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The Effects of Strain Softening in Adult and Pediatric Dura Mater

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ABSTRACT

Head and neck injuries are a substantial source of morbidity and mortality in children in the US, accounting for about 30% of child deaths and $10 billion in estimated annual cost (CDC 1990; Kraus et al. 1990; James et al., 1999). To study these injuries, providing routes for potential injury prevention, computational Finite Element Models (FEM) of children must have representative constituent material properties. This study focuses on the strain softening properties of the dura mater, the phenomenon whereby a material experiences a decrease in stiffness after undergoing previous strain. This behavior may be important in computing dynamic response in impact and failure scenarios (Kirton et al; 2005), especially in young children, and is rarely characterized. Eleven post-mortem human subjects (3-adult; 9-pediatric) were used to produce 46 dura mater samples. Each sample was repeatedly loaded to three increasing strain levels, including 1/24, 1/12, 1/8, 1/6, 1/3 and ½ of the estimated average yield strain of the dura mater. Changes in modulus, peak stress and hysteresis energy were analyzed. Strain softening was characterized using a strain amplification factor, the change in the Young's modulus of the dura as it undergoes repeated loading at increasing strain levels. In oscillatory tests to 2% Lagrangian strain, there was a 9.7% decrease in peak stress and a 39% decrease in hysteresis energy loss from the first to the last cycle. In contrast, for strains larger than 2%, there was a 28% decrease in peak stress and a 68.9% decrease in hysteresis energy loss from the first to the last cycle. These differences suggest evidence of strain softening at large strain levels.

INTRODUCTION

Head and neck injuries are common among children in the United States accounting for about 30% of the overall child deaths due to injury (CDC 1990; Kraus et al., 1990; James et al., 1999). The annual cost of such injuries has been estimated as $10 billion in children 18 and younger (Ommaya et al., 2002). Currently, finite element models (FEMs) are an important tool for studying child head and neck injuries; FEMs may give insights into brain mechanical response and brain injuries; information that cadaver tests cannot directly provide (Margulies and Thibault 2000; Zhang, Yang et al. 2001; Zhang, Yang et al. 2001; Klinich, Hulbert et al. 2002). To produce accurate FEMs for detailed mechanical response, local and global anthropometry is needed, including component anthropometry. For these material components, accurate constitutive relationships or material properties are required for the range of strains and strain rates desired in the calculation. This study focuses on characterizing the strain softening properties of the dura mater to further the development of more accurate FEMs, especially in high strain regimes for young children.

Dura mater is the layer of tissue that encapsulates the brain. It lies between the brain and the skull and is made up primarily of collagen fibers and elastin (Nolte 1999). The dura mater functions to protect and support the brain (Nolte 1999) and has an estimated Young's modulus of about 50MPa in adults (McElhaney; 1970). It also allows for pressure variation in the cerebrospinal fluid within the skull (van Noort et al. 1981).

Several studies have described the dura mater as grossly isotropic and shown that mechanical properties are independent of tissue orientation (McGarvey et al. 1984; Sack et al. 1998; van Noort et al. 1981; Wolfinbarger et al. 1994). For adults specimens, age has been found not to correlate with mechanical properties in dura mater, but this study only examined ages 20 to 80 years-old (van Noort et al. 1981) and no studies have reported mechanical properties in the pediatric age range.

Two studies have looked at the structural properties of the dura mater. Kriewall tested pediatric dura mater in tension cause by inflation and reported non-linear stiffnesses and stiffness values that averaged 3.7 N/mm fitted using the Skalak method (Kriewall et al. 1983; Skalak et al. 1973). Kriewall also found a positive correlation with fetal weight and stiffness. Byskil later studied the pediatric dura mater using biaxial tension and again found non-linear stiffnesses (Bylski et al. 1986). Byskil also found his biaxial tension stiffness values (ranging from 1.3 to 3.8 N/mm) were significantly less the inflation stiffness values reported by Friewall. Also contrary to Friewall's findings, no correlation was found between stiffness and weight (Bylski et al. 1986). No pediatric dura mater constitutive properties have been reported in the literature. Properties such as ulimate stress and strain and modulus of elasticity are still unknown for the pediatric dura mater. Further, this study is the first to investigate the strain softening behavior of the dura mater.

