ROLE OF MOISTURE CONTENT IN MECHANICAL CHARACTERIZATION OF BRAIN TISSUE

HENRY W. HASLACH, JR.
DEPARTMENT OF MECHANICAL ENGINEERING
CENTER for ENERGETICS CONCEPTS DEVELOPMENT
UNIVERSITY OF MARYLAND
COLLEGE PARK, MD 20742 USA

INTRODUCTION

A. RAT BRAIN SERVES AS AN ANIMAL MODEL FOR mTBI

B. FOR A FEM, CHARACTERIZE THE MECHANICAL RESPONSE

C. SEEK MECHANICAL CAUSE OF mTBI

D. INCLUDE MOISTURE CONTENT OF THE TISSUE

    1. QUESTION NEGLECTED BY MOST OTHER RESEARCHERS

ROLE OF MOISTURE

A. ROLE OF MOISTURE CONTENT IS A KEY TO UNDERSTANDING THE DAMAGE CAUSED BY SHOCK WAVES

1. MOISTURE CONTRIBUTES TO THE VISCOELASTIC (TIME-DEPENDENT) MECHANICAL RESPONSE TO LOADS
2. SHOCK WAVES MAY MOVE INTERNAL TISSUE MOISTURE
3. CAN EFFECT GLASS TRANSITION OF TISSUE PROTEINS

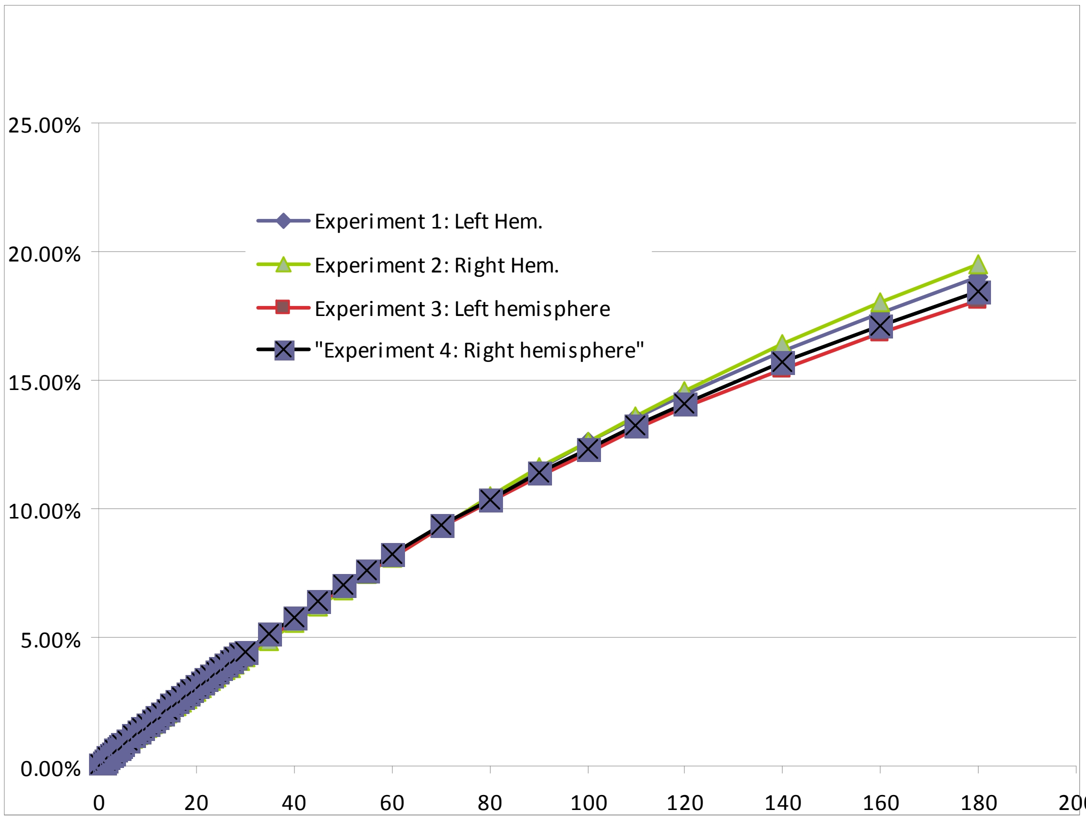
B. WE MEASURED MOISTURE CONTENT BY WEIGHT AS 81.5%

1. BRAIN TISSUE DENSITY IS ABOUT 1.04 g/cc.
2. MOISTURE CONTENT BY VOLUME IS ABOUT THE SAME AS MOISTURE CONTENT BY WEIGHT

EVAPORATION TEST

A. HOW SOON AFTER HARVEST MUST THE TEST BE PERFORMED IF SPECIMEN IS NOT KEPT IN PBS TO REHYDRATE

B. AMBIENT 30% RELATIVE HUMIDITY



RESULTS IN THE BIOMECHANICS LITERATURE

A. PROPOSED MATHEMATICAL MODELS

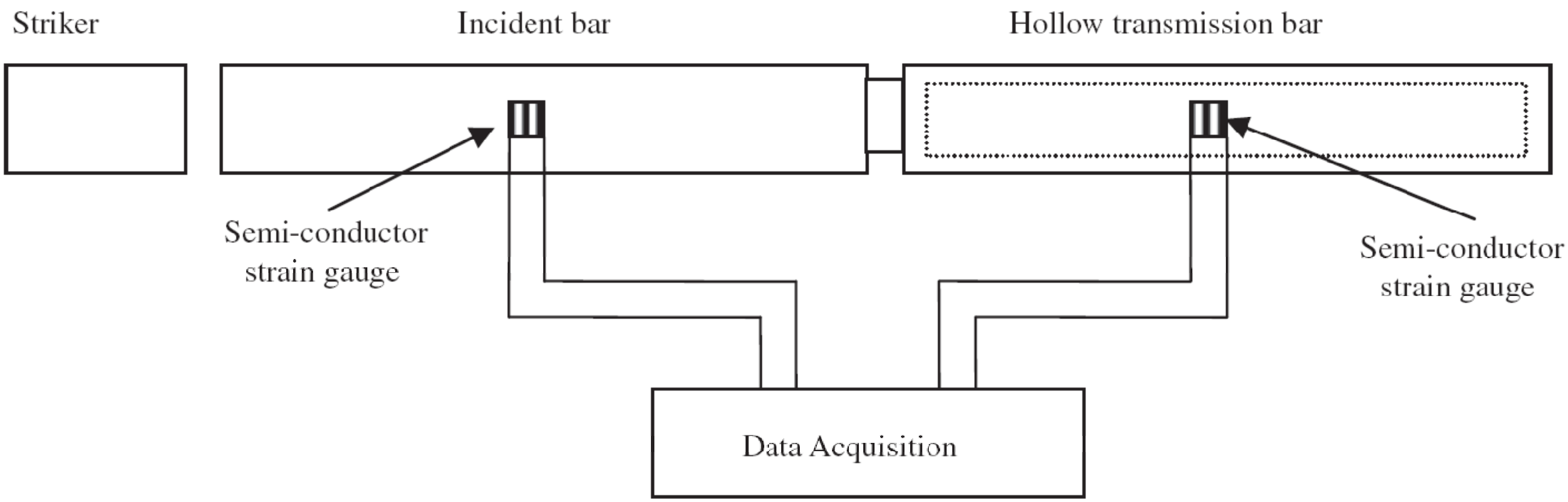
1. LINEAR VISCOELASTIC (SUPERPOSITION HOLDS)
2. STRESS-STRAIN TESTS SHOW
   a. BRAIN TISSUE IS NONLINEAR VISCOELASTIC
      e. g. MILLER AND CHINZEI 2002
   b. AD HOC NONLINEAR VISCOELASTIC BASED ON RUBBER
3. IGNORE ROLE OF MOISTURE CONTENT

