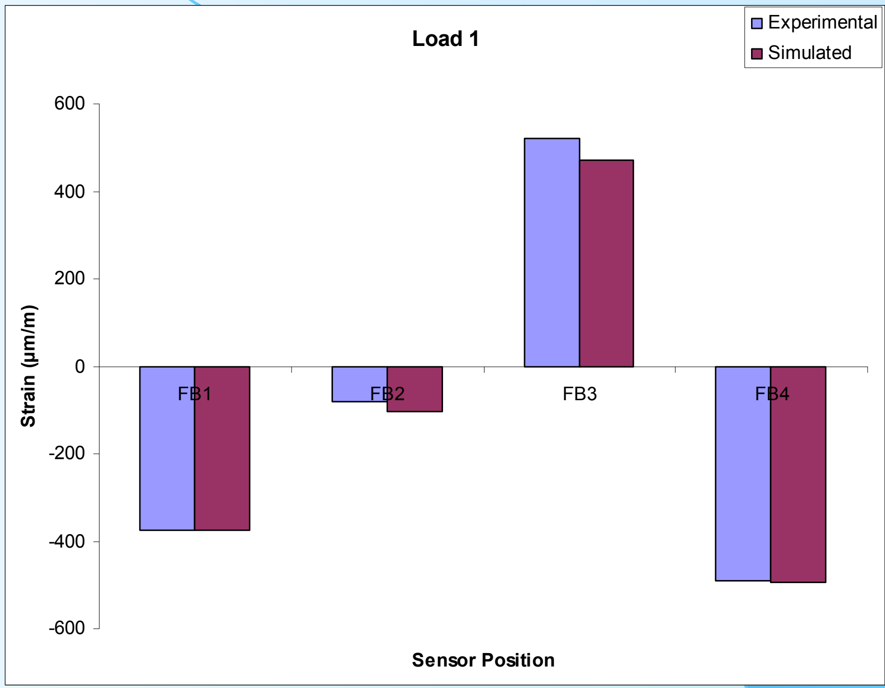
- Load position given by external support tip
- FBG coding:
  - 1 : incisive
  - 2 : canine
  - 3 : molar
  - 4 : condoyle
- Results clarify strain caused in bone due to masticatory action over different teeth
- At canine region, strain changes sign with load position
- Strain at the mandible angle region (branch) is always of opposite sign

Comparison FBG x FEM



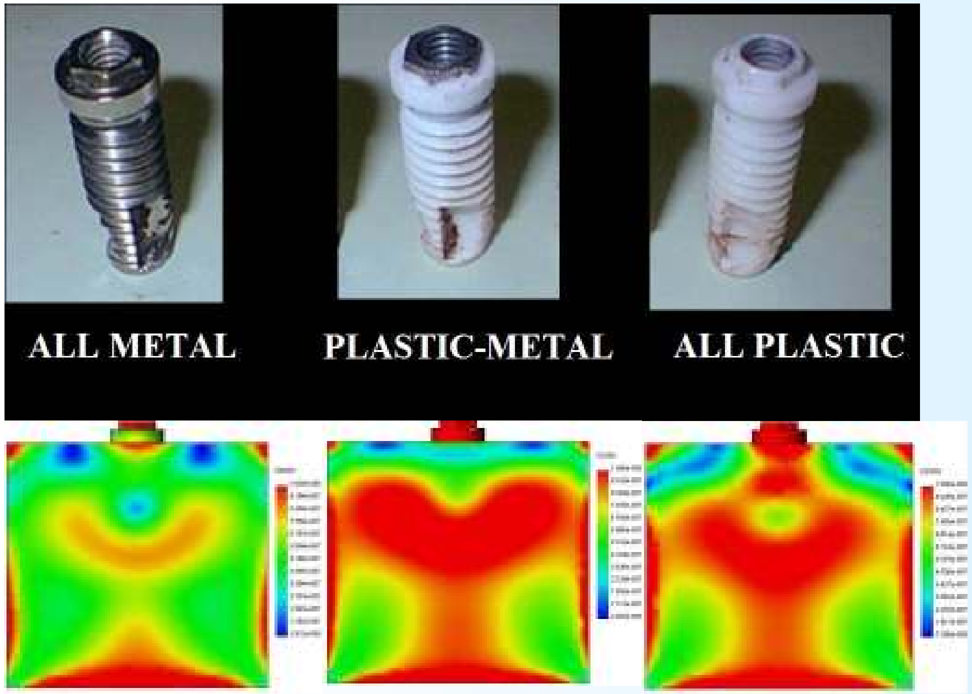
FEM Mesh of Model Mandible

Comparison between obtained strain at several positions



- Strain on model mandible simulated by FEM versus strain measured by FBG at four different positions
- Excellent agreement of simulation to experimental data
- Permits to validate simulation results for real applications (bone information from densitometry and TAC)