Strain softening is the phenomenon observed when a material experiences a reduced stress response at a given strain level as a result of undergoing previous loading at strain levels less than the yield strain of the material (Mullins and Tobin, 1947) (Figure 1). Strain softening behavior has been observed in biological tissues such as the myocardial and ventricular cells of the heart (Emery et al. 1997) and small intestines of guinea-pig and in the smooth muscles of rabbits (Speich et al. 2005; Gregersen et al. 1998).

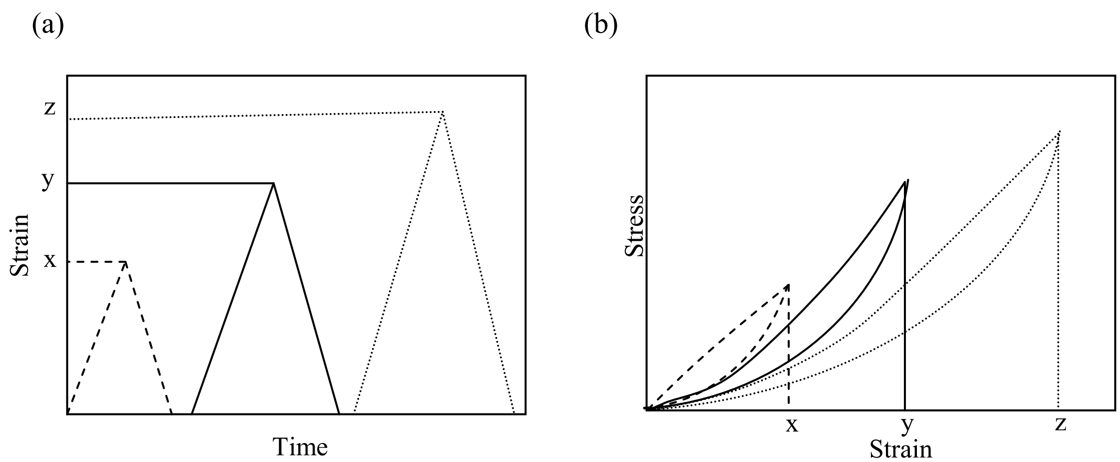


Figure 1: Strain softening. (a) Loading at three increasing strain levels, (b) Stress response for the corresponding loading tests. (Adapted from Marchmann et al; 2002).

It is therefore hypothesized that the human dura mater experiences strain softening and the main goal of this study was to investigate the effects of strain softening on the dura mater. Changes in Young's modulus at increasing strain levels were calculated and analyzed. The change in stress at a given strain level was determined for successive ramp and constant velocity loading tests, and the percentage of hysteresis energy loss and peak stress due to strain softening was calculated for oscillatory force/displacement tests.

METHODS

Twelve post-mortem human subjects were tested. Test subjects included three adults (ages: 67, 57 and 67 yrs) and nine pediatric (ages: 34, 37.5 week gestation; 1, 3days; 5, 9, 11 months; 6years and 9years) producing a total of 46 samples. Whole heads were dissected from the cervical spine at the atlanto-occipital joint, the cranial cap removed and the dura mater was gently peeled off the skull in broad sheets. Using a 4mm by 24mm rectangular steel punch, samples of dura mater were cut from the broad sheets. Lateral view pictures of sample thickness were taken to calculate the cross sectional area.

(a) (b)

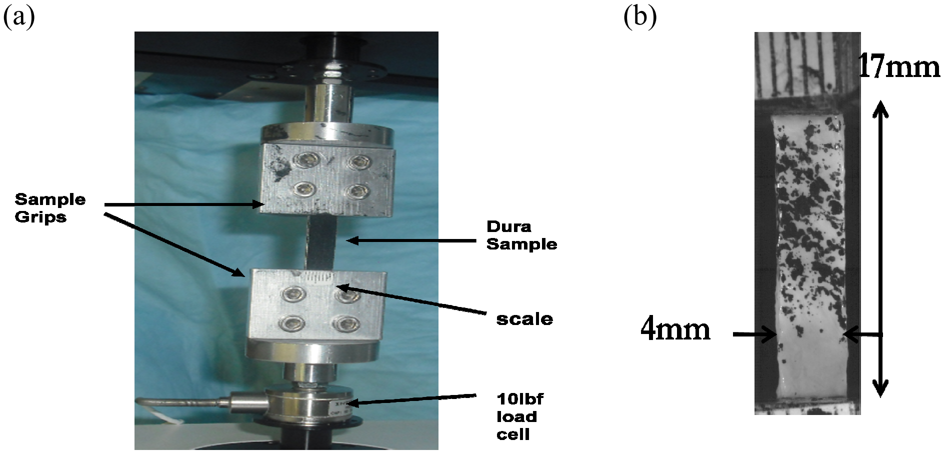


Figure 2: a) Experimental Set-up. b) Grip to grip section of sample.

