DYNAMIC CHARACTERIZATION OF BOVINE MEDIAL COLLATERAL LIGAMENTS

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ABSTRACT

Knee injuries are common in automobile pedestrian crashes. Lateral impact on the knee results in varus-valgus bending and causes injuries to collateral ligaments. Mechanical properties of ligaments under different loading conditions are important for developing human body finite element model to predict the injury risk to pedestrians in automobile crashes and for safer design of vehicle fronts. Tensile properties of the middle region of medial collateral ligament are reported between 0.0001/s to 140/s as obtained from isolated ligament tests. The results show a linear stress-strain response at lower strain rate whereas it is nonlinear and strain rate sensitive in dynamic loading conditions.

Knee Joints, Injuries, Pedestrians, Ligament, Viscoelasticity

PEDESTRIAN–AUTOMOBILE COLLISIONS often result in severe injuries to the lower extremities. In lateral impact the varus - valgus strain results in injuries to the collateral knee ligament (Kajzer et al. 1990, 1993, 1999, Kerrigan et al. 2003). In lateral impact on knee during automotive crashes, varus –valgus deformities result in failure of ligament by avulsion or rupture (Teresinki et al. 2001). Medial collateral ligament is the main focus of attention as it is the most frequently injured ligament. Further, it is known that constitutive properties of ligaments are not the same in different regions of the ligament (Robinson et al. 2005). There have been some studies on the mechanical properties of collateral ligaments (Trent et al. 1976, Kennedy et al. 1976, Butler et al. 1986, Quapp et al. 1988, Kerrigan et al. 2003, van Dommelen et al., 2005 & 2006). While most studies are for quasi-static properties, Van Dommelen et al. (2005 & 2006) have reported MCL properties at strain rate up to 45/s. These properties are thus at low strain rates, which does not correspond to the loading seen in pedestrian automobile crashes. Hence determination of dynamic mechanical properties is significant for predicting injury risk in pedestrian automobile crash. The variation in between quasi-static and dynamic estimate of stiffness and failure stress would be significant in deciding injury thresholds.

Further, most of the studies have reported properties of the combined bone-ligament-bone complex as opposed to only the ligament (Trent et al., 1976, Kerrigan et al., 2003, Robinson et al., 2005, van Dommelen et al., 2005). As ligaments are known to be non homogeneous, anisotropic and viscoelastic in nature, regional properties are important in predicting injury levels in pedestrian-automobile collision and for FE simulation to study pedestrian impact kinematics. Ligament function and propensity for injury are directly related to regional stresses and strains (Phatak et al. 2007). Avulsion failures of ligaments from bony attachment are usually associated with bone weakness at the attachment site due to age of the donor (Robinson et al. 2005). The structure and architecture of the tissue plays an important role in determination of mechanical properties. The properties are dependent not only on the constituent but also on the proportions of various components at different locations (Netti et al., 1996). In the present study, the middle region properties of nine (N=9) isolated bovine medial collateral ligaments are determined in quasi-static and dynamic loading. Bovine ligaments have been used in the current study because of easy availability and to understand overall trends under dynamic loading. Their properties are known to be similar to human ligaments. Kerrigan et al. (2003) have reported human MCL elastic modulus in the range 182.5 ± 87.2 Mpa at strain rate of 12/s (STD ±3), while in this study the modulus of the bovine MCL has been found to be (235.66 ± 84 MPa) under quasi-static loading. Consequently it was decided to use bovine ligaments in this initial study.

SPECIMEN PREPARATION

Bovine knee medial collateral ligaments were obtained and dissected within one hour after sacrificing the animal. The knee ligament specimens were then stored at -20 ^{0}C prior to test. Thawing of specimen was done for about two hours to bring the specimen to room temperature. In quasi-static test, pre-conditioning for 3 cycles for load variation from 0 to 50 N was done. In dynamic test the specimen were preloaded to 15 N (weight of guiding frame). Ligament length subjected to test and minimum cross sectional area obtained through localized section thickness measurements (TABLE A).