Studies with Macromodels



Scaled models of dental implants

- standard metal type
- polymer coated or
- polymer made

Screwed on real fresh cancelous bovine bone

Static load experiments comparison to FEM modelling

Dynamic load experiments

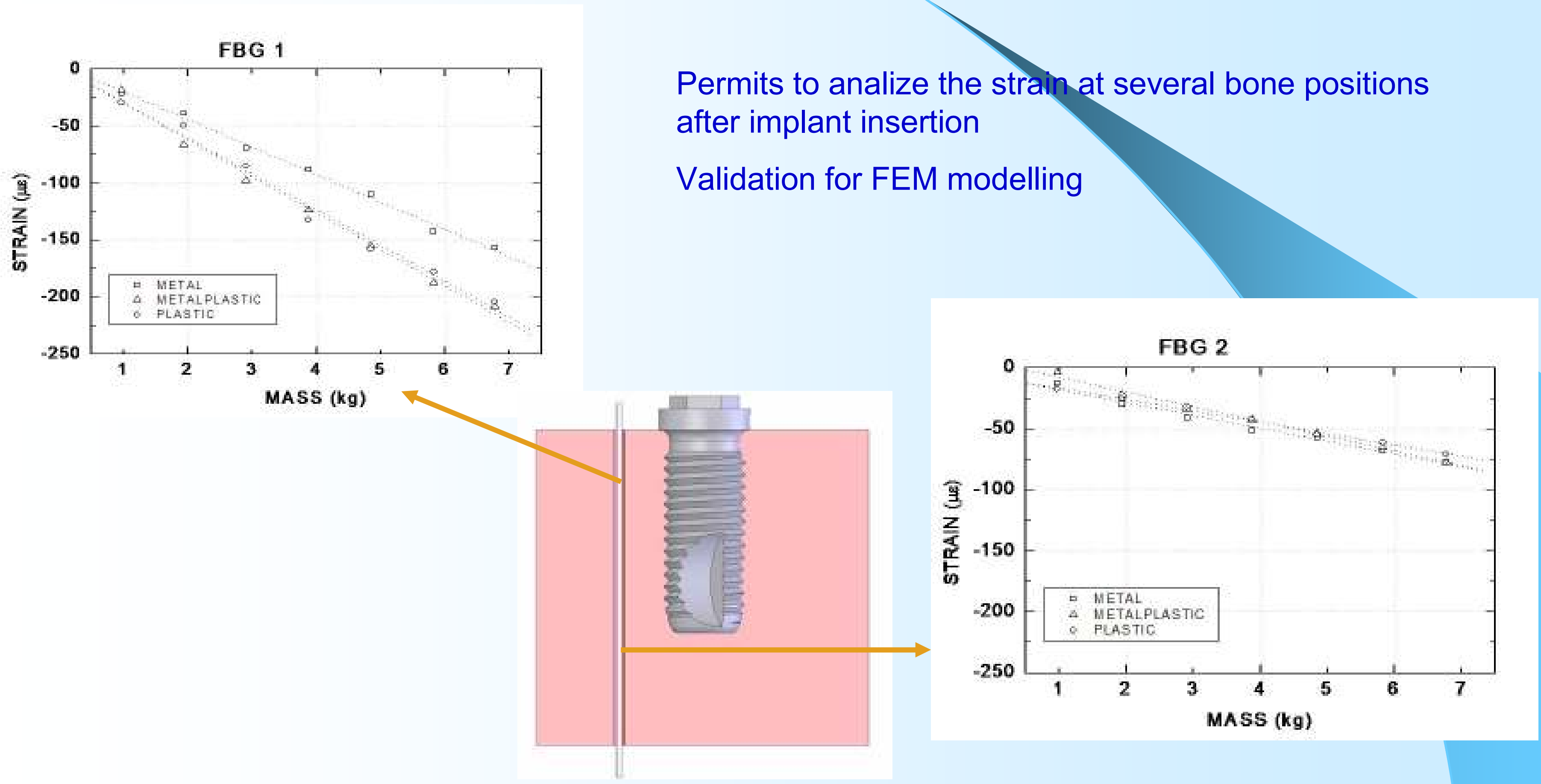
- effects of loading before
- osseointegration