B. EXPERIMENTAL

1. INDENTERS FOR LOAD-DEFORMATION RELATION
   a. CAN ONLY GIVE LINEAR VISCOELASTIC $\sigma - \varepsilon$

2. HOPKINSON BAR FOR HIGH STRAIN RATES

a. ONLY GIVES COMPRESSION AND ONLY AT CONSTANT RATES



Zhang et al., 2011

SMALL-SIZED SAMPLE TESTS

A. DETERMINE STRESS-STRAIN CURVES IN COMPRESSION AND IN SHEAR

1. SUCH LOADS BELIEVED RELATED TO mTBI
2. CONFINED COMPRESSION TESTS
3. TRANSLATIONAL SHEAR TESTS

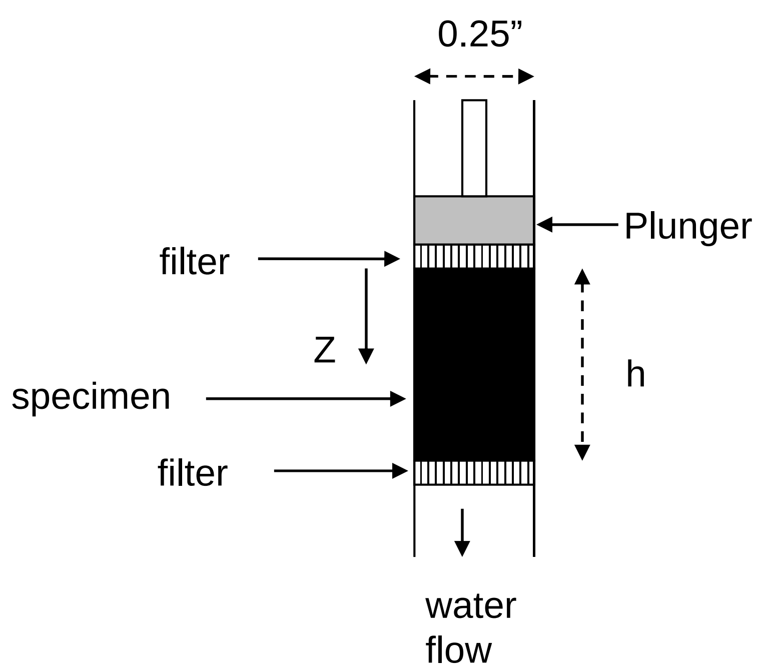
B. MEASURE PERMEABILITY TO ACCOUNT FOR MOISTURE ROLE

C. FIT WITH NEW NONLINEAR VISCOELASTIC MODEL

I. CONFINED COMPRESSION TEST

A. METHOD TO DETERMINE UNIAXIAL PERMEABILITY

B. APPARATUS – SPECIMEN IN CYLINDER



PROPERTIES TO MEASURE

A. UNDER LINEARLY INCREASING COMPRESSION, HOW DOES RATE INFLUENCE LOAD RESPONSE

B. IS TISSUE STRAIN HARDENING OR SOFTENING?

1. REFLECTED IN CONCAVITY OF LOAD CURVE
2. INERTIA OF INTERCELLULAR WATER OR PORE CLOSING?

C. PERMEABILITY AS A FUNCTION OF STRAIN AND STRAIN RATE

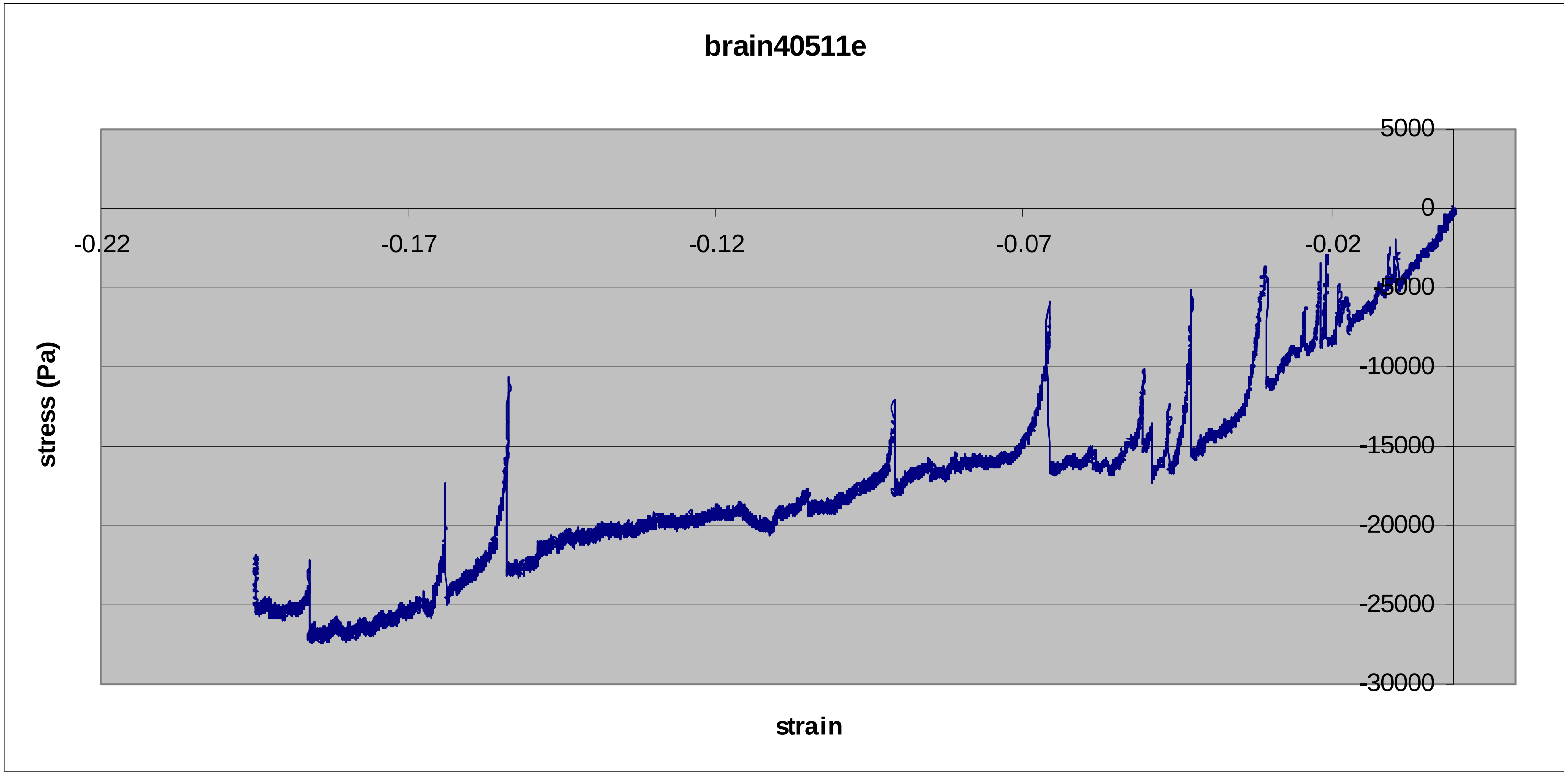
1. MEASURED BY FITTING SOLUTION TO THE BIPHASIC PDE TO A STRESS RELAXATION CURVE
2. PERMEABILITY INCREASES IF STRAIN SOFTENING