EXPERIMENTAL SETUP

Quasi-static (Screw driven) and dynamic (drop type) test setups were designed and developed as shown in Fig. 1 and Fig. 2. The specimens were held using a cryogenic gripper with liquid nitrogen flowing through them causing frost formation between the gripper faces and the ligament. The ligament ends were held lightly between the jaws of the gripper. The jaws were cooled by liquid nitrogen that flows through them, causing the ends to freeze. An ambient temperature control unit was used to maintain the temperature of the specimen within 20 ± 1^0 C in both types of tests. A temperature control unit regulates the midpoint temperature of the ligament through thermocouple measurement and on-off control of an hot air flow. Humidity of the specimen was maintained by intermittently spraying brine solution. The quasi-static setup has been designed to obtain a linear speed between 0.5 to 1 mm/min. In dynamic setup a maximum velocity of 8 m/sec can be achieved. Strain gauge based transducers; S type load cell (ADI ARTECH) capable of measuring up to 5000 N and 7500 N were used in quasi-static and dynamic tests respectively.

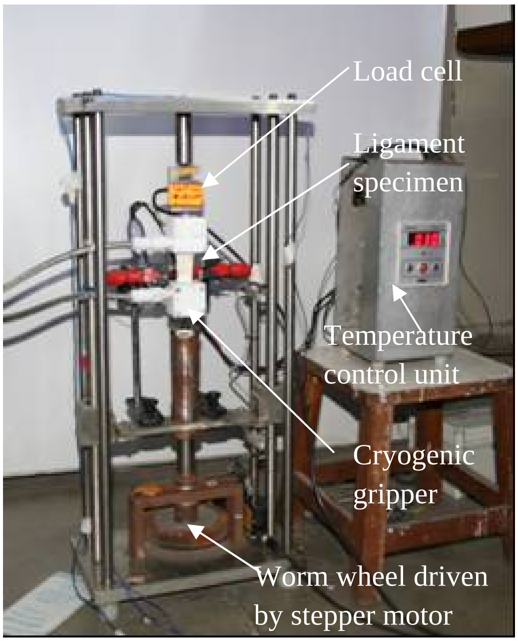

Fig.1 Quasi-static Tensile Setup

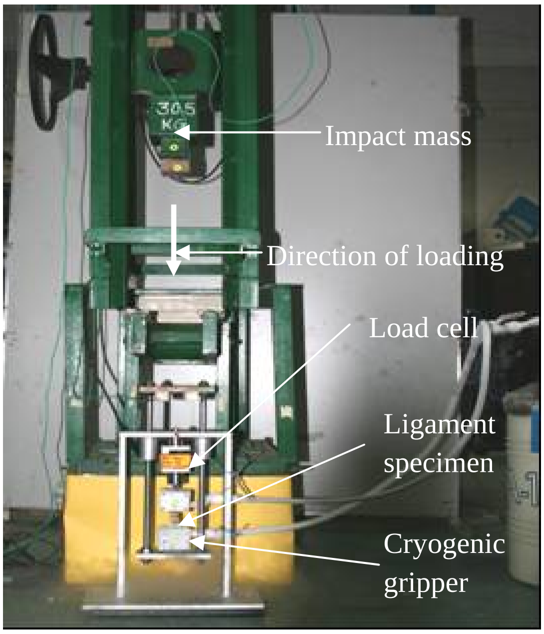

Fig.2 Dynamic Tensile Setup

A laser based sensor as well as video film analysis were used to determine the specimen elongation in quasi-static tests, with load and displacement data being recorded at 1 Hz. In dynamic test, a high speed motion camera (REDLAKE, San Diego, CA, USA) was used to capture the event at 10000 fps. The video was subsequently analyzed to find out the displacement of ligament and initial velocity of the impactor. Sensor data was acquired using an e-DAQ module (SoMat Corporation, Urbana, IL, USA). A buffered trigger switch was used to trigger high speed camera and data acquisition system in dynamic test, which synchronizes the displacement data and force data acquired at 10,000 Hz. Acquired force data was obtained with N-Soft^{TM} (N-Code, Sheffield, UK) data analysis package. The displacement and velocity data was measured from high speed motion camera by using Image express^{TM} software.

