INVERSE MATERIAL CHARACTERIZATION OF HEART UNDER DYNAMIC IMPACT

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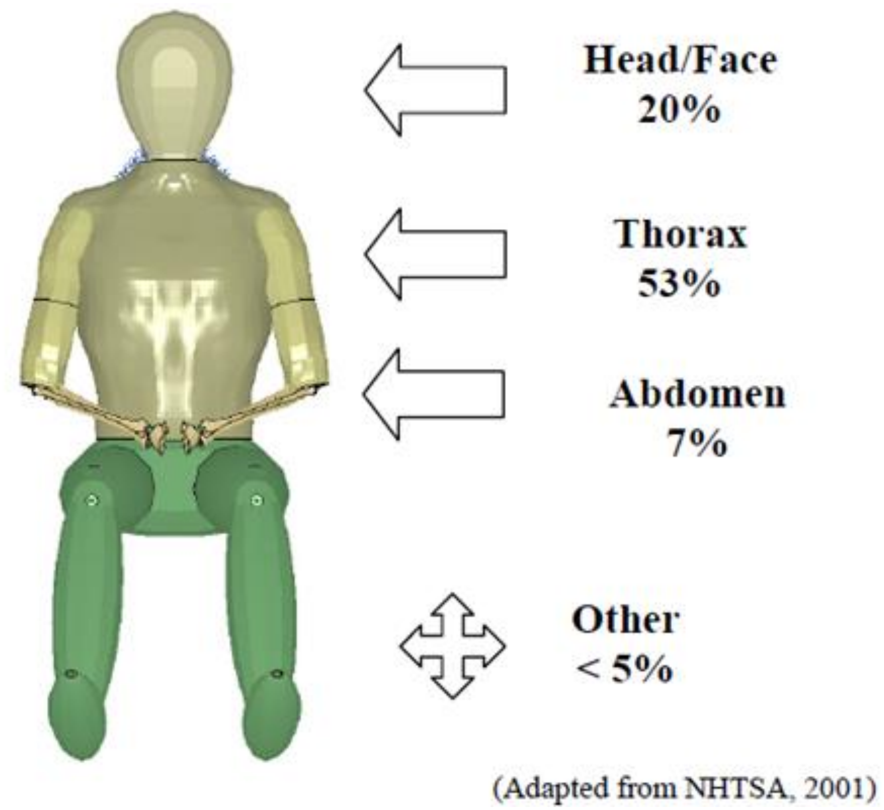
Introduction



Fatality injury distribution

- Road traffic injuries leading cause of death.(WHO 2004, 2009, 2013, 2015)
- Safety devices and features protect the vehicle occupants from major injuries and fatalities (Mukherjee et al. 2007)
- In automotive crashes thoracic region is more susceptible to get injured as compare to other body region.

Why characterize heart tissue??

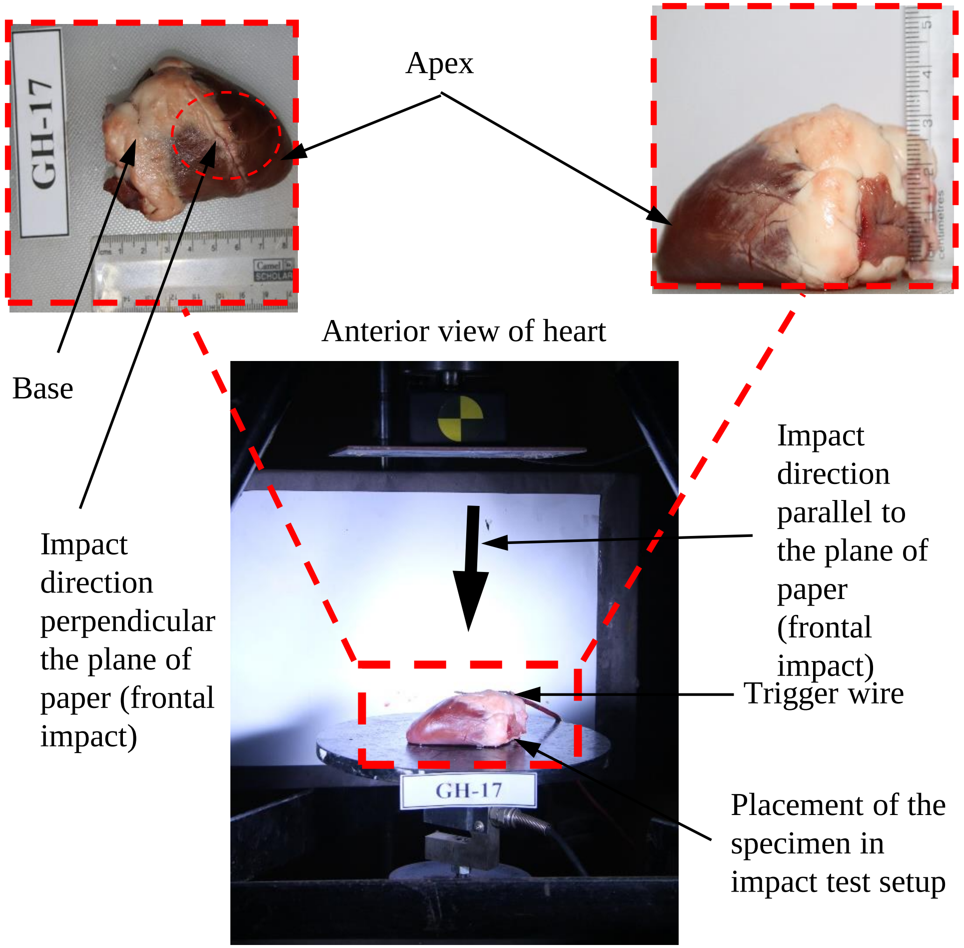
- Biomechanical behavior is important to design safer vehicle.
- Several FE HBMs (GHBMC, THUMS etc.) used to test safety features in vehicle.
- Biofideility of finite element model is dependent on the material properties of the organ.
- In thoracic region, heart is critical organ to get injured.
- Mechanics of the heart tissue under impact is not well understood.
- During crashes, heart loaded up to strain rate of 300 /s.
- Available material model for the heart tissue are at lower strain rate

There is a need to characterize the heart tissue at high strain rate.

Methodology

- 26 samples of heart were excised from the goat post mortem.
- Experiments conducted using customized electromechanical impact gun.
- Force vs displacement data recorded
- Strain rate dependent material model hypothesized
- Material parameters of constitutive model obtained from inverse characterization.