QUASI-STATIC CONFINED COMPRESSION

A. STRAIN RATE IS 6.4 X 10^{-4}/s (16 HRS), INNER SAGITTAL SLICE

B. DAMAGE APPARENT

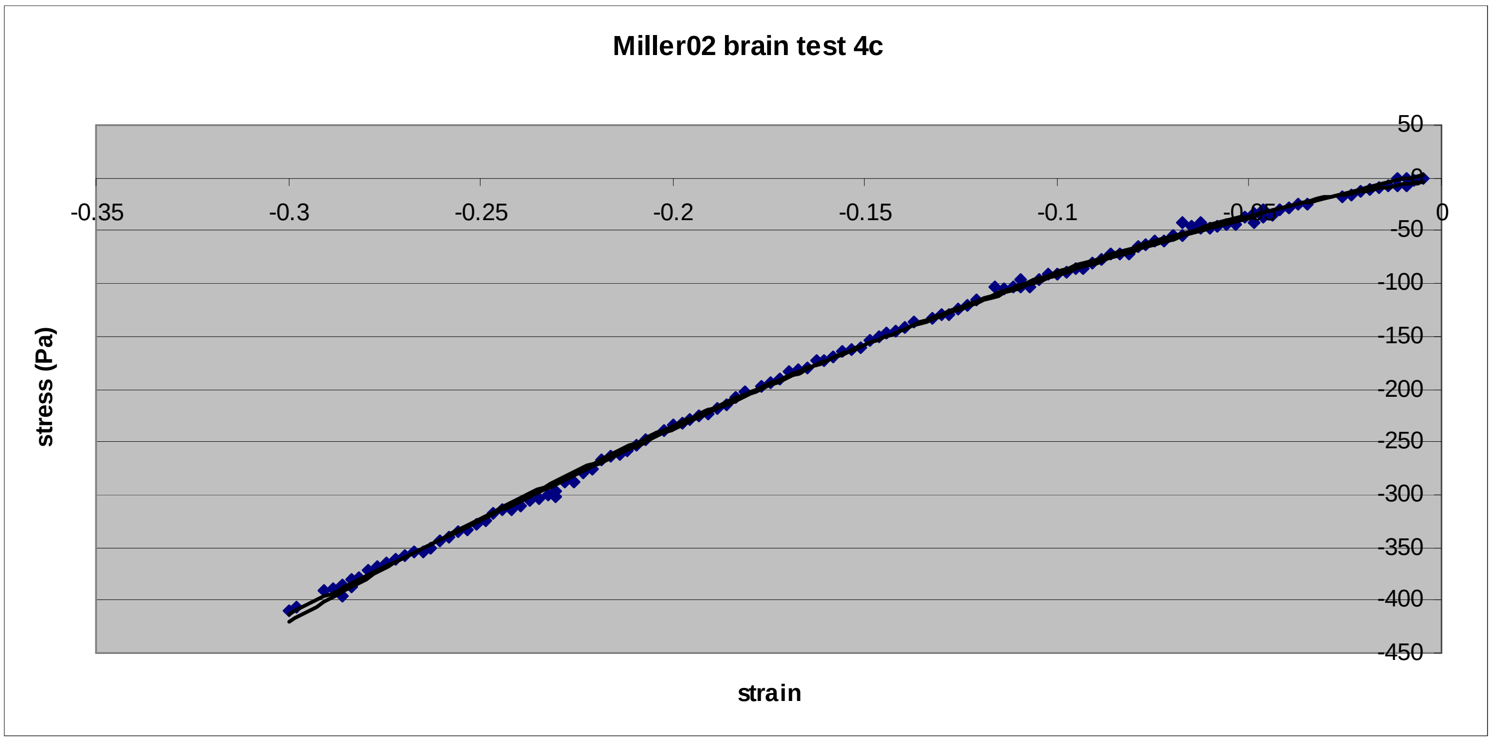
C. STRAIN SOFTENING



QUASI-STATIC UNCONFINED COMPRESSION

A. MILLER-CHINZEI: SWINE CORTEX 30 mm DIA, 10 mm HIGH AT 6.4 X 10^{-4}/s
IS STRAIN HARDENING

B. DUE TO MULTI-AXIAL MOISTURE FLOW? RADIAL EXPANSION OBSERVED



EVIDENCE OF DAMAGE AND MOISTURE FLOW

A. STRAIN 5%, THEN STRESS RELAX
REPEAT CYCLES FOR STRAIN TO 10, 15, 20, 25%

B. PLATEAU AT END OF LINEARLY INCREASING DEFORMATION REGION TO 10%

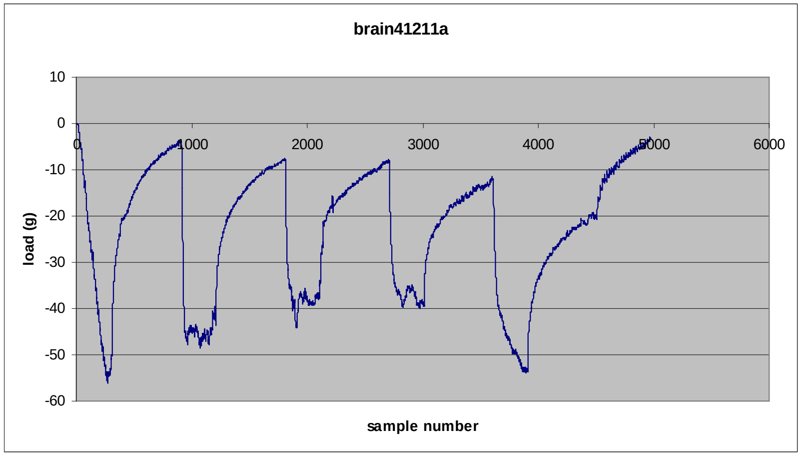
C. DAMAGE IN PLATEAU REGION

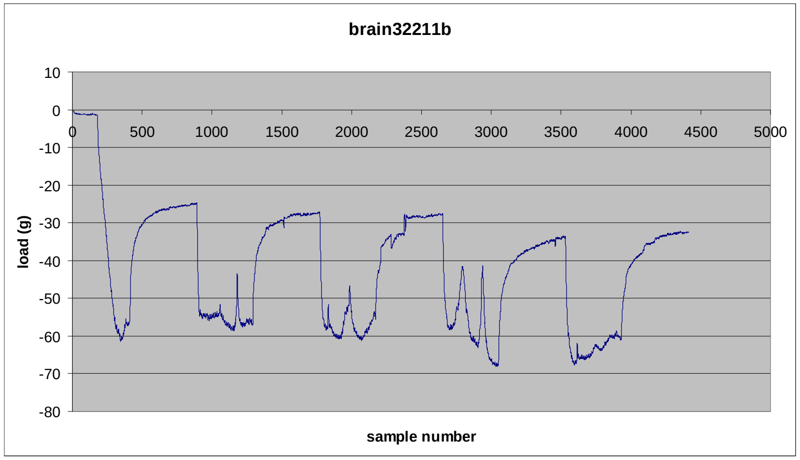
IS TYPICAL OF DRYING (AT PLUNGER)