M.W. Schiler et al. Proc. OFS-18, Cancun (MX) 2006

Strain Measurement

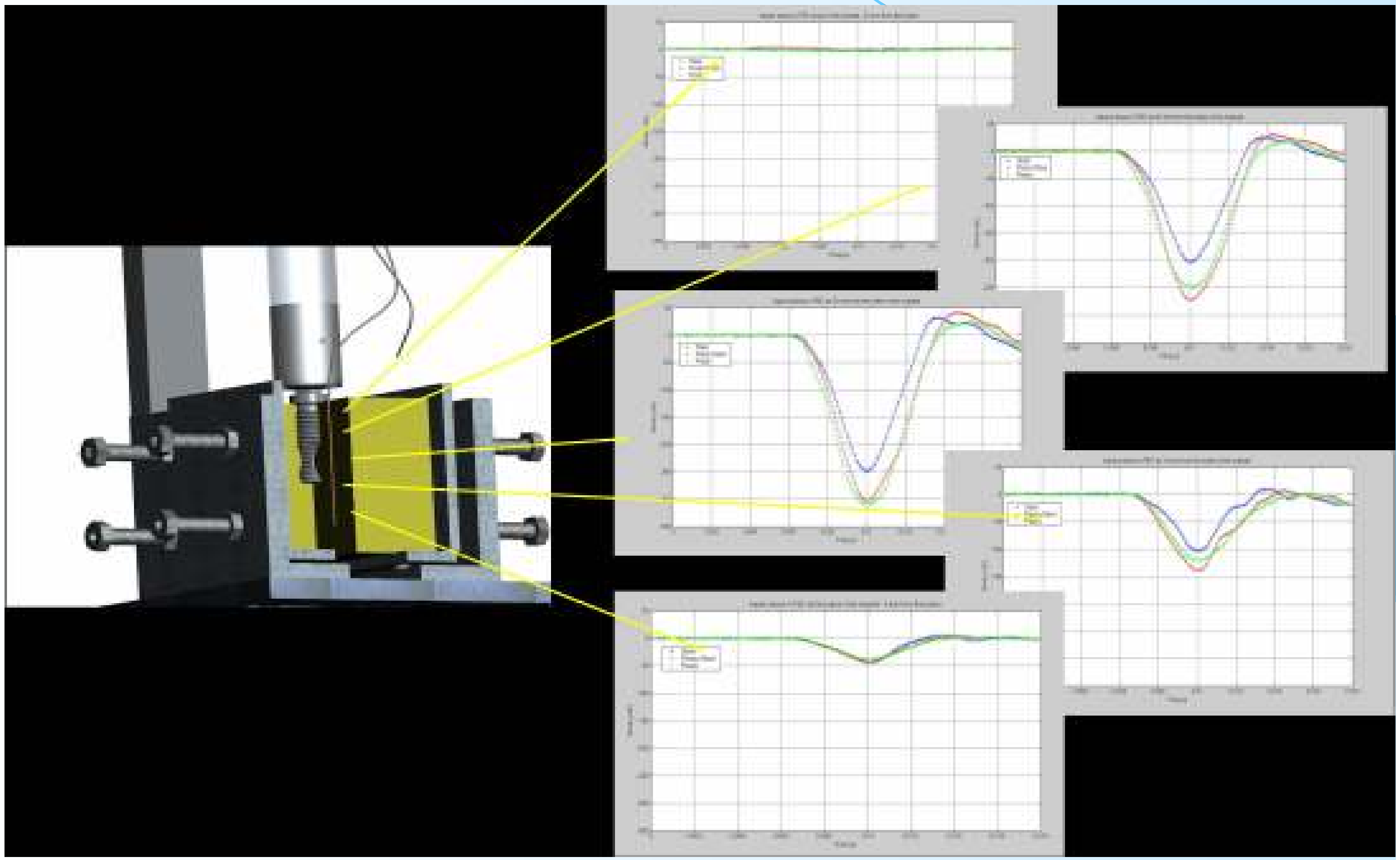
Permits to analize the strain at several bone positions after implant insertion

Validation for FEM modelling



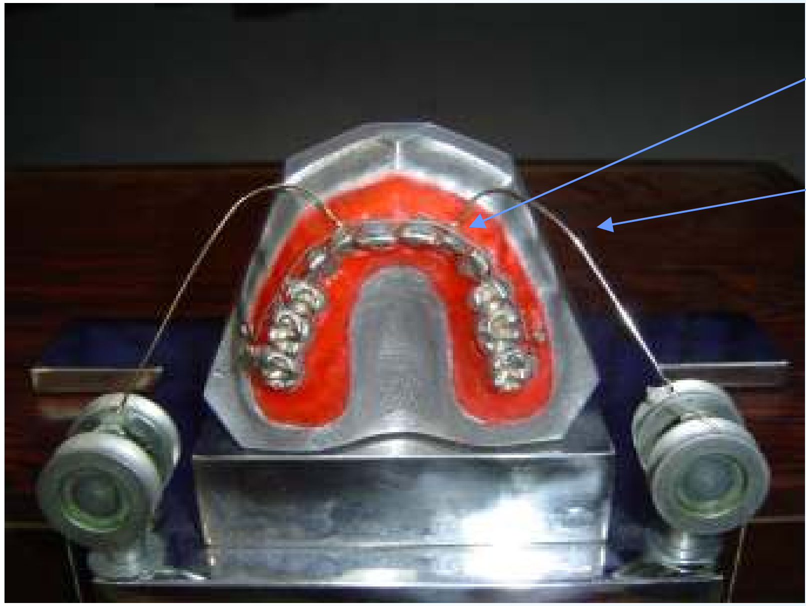
Dynamic Studies

Dynamic Studies



Time evolution of strain at several bone positions after insertion of implant, before osseointegration ("immediate loading")