Strain softening samples were kept in saline solution (0.9% NaCl) and refrigerated prior to testing. Separate samples were harvested to obtain the physiological strain of the dura mater. With initial dimensions of 24 by 4mm, these samples were left to relax for an hour in saline solution. Using this change in length, the Lagrangian strain of the samples was calculated and this strain was used as the physiological strain of the dura mater in vivo. The strain softening samples had the physiological strain imposed on them at the start of testing.

Data obtained from previous dura mater failure testing was used to calculate yield strain (AM Loyd, TG Verla et al; 2010). The strain softening test battery used included preconditioning, three oscillatory tests and three ramp and hold tests both at three increasing strain levels as shown in Figure 2. Oscillatory tests consisted of 10 cycles at a frequency of 1Hz and the loading tests were carried out at a ramp velocity of 100mm/s with 10s of relaxation time. Wait time between two successive tests was 100 seconds (10 times the duration of the test). Samples underwent one out of the two sets of strain levels imposed dura mater. Some samples had the following imposed strain levels: 1/24, 1/12 and 1/8 of the average yield strain of the specimen (low strain levels). Other samples were strained at high strain levels of 1/6, 1/3 and ½ of the yield strain. The dura mater was sprayed constantly with saline solution throughout the experiment to keep it moist.

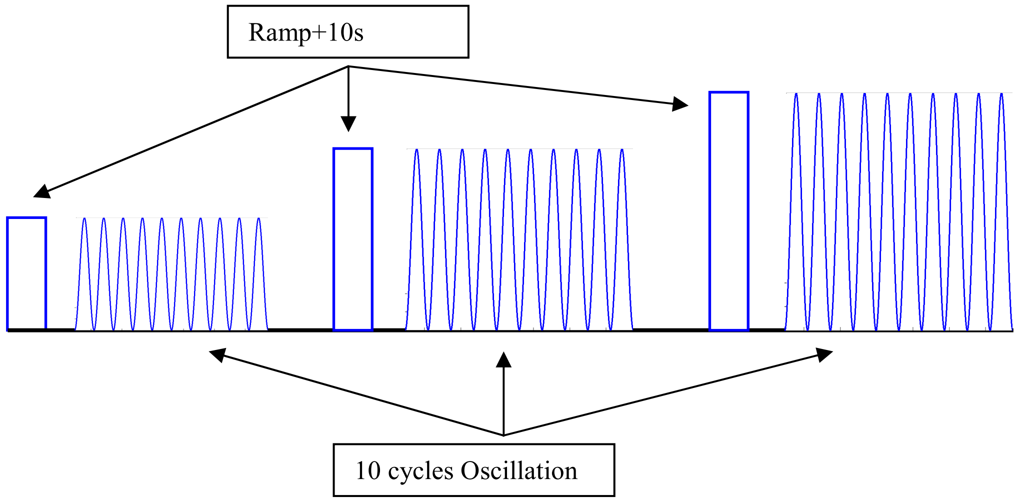


Figure 3: Test Protocol (Displacement profiles)

The tests were performed on a Bose Electroforce 3200 (Minneapolis, MN). The force was measured using a 10 lbs Honeywell Load cell (Columbus, OH) and the displacement was measured using the internal LVDT of the testing machine. Force, time and displacement data were acquired using labVIEW, and video was recorded using the Phantom Camera System (Vision Research Inc. NJ). Data were filtered in MATLAB using a finite impulse response low pass filter with cutoff frequency of 200Hz. Stress was calculated as

$$\sigma = Force/Area$$

where the area was measured as the initial cross sectional area of the dura specimen
Lagrangian strain was calculated as

$$\epsilon_s = \frac{\Delta L}{L_o} + \frac{1}{2}\left[\frac{\Delta L}{L_o}\right]^2$$

where L_o is the original length of the dura and ΔL is the change in length as it is being loaded. The Young's modulus of the dura was calculated as the slope of the stress-strain curve