AND SHIFTING OF SOLID MATERIAL

D. STRESS RELAXATION REGION, WATER REDISTRIBUTES

E. PATTERN REPEATS AT ALL STRAIN LEVELS 10,15,20 25 %

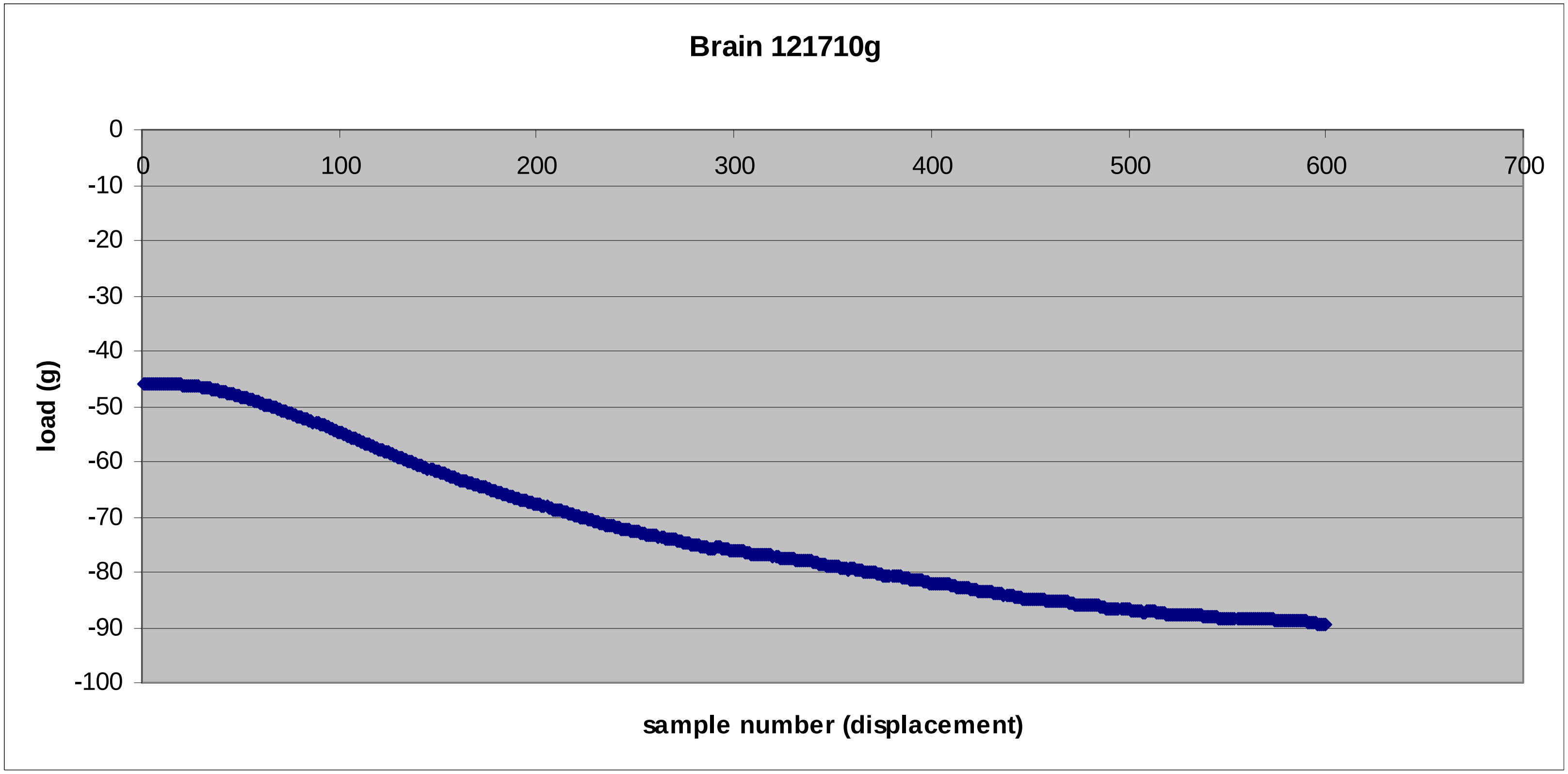




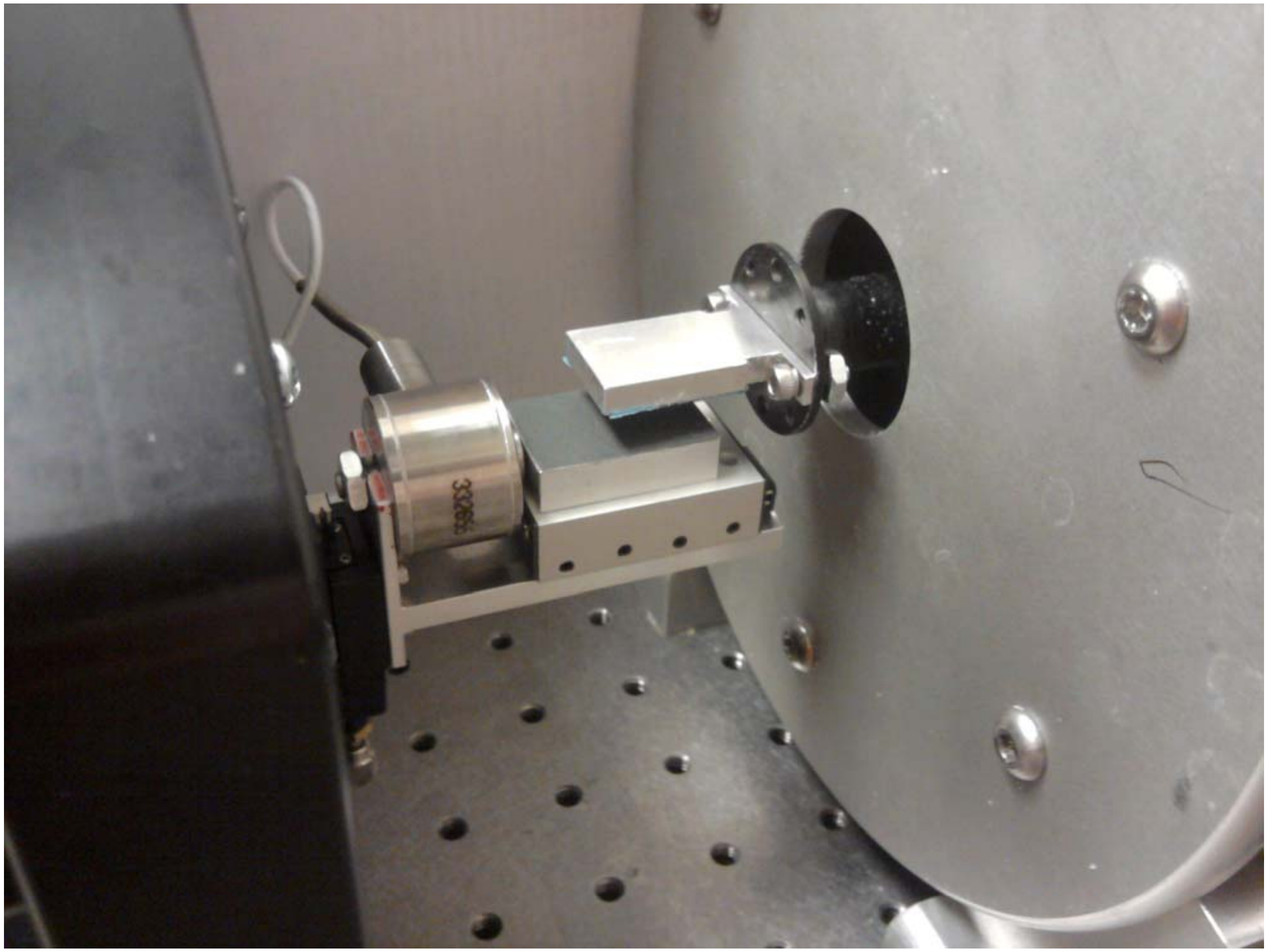
LOAD SEGMENT OF LOAD-RELAXATION