Orthodontic appliances

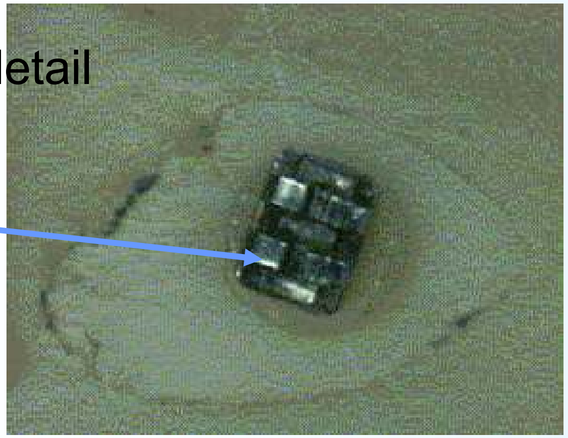


Wire arch

Tensioning arm

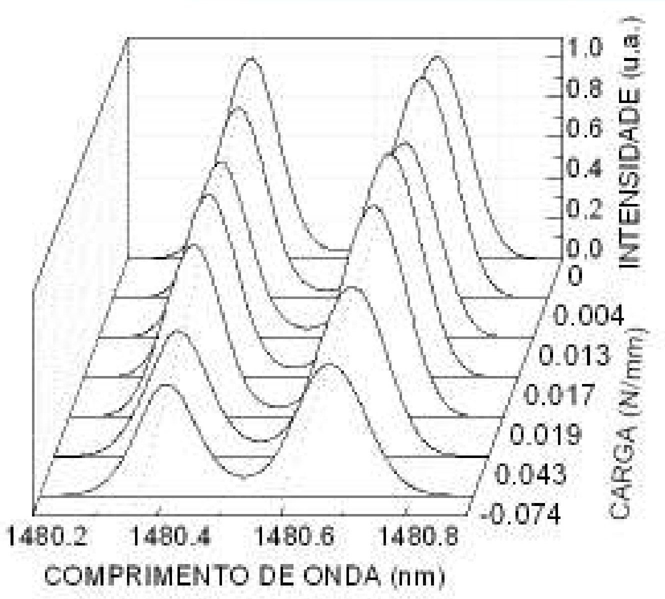
- Typodont© simulator
  - Dental waxes to hold teeth replica
  - Thermal heating ≈ tissue consistency
- Tweed-Merrifield Technique
- Study of teeth displacement with transversal forces
  - Magnitude
  - Angle of application (arm)

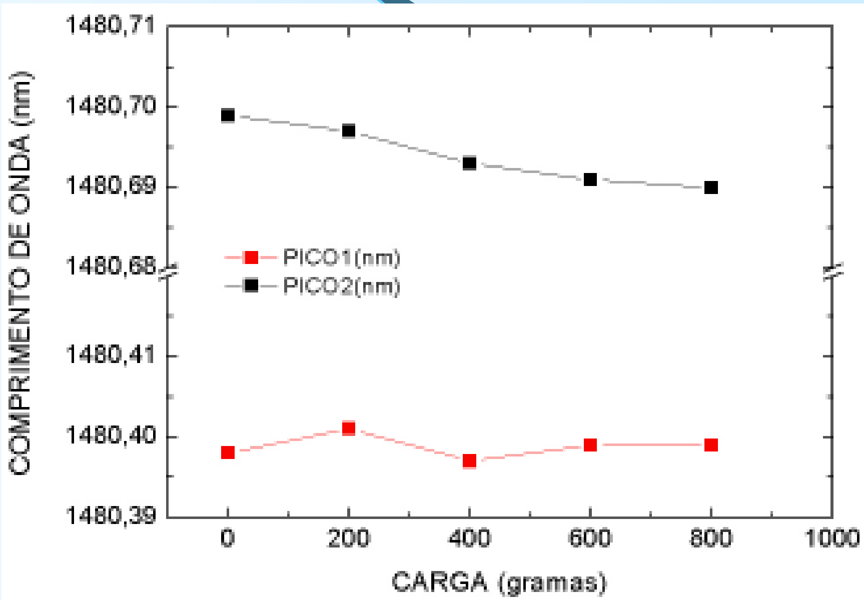
Bracket detail



Channel

Measurements



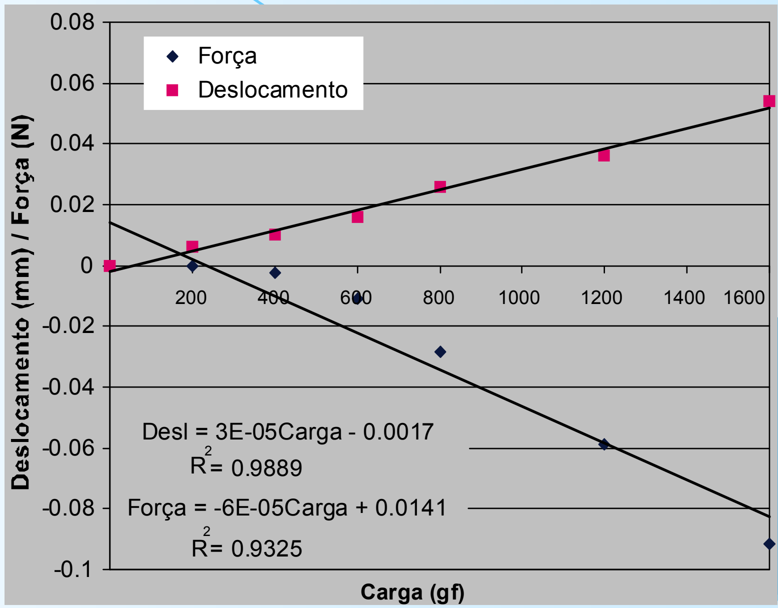


HiBi FBG spectra versus load

HiBi FBG peak position versus load

M.S. Milczewski et al. Meas. Sci. Technol. 17, 1152 (2006)