$$E_y = \sigma/\epsilon_s$$

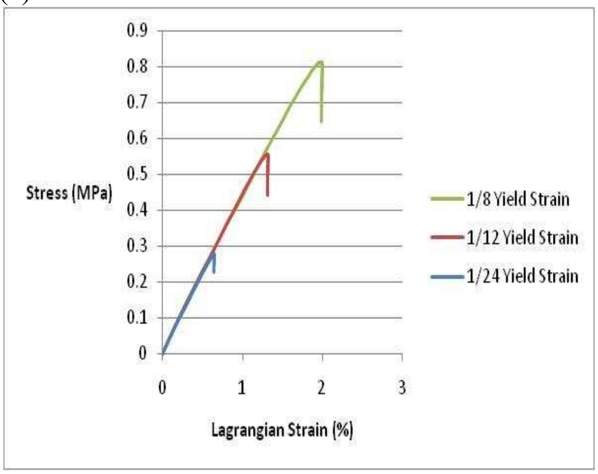
Data Analysis

For a given strain level, ϵ_o, changes in stress response at that strain level for the three loading tests were compared by calculating the percentage differences. The stress values at the lowest strain level for three three successive loading tests on a given sample were recorded for both the low and high strain tests. Using the smallest strain level for each test as the reference point, the stress values were calculated at that strain level for all three ramps, normalized and averaged for all specimens. A strain amplification factor was calculated for the high strain tests by dividing the modulus of the 1/6 yield strain ramp by that of the 1/6, 1/3 and ½ yield strain ramps. For the oscillatory tests, the energy loss between loading and unloading was averaged and normalized for 10 cycles.

RESULTS

For samples tested at low strain, the stress-strain plots follow a similar trajectory and the average Young's moduli were 17.5MPa, 16.4MPa and 18.0MPa for the 1/24, 1/12 and 1/8 yield strain tests respectively. A set of representative tests is shown in Figure 4a. High strain levels were imposed on another set of samples as shown in Figure 4b and the moduli were 16MPa, 10.8MPa and 6.7MPa for the 1/6, 1/3 and ½ yield strain tests respectively. The average yield strain from our failure data of dura mater samples was in the range of 9 – 15%. The wait time between successive tests was 100 seconds.

(a)



(b)

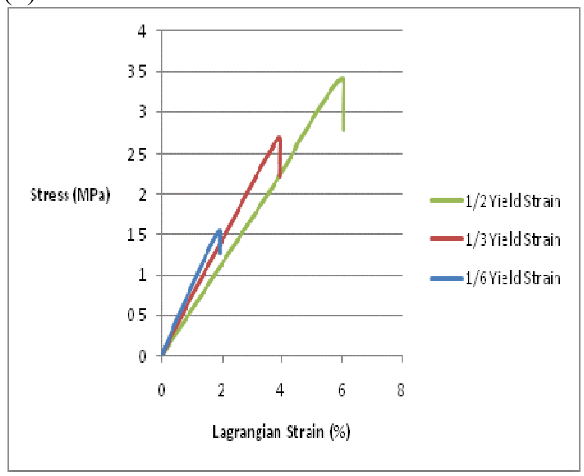


Figure 4: Example plots from two specimens. (a) is a 34 week gestation specimen showing no evidence of strain softening as seen in the alignment of the stress strain curves for three increasing strain levels. (b) is a one day old specimen undergoing strain softening. Subsequent loading experiences decrease young's modulus.

Figure 5 shows the first cycles for the three oscillatory tests at increasing strain levels (one day old specimen). The path of the stress response is different for each loading strain level. This indicates how the stiffness of the dura mater reduces in successive loading tests.