A. STRAIN SOFTENING IN COMPRESSION (0.001 mm/s)

B. FROM 0.2 TO 0.29 GLOBAL STRAIN, LENGTH = 3mm



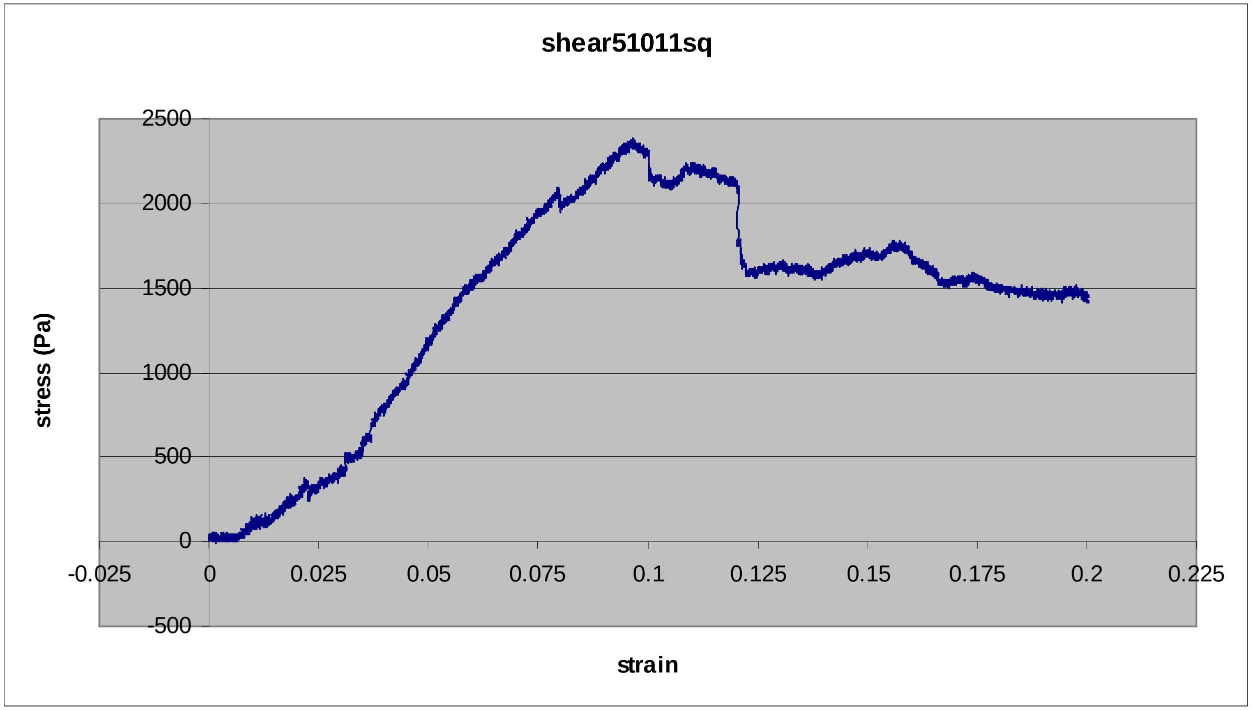
SHEAR FIXTURE



QUASI-STATIC TEST

A. STRAIN RATE IS 3.2 X 10^{-4}/s (16 HOUR TEST)

B. INNER SAGITTAL SLICE: 6x6x4 mm