RESULT AND DISCUSSION

Bovine medial collateral ligament specimens were tested at 0.0001/s to 0.0003/s in the quasi static setup. By setting the drop height, strain rates up to 137/s were attained in the dynamic tests. The stress-strain plot is shown in Fig.3. The identified ligament properties are indicated in table A.

Table A: Bovine MCL properties derived from the quasi-static and dynamic loading

Test ID/ Type	Ligament length tested (mm)	Min. Cross sectional area (mm sq)	Strain rate (1/s)	Peak strain (%)	Max. stress (MPa)	Modulus of elasticity (MPa)	Strain rate (Mean ± STD) (%)	Modulus of elasticity (Mean ± STD) (MPa)
Quasi-static tests								
QS-BF-MCL-12	25.1	76.56	$1x10^{-4}$	20.32	23.07	142	$23x10^{-5}$ ± $1x10^{-4}$	235.66 ± 84.18
QS-BF-MCL-09	44.5	61.95	$3x10^{-4}$	16.27	40.73	260		
QS-BF-MCL-10	39	45	$3x10^{-4}$	19.60	47.71	305		
Dynamic Tests								
DY-BF-MCL-02	38.30	57.00	82.65	12.47	51.46	527	92.23± 8.43	601.33± 210.5
DY-BF-MCL-06	42.40	106.40	98.55	12.15	38.96	438		
DY-BF-MCL-07	35.41	88.19	95.5	13.92	52.17	839		
DY-BF-MCL-01	32.00	61.05	137	8.29	41.70	972	119.83 ±14.19	1217.66 ±243.52
DY-BF-MCL-08	37.40	79.62	112.5	9.02	97.46	1459		
DY-BF-MCL-12	32.74	73.18	110	9.67	61.22	1222		

Fig. 4 shows the failed ligament in one of the test. The ligament failure was fiber based and often different fibers failed at different positions along the length of specimen. The failure were mostly at the mid substance region (even though they were offset from the center) as opposed to at the gripper.

These results establish the significance of strain rates in loading of the collateral knee ligament. In addition, the strain rate dependence of modulus and maximum stress has been established.

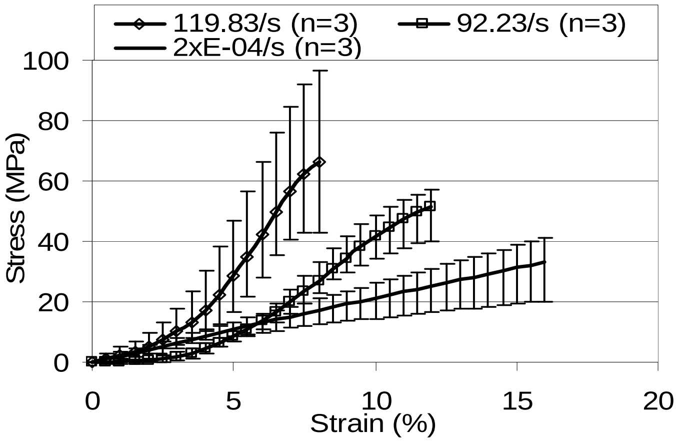

Fig.3 Stress-strain plot of bovine MCL   Fig.4 Failure photograph of ligament in dynamic test

It is observed that the stress strain curve is almost linear under quasi-static conditions, while in dynamic conditions it tends to become linear after 4% strain. Regional strain variation is observed as clamp to clamp strain was different from that obtained from image analysis of markers on ligaments.

CONCLUSION

The results show substantially linear stress-strain response at very low rate of loading for bovine MCL whereas it is nonlinear and strain rate dependant in dynamic conditions. Maximum strain to failure decreases as the strain rate increases, which is the characteristic of viscoelastic material. At a strain rate of about 140/s, the measured elastic modulus is about four times the quasi static value.. In the future it is proposed to populate the data further to establish limits of inter-sample variation, to populate the strain range further and to conduct tests on human ligaments.

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