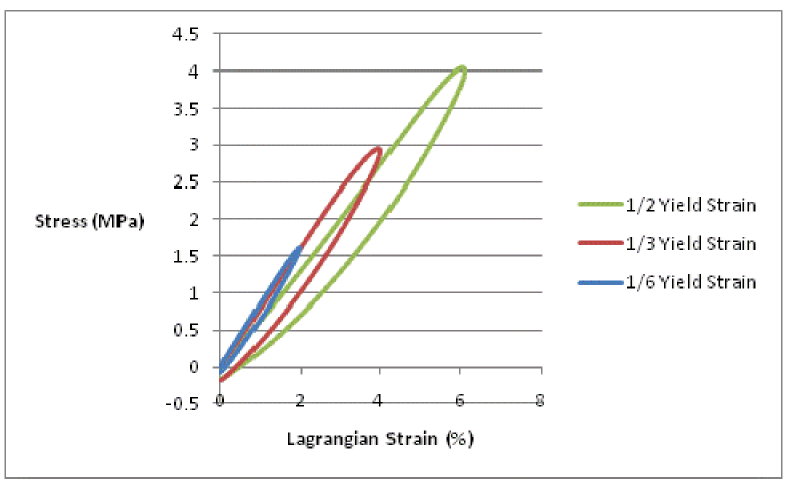


Figure 5: First cycle of oscillation tests at three increasing strain levels

For the low strain tests, there was little variation in the young's modulus in successive loading tests as shown in Figure 6b. On the contrary, high strain tests show a constant decrease in modulus as the strain level increases (Figure 6a) with a 27% decrease in modulus from the 1/6 to the 1/3 yield strain tests and a further 25.8% decrease from the 1/3 to ½ yield strain test.

(a) (b)

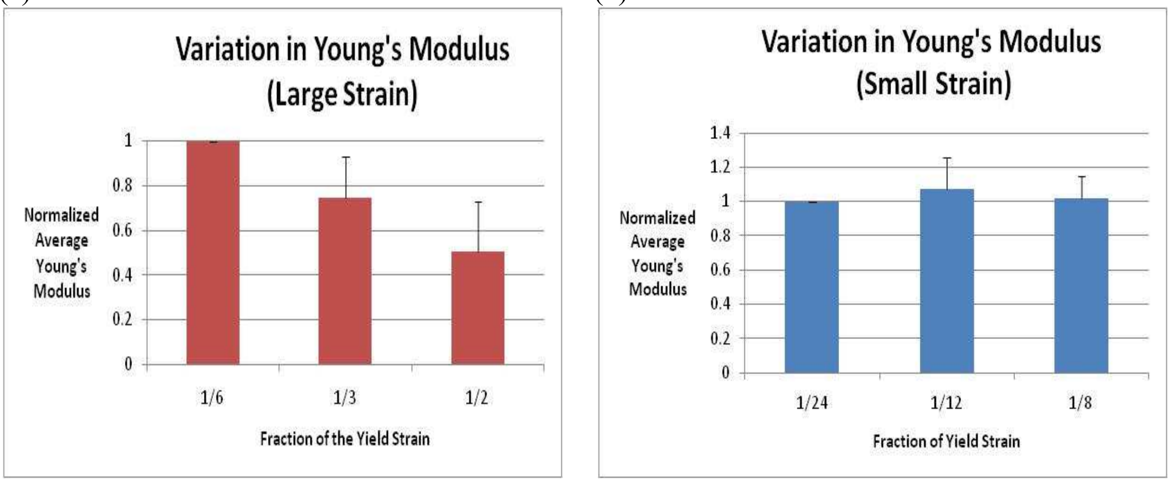


Figure 6: Change in Young's modulus with increasing strain levels

The stress values at the lowest ramp for three successive loading tests on a given sample were recorded for both the low and high strain tests. Results are shown in the Figure 7. At high strain levels, there was a constant decrease in stress at the lowest strain level (18.7% decrease in the 1/3 yield strain test and a 43.5% decrease in the ½ yield strain test), (Figure 7a). This decrease was more than what was observed at low strain levels (0.2% difference between 1/24 and 1/8 yield strain test), (Figure 7b).

(a) (b)