Load Results



Force (black) and displacement (pink) against load

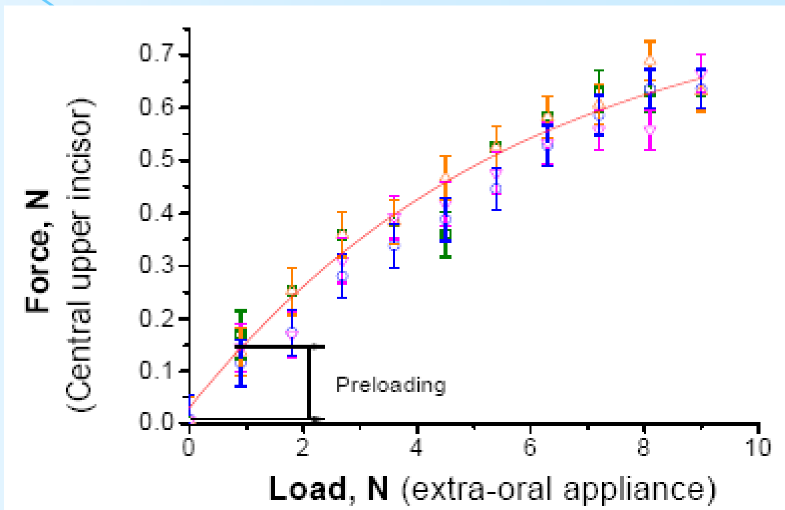
- Strain relatively constant up to a load threshold
- Linear increase of strain
  - Up to 2000 µm/m (0.02% relative deformation)
- Longitudinal (along wire arch) component

Better Model (rev. 3)

- All polymer made (bone structure)
  - Known mechanical properties
- Based on the plaster (original)
- FBG instrumented
  - Internal: 3 FBGs x 3 teeth + bone positions
  - External: along strain line on surface

Force Measurements using Polymer PCF

- Sensor mounted on maxilla model (polymer) + appliance
  - (previoully callibrated)
- Load applied by weights to the wire arch of appliance (extra-oral)
- Loss determines the normal component of the force on the teeth



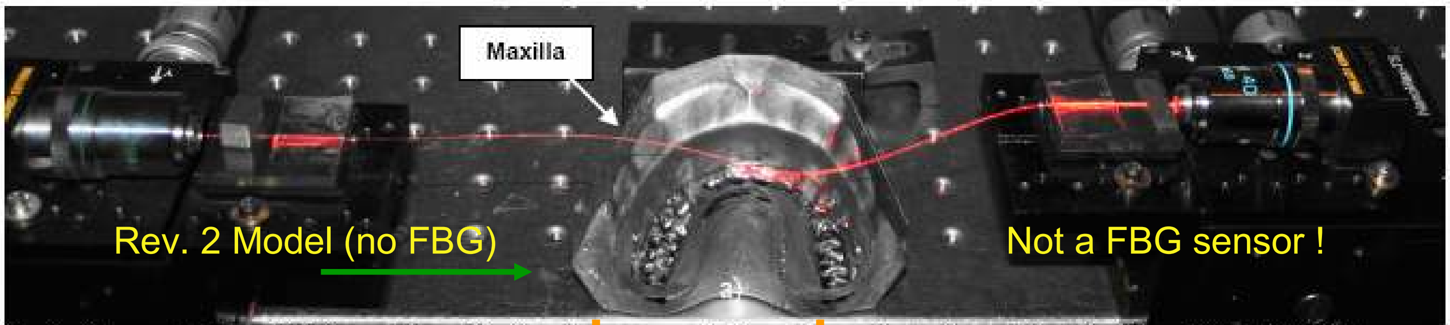
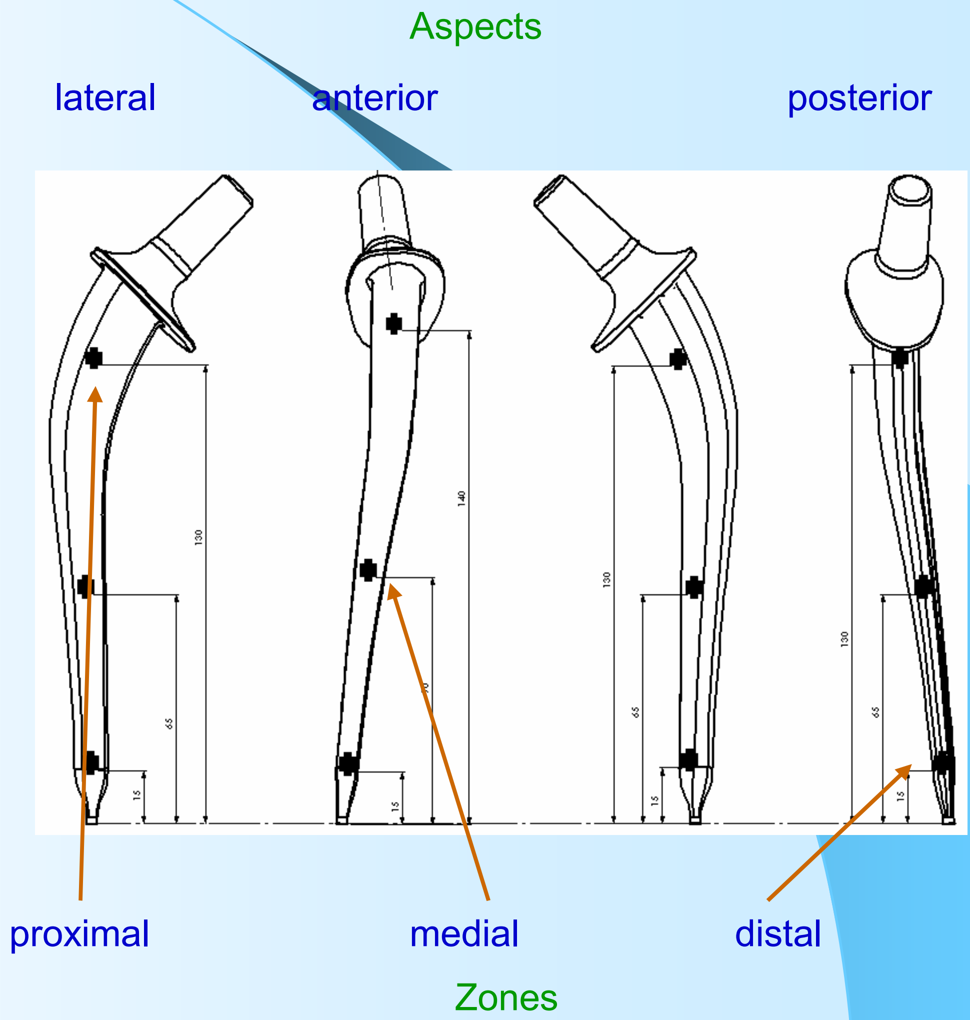