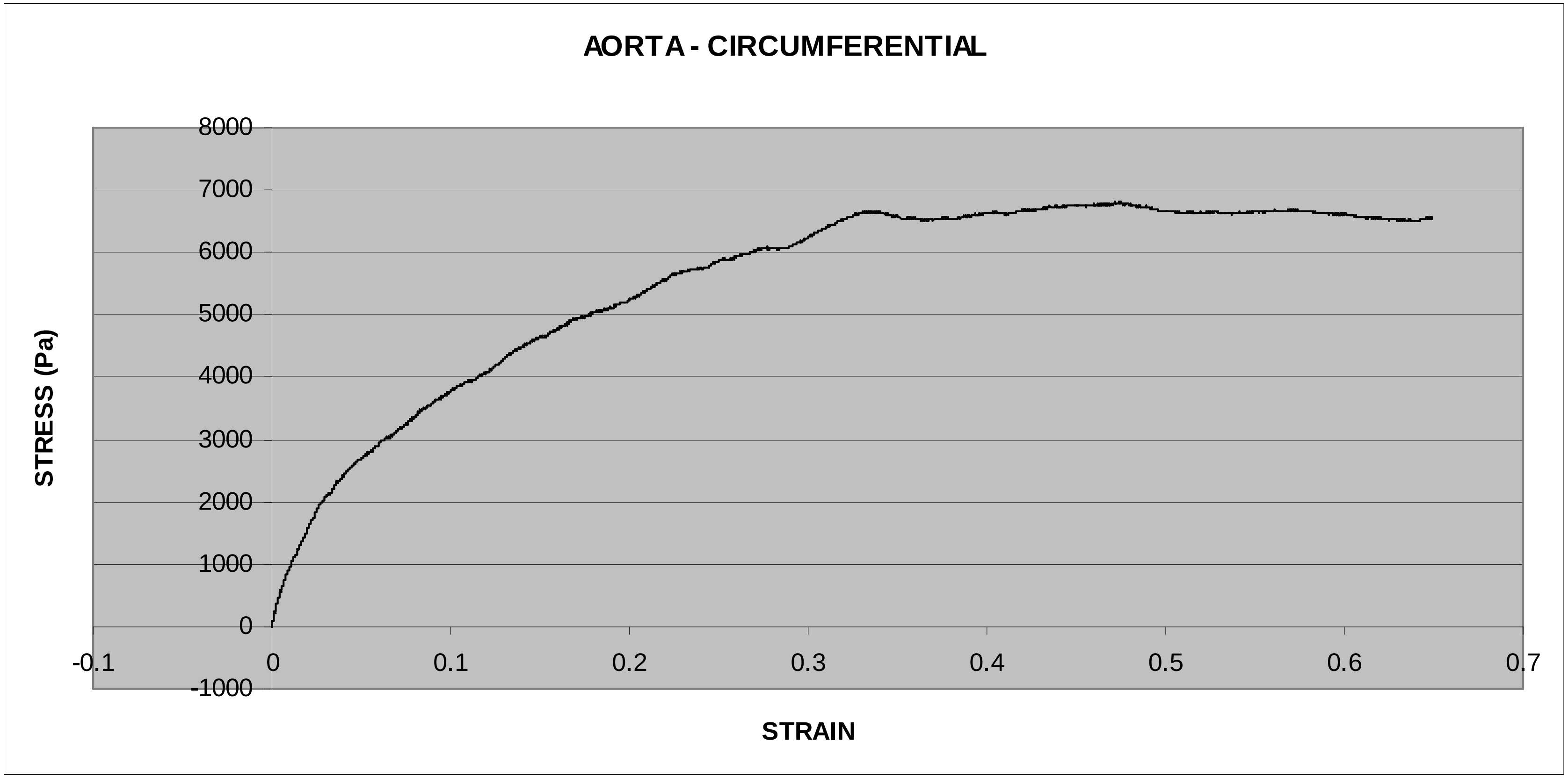


C. FAILURE AT 10% - DUE TO DEHYDRATION?

ARTERY TISSUE

A. THE AORTA IS A LOAD BEARING MATERIAL

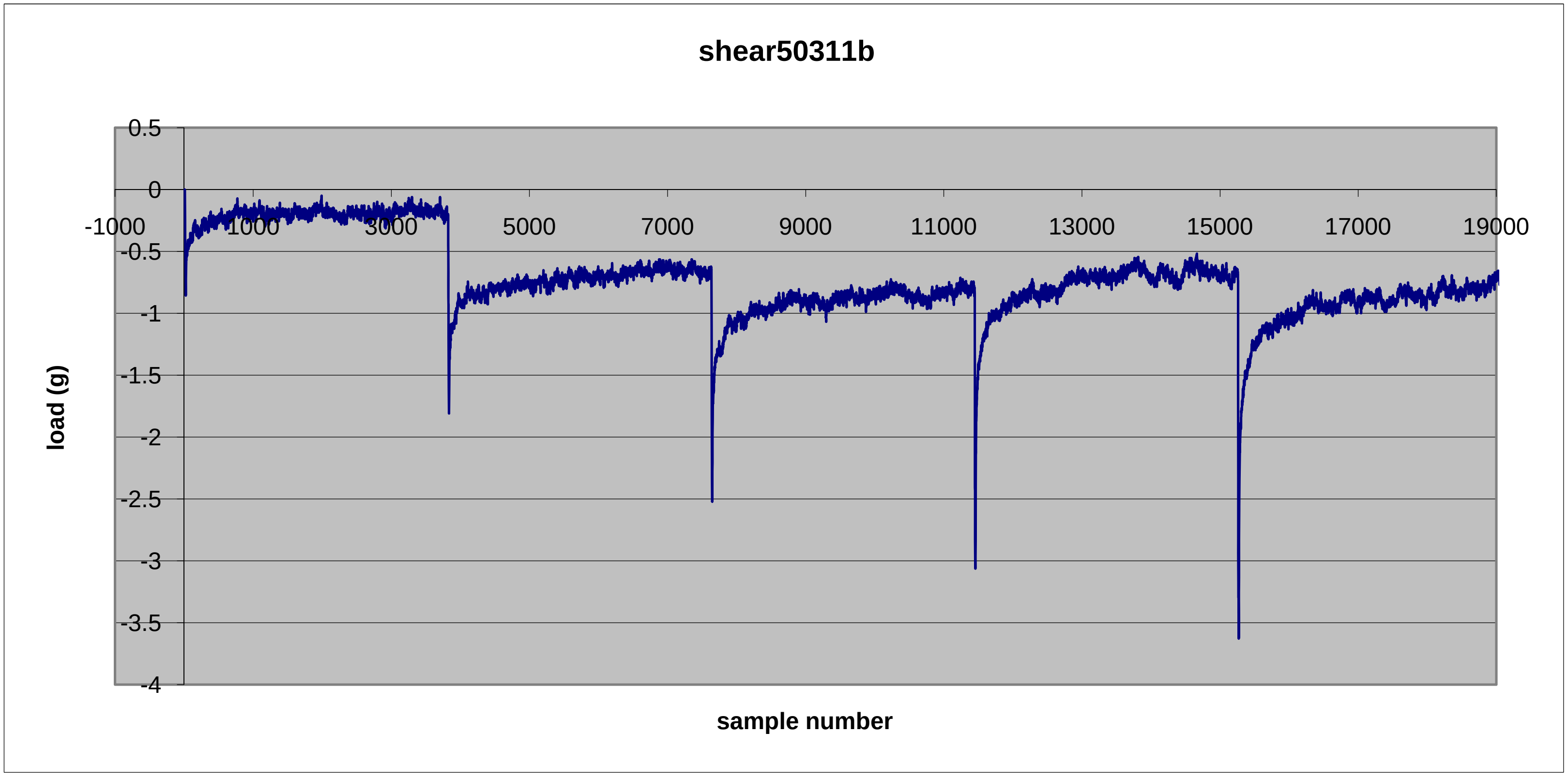
B. SOFTENS WHEN SHEARED PARALLEL TO COLLAGEN FIBERS