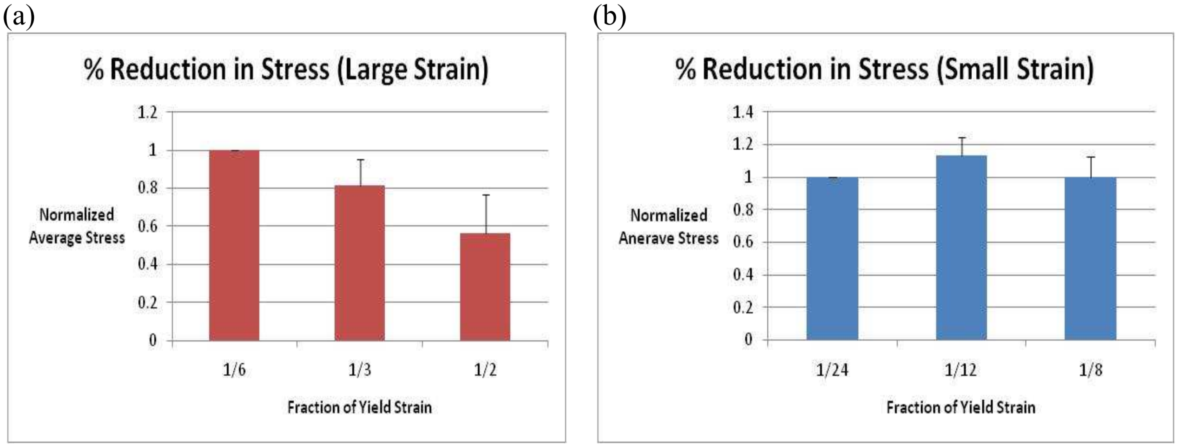


Figure 7: Average change in stress at 1/6 yield strain. Stress at 1/6 yield strain was compared for all three ramp tests and the data normalized.

In the oscillation tests, for every cycle, the dura mater undergoes loading and unloading events. The peak stress and the amount of energy lost decrease with cycle number. This decrease is observed more in the high strain tests compared to the low strain tests (Figure 8). Comparison of the first and last cycles of the oscillation tests shows 68.9% and 28% decrease in hysteresis energy loss and peak stress respectively for the high strain tests. For the low strain tests, there was a 39% and 9.7% decrease in hysteresis and peak stress respectively.

(a) (b)

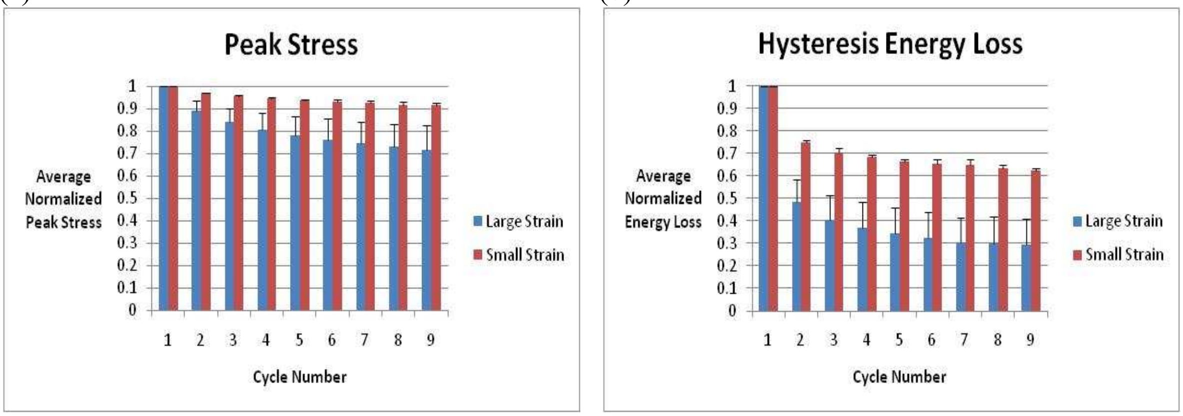


Figure 8: a) Changes in peak stress for each cycle b) Changes in hysteresis energy loss for each cycle

The strain amplification factor (S_{AF}) is the young's modulus of the dura mater in the high strain tests normalized to the modulus (E_o) obtained when loaded to 1/6 of the yield strain (lowest strain level in the high strain level tests).

$$S_{AF} = \frac{E(\epsilon \geq \epsilon_o)}{E_o}$$

where ϵ_o is the lowest strain level (1/6 of the yield strain in the high strain test). It was calculated for the high strain tests and the results are represented in Figure 9. The amplification factor starts at 1 and increases to 1.4 in the 1/3 yield strain test and to 2.4 in the ½ yield strain test.