Fig. 3. Set up with the artificial maxilla and the Bracket sensor with the polymer photonic crystal optical fibre. HeNe light lights up the fibre.

Load

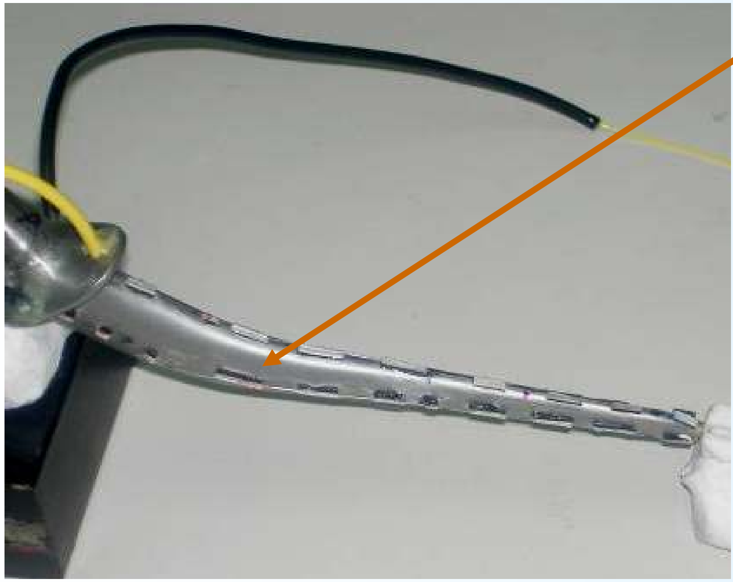
Studies on Femural Prosthesis

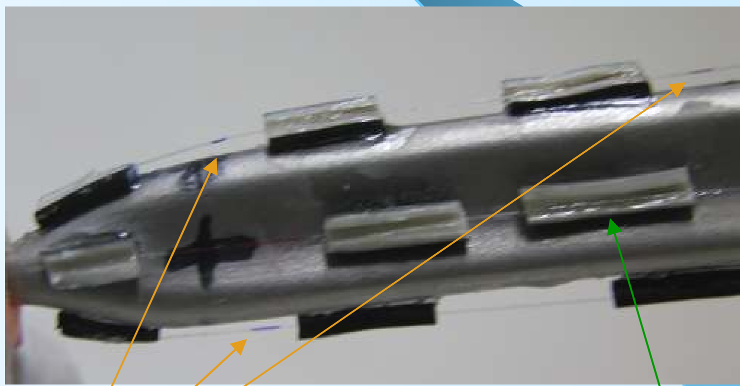
- Aging of population leads to increase in femur linked fractures -> prosthesis (~0.5 Million in US by 2020 !)
- Most of them are cemented to the bone (after drilling !!)
- Failure usually associated to the interfaces, bone-cement or prosthesis-cement
- Cement failure due to excessive traction strain on lateral-proximal position and excessive compressive strain on medial-posterior position
- Necessity for pre-clinical testing in order to evaluate prosthesis adequacy.