LOAD-RELAXATION

A. RELAXATION ALSO OCCURS IN SHEAR

B. 1mm/s RATE, 12x6x3mm, INNER SAGITTAL SLICE



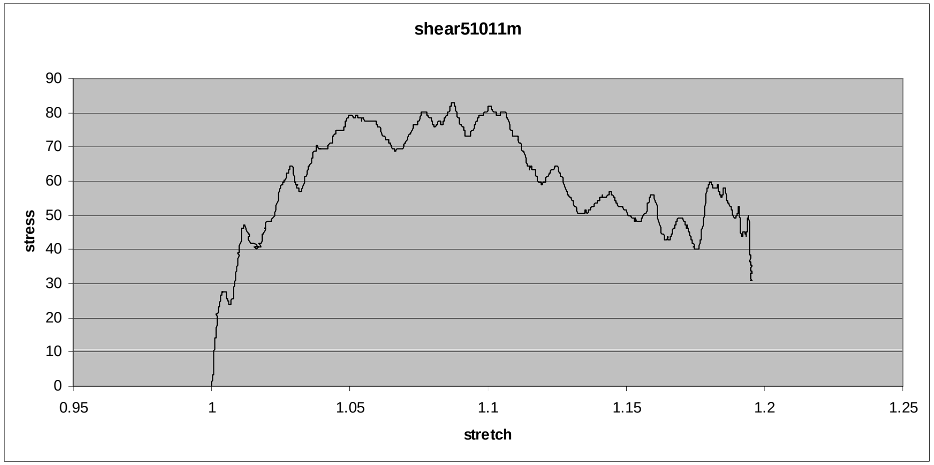
HALF SINE DISPLACEMENT

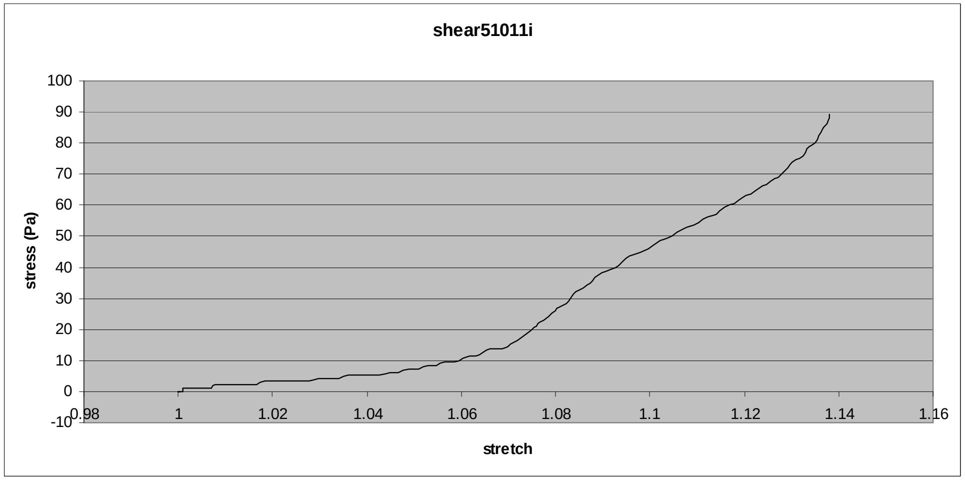
A. SINUSOIDAL RAMP TO INVESTIGATE VARIABLE STRAIN RATE

<u>TOP</u>: 0.1 mm/s, 7x6x3 mm, INNER SAGITTAL SLICE

1. SLIP WITHIN SPECIMEN, LARGE DAMAGE AT 10 %

<u>BOTTOM</u>: 10 mm/s,   5x6x3 mm INNER SAGITTAL SLICE





NONLINEAR NON-EQUILIBRIUM PROCESSES

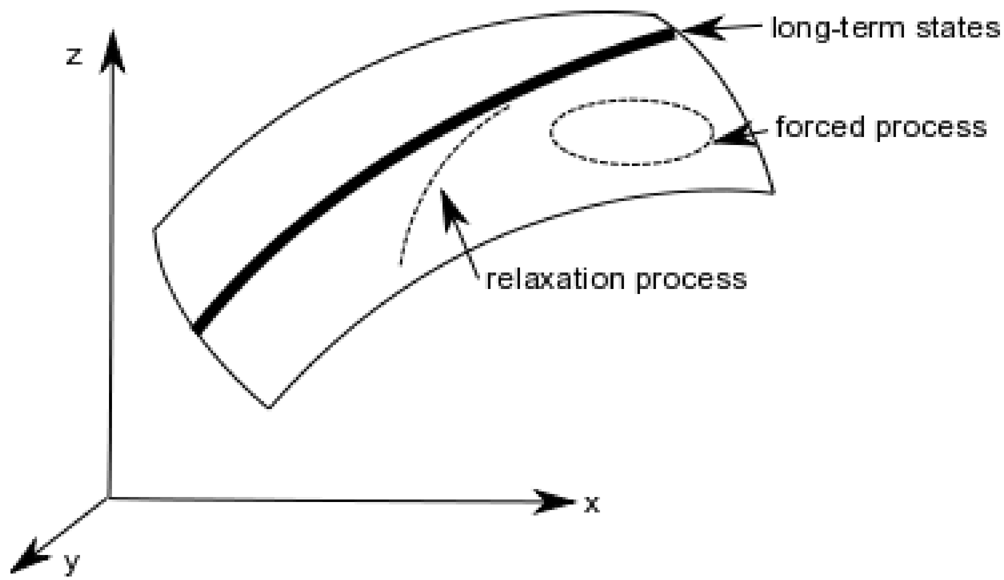
A. BRAIN TISSUE MATHEMATICAL MODEL CANNOT BE AD HOC

B. BASED ON NONLINEAR THERMODYNAMICS OF SOLIDS

C. DYNAMIC RESPONSE ORGANIZED BY EQUILIBRIUM STATES

1. THIS IS WHY QUASI-STATIC RELATIONS NEEDED

D. SUPPLEMENTS THE SECOND LAW BY A MAXIMUM DISSIPATION PRINCIPAL TO GIVE PROCESS DIRECTION



THERMODYNAMIC MODEL

E. THERMODYNAMIC MODULUS, k, DEFINES SPEED

F. LONG-TERM HYPERELASTIC STRAIN ENERGY DENSITY φ
WHERE x IS STATE VARIABLE (e.g. STRESS)
AND y IS CONTROL VARIABLE (e.g. STRAIN)

G. GIVES A UNIQUE NON-EQULIBRIUM EVOLUTION EQUATION

1. CONTRAST TO CONTINUUM THERMODYNAMICS CLAUSIUS-DUHEM INEQUALITY WHICH DOES NOT DETERMINE THE RESPONSE
2. THE SMALLER k, THE MORE VISCOUS

$$\frac{dx}{dt} = -k\left(\frac{\partial^2\varphi}{\partial x^2}\right)^{-2}\left(-y(t) + \frac{\partial\varphi}{\partial x}\right)$$