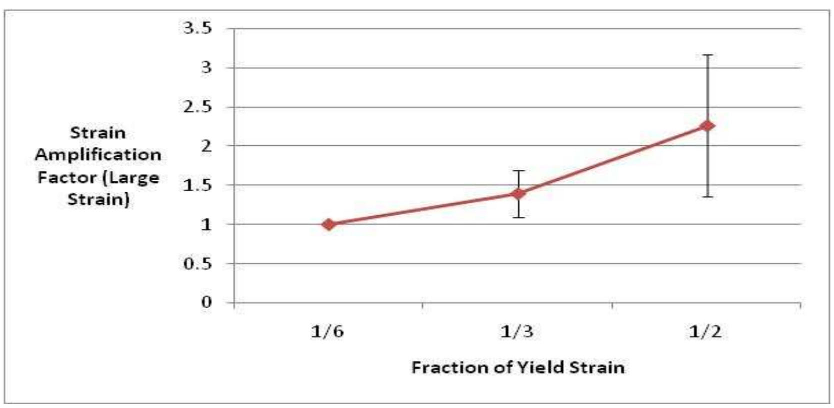


Figure 9: Modulus reduction factor of the dura mater

DISCUSSION

When loading was done at high strain levels: 1/6, 1/3 and ½ of the average yield strain, the dura mater experienced strain softening (fig 6a; fig 7; fig 8). At high strain levels there was a significant reduction in the young's modulus in repeated loading tests. These strain softening effects appear to be irreversible since the dura mater samples failed to return to their initial stress states after being strained. This irreversible softening may be the result of an irreversible change in the fiber orientation of the collagen fibers and elastin (cf. Jonson and Beatty; 1993). Alternatively, the polymer chain cross-linkages in the collagen, elastin and fibroblast in the dura matrix might be breaking during high strain loading (cf. Speich et al. 2005).

There was a 9.7% decrease in peak stress and 39% decrease in hysteresis energy loss between the first and last cycle in the oscillation tests at low strain levels. For high strain levels, there was a 28% decrease in peak stress and a 68.9% decrease in hysteresis energy loss from the first to the last cycle. During the oscillation tests, as the dura mater was loaded and unloaded to the same strain level, there was constant decrease in the potential energy that exist in the bonds holding the collagen fibers together. This decrease in potential energy may be attributed to the change in fiber orientation and destruction of cross-linkages. As the loading and unloading sequence continued, the energy that the fibers possess decreased and consequently, a decrease in the hysteresis energy loss between loading and unloading. In addition, there was a decrease in peak stress as the dura mater oscillated from one cycle to the next. This decrease in hysteresis energy and peak could be caused by both strain softening and viscoelastic effects.

The strain level over which the dura mater experiences strain softening is within the strain levels of certain events in infants. During childbirth, the head undergoes repeated loading and unloading as a result of contraction and relaxation of the uterine walls and pelvic muscles in an effort to expel the baby from the uterus. This causes the dura mater to experience strain softening and as a result, it may require a smaller force to produce a good amount of deformation to allow for safe passage of the baby. At the same time, the dura mater at the boundaries of the sutures and the fontanel could experience strain that could lead to strain softening.

The effects of strain softening have lead to serious questions about the implication of preconditioning in material testing. In most engineering material testing, precondition is normally done at strain levels greater than the in vivo strain of the material to be tested. The material in this case slowly undergoes strain softening until it attains a steady state level whereby there is no change in peak stress as a result of a previous cycle of loading and unloading. Such material will eventually exhibit properties (Young's modulus and peak stress) which are less than what they would be had the material been preconditioned at a strain level less than the in vivo strain. Thus, can strain softening from single or repeated impacts cause changes in injury behavior? This matter is still open to further research.

CONCLUSION

The dura mater experiences strain softening when it undergoes repeated loading at strain levels higher than its physiological strain. This is evident from the reduction in young's modulus in repeated loading tests at increasing strain levels (27% decrease in E from 1/6 to 1/3 yield strain test and 25.8% decrease from 1/3 to ½ yield strain tests). Furthermore, the overall decrease in the amount of hysteresis energy loss and peak stress of the dura as it undergoes an oscillatory trajectory is far greater at high strain levels (68.9% decrease in H.E loss and 28% decrease in peak stress) compared to low strain levels (39% decrease in H.E and 9.7% decrease in peak stress). Viscoelastic softening could contribute to this decreased stress response, young's modulus and hysteresis energy loss; however it is a reversible process. On the contrary, strain softening is an irreversible process which might be caused by an irreversible change in the fiber orientation of the collagen and damages in the cross-linkages of the polymer chains in the dura matrix, or simply the irreversible squeezing of water out of the dura matrix. Thus in order to fully understand the dura mater and its protective role towards the brain, the strain softening behavior has to be considered, especially in the development of Finite Element Models of the dura mater.

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