Multisensor System (WDM)

Instrumented Cr-Co phrosthesis
for femur head





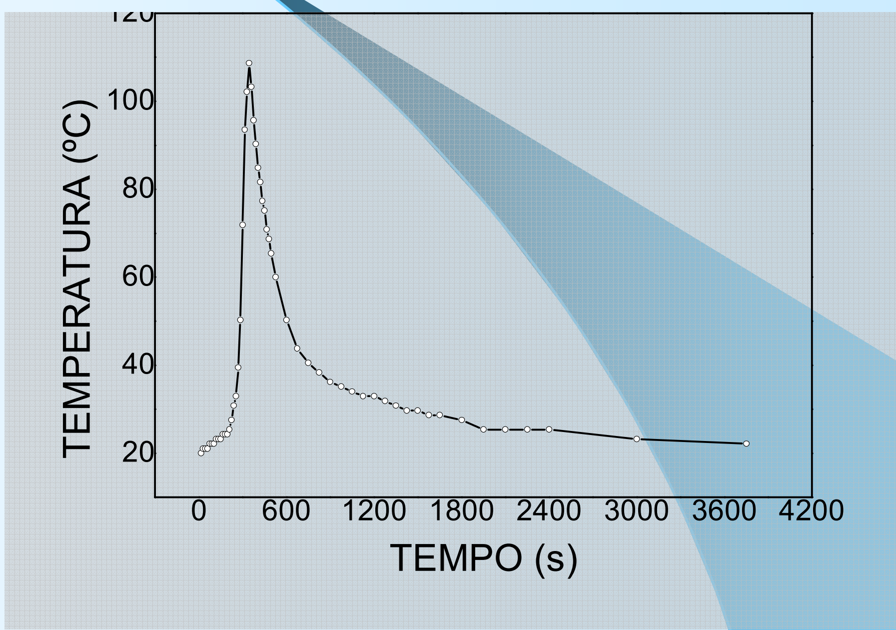
Plastic spacer

Strain measuring FBGs (4 lines / aspects x 3
FBG each /zones)

I. Abe et al., 2. ENBiomec (PT), Evora 8-9 Feb 2007

Cement mantle 2 mm thick

Curing Sensor



Temperature evolution after insertion of cement

Extra FBG sensor used to monitor the temperature during the cure process of the cement

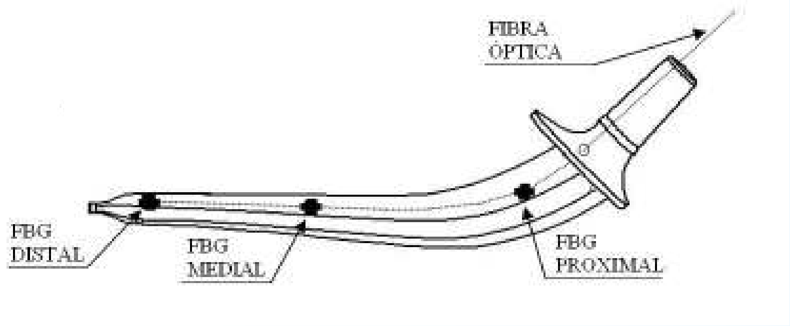
Static Load Testing

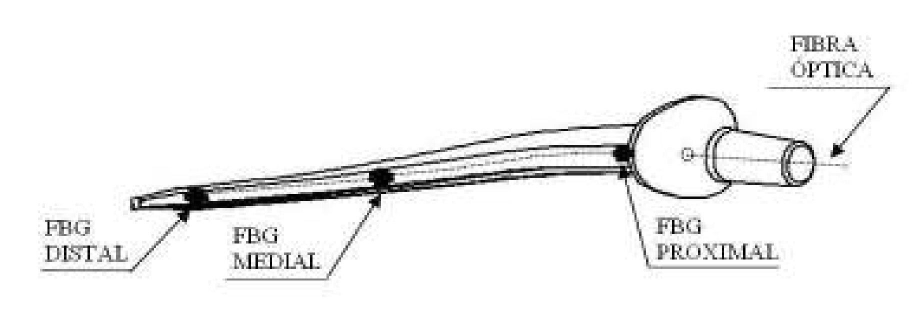
Universal Test Machine (UTM) for load application

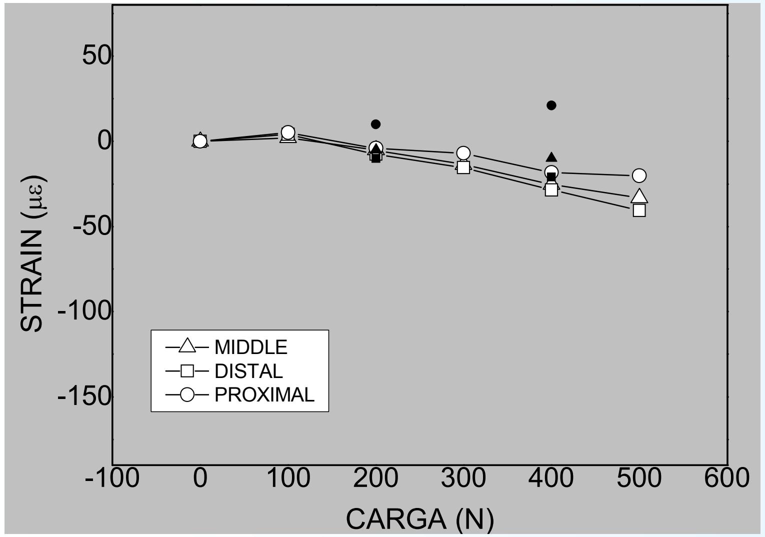
Static and dynamic load testing

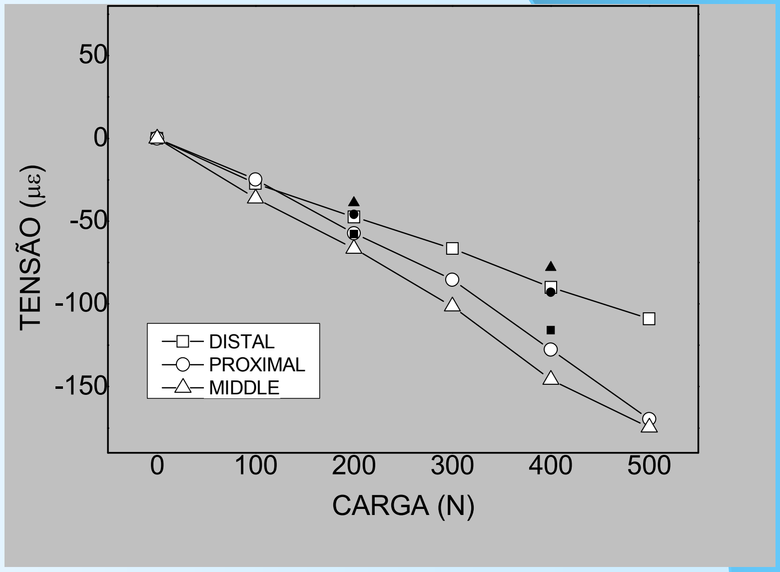
Simulation for the weight of patient, walking stress, sports, ...

Strain measurements under load

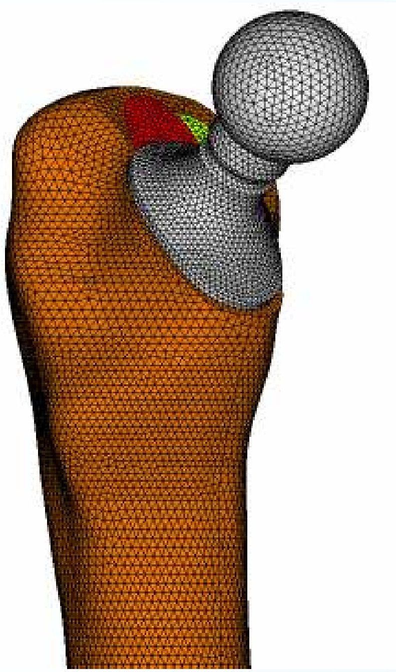


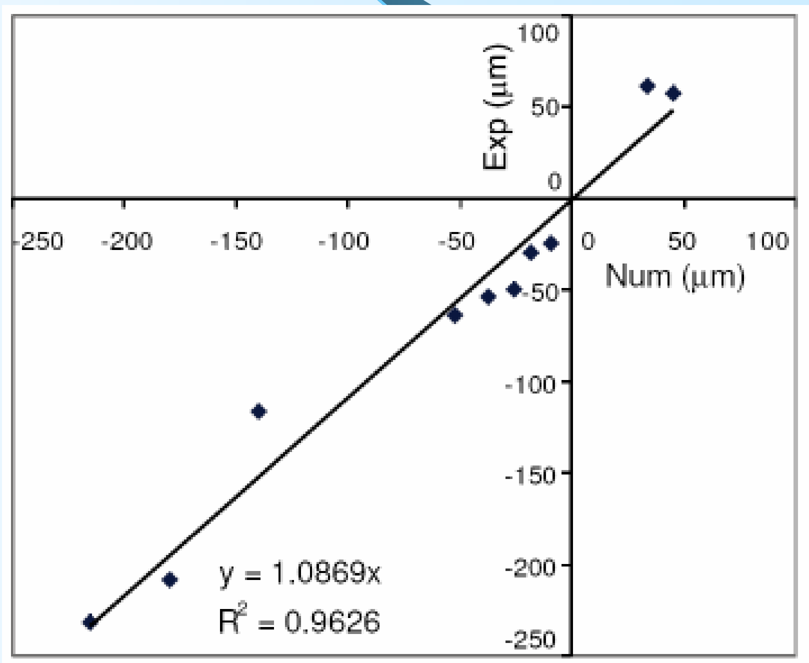






Correlation with FEM model





Validation of numerical model can lead to customized design of phrosthesis & cement mantle

Results

- Good correlation between experimental and numerical modelling (FEM OK !)
- Local temperature during curing of cement is high, might induce residual strain
- Information obtained about the strain on the cement mantle between prostheis and bone

Sumary

- FOS (particularly FBGS) suitable to devices and measurements in biomedical applications
- Extensive range of applications, from physioterapy to prosthesis design
- Open field for newcomers

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