POSSIBLE PRIMARY MECHANICAL CAUSE OF mTBI

A. AXON STRAIN (WHITE TISSUE) - DIFFUSE AXONAL INJURY (DAI)

1. DYNAMIC STRETCH OF AXON MAY INDUCE SWELLING BULBS ALONG THE AXON
2. BULBS ARE FOCUS OF DEGENERATION

(SMITH AND MEANEY, 2000)

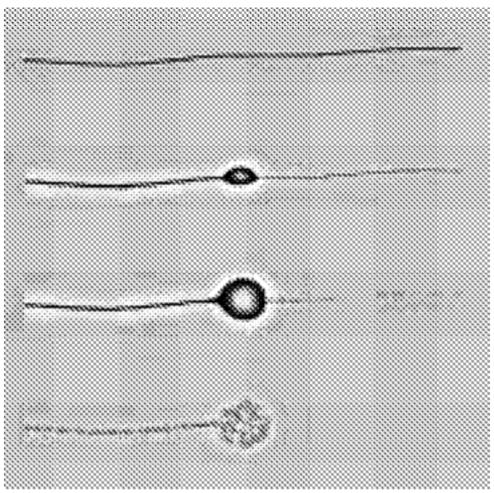


Fig. 8. Illustration demonstrating the evolution of axonal bulbs and disconnection following brain trauma. Localized mechanical damage in the axon results in swelling in one discrete region of the axon. With further swelling and cytoskeletal disarray, the axon disconnects immediately distal to the swollen region. Ultimately, the entire axon undergoes degeneration.

THRESHOLD CRITERIA FOR mTBI?

A. SMALL STRAINS KNOWN TO REDUCE AXON CONDUCTIVITY

B. SWELLINGS IN RAT SPINAL NERVE ROOTS ACCUMULATE β AMYLOID PRECURSER PROTEIN (β-APP), A MARKER FOR IMPAIRED TRANSPORT (SINGH ET AL., 2006).

1. COMPLETE IMPAIRMENT AT 9% STRAIN AT 15 mm/s

C. DAI DUE TO INERTIAL LATERAL ROTATIONAL LOAD

1. 5-10% STRAIN COMPLETE IMPAIRMENT (MARGULIES AND THIBAULT, 1992)

D. EVEN SMALLER STRAINS CAUSE DAMAGE

HYPOTHESIS

A. INTERCELLULAR MOISTURE FLOW FROM PRESSURE DEFORMS AXON TRACTS

1. KEY: MECHANICAL RESPONSE OF SUBSTRUCTURES

B. LEADS TO AXON STRAIN AND DAMAGE

1. SECONDARY BIOCHEMICAL CHANGES

C. IN RAT, TEST HIPPOCAMPUS AND CORPUS CALLOSUM FOR AXON MOTION UNDER HIGH STRAIN RATE

D. CHANGE IN OSMOTIC PRESSURE MAY CAUSE CELL DEATH

SOME OPEN QUESTIONS

I. HOW ARE MECHANICAL PROPERTIES OF BRAIN TISSUE RELATED TO mTBI?

A. THREE CAUSES OF PRIMARY MECHANICAL INJURY

1. SHOCK WAVE, 2. IMPACT, 3. INERTIAL ACCELERATION

B. HOW DO LOCAL FLUID PRESSURE, STRAIN, STRAIN RATE, VARIABLE STRAIN RATE AFFECT PERMEABILITY?

C. HOW IS STRAIN SOFTENING RELATED TO mTBI?

D. HOW DOES PERMEABILITY RELATE TO STRESS WAVE SPEED AND AMPLITUDE IN TISSUE?

E. HOW DO LOCAL INTERCELLULAR FLUID PRESSURE AND FLOW RELATE TO AXON DAMAGE?

F. DOES SHOCK WAVE DEHYDRATE LOCAL REGIONS?

OPEN QUESTIONS

II. HOW CAN A FINITE ELEMENT MODEL PREDICT mTBI?

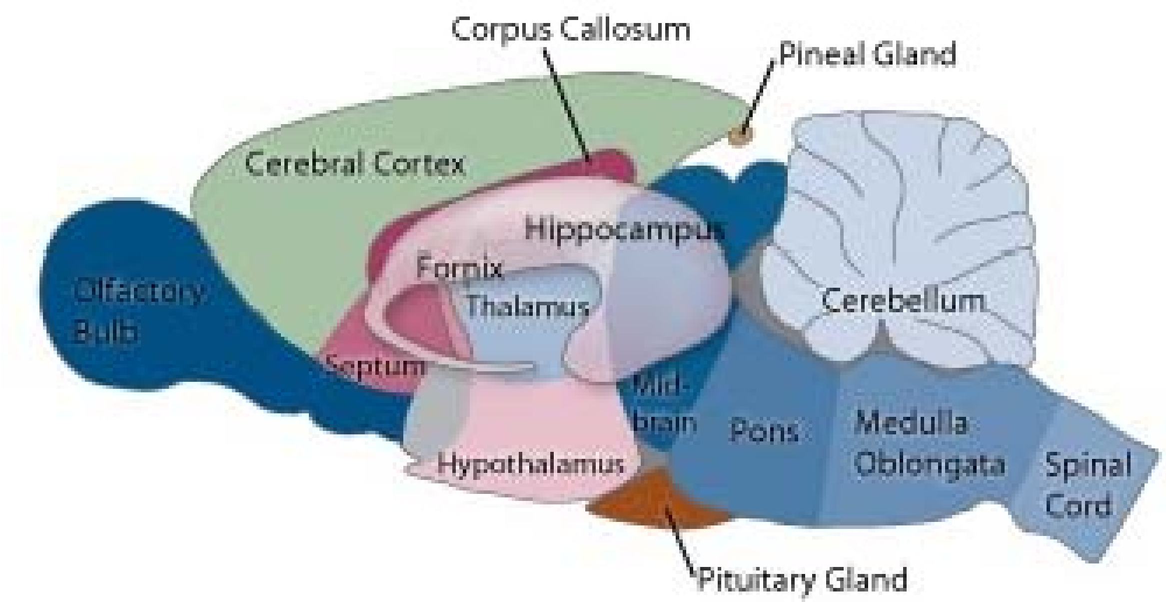
A. WHAT LEVEL OF SUBSTRUCTURES MUST BE INCLUDED IN A FEM?

B. IS THERE REALLY A THRESHOLD CRITERION?

1. OR JUST A THRESHOLD AT WHICH mTBI IS IMMEDIATELY NOTICEABLE?

C. FEM MUST ACCOUNT FOR INTERCELLULAR FLUID BEHAVIOR

RAT BRAIN SCHEMATIC



From http://learn.genetics.utah.edu/content/addiction/genetics/images/brains_large.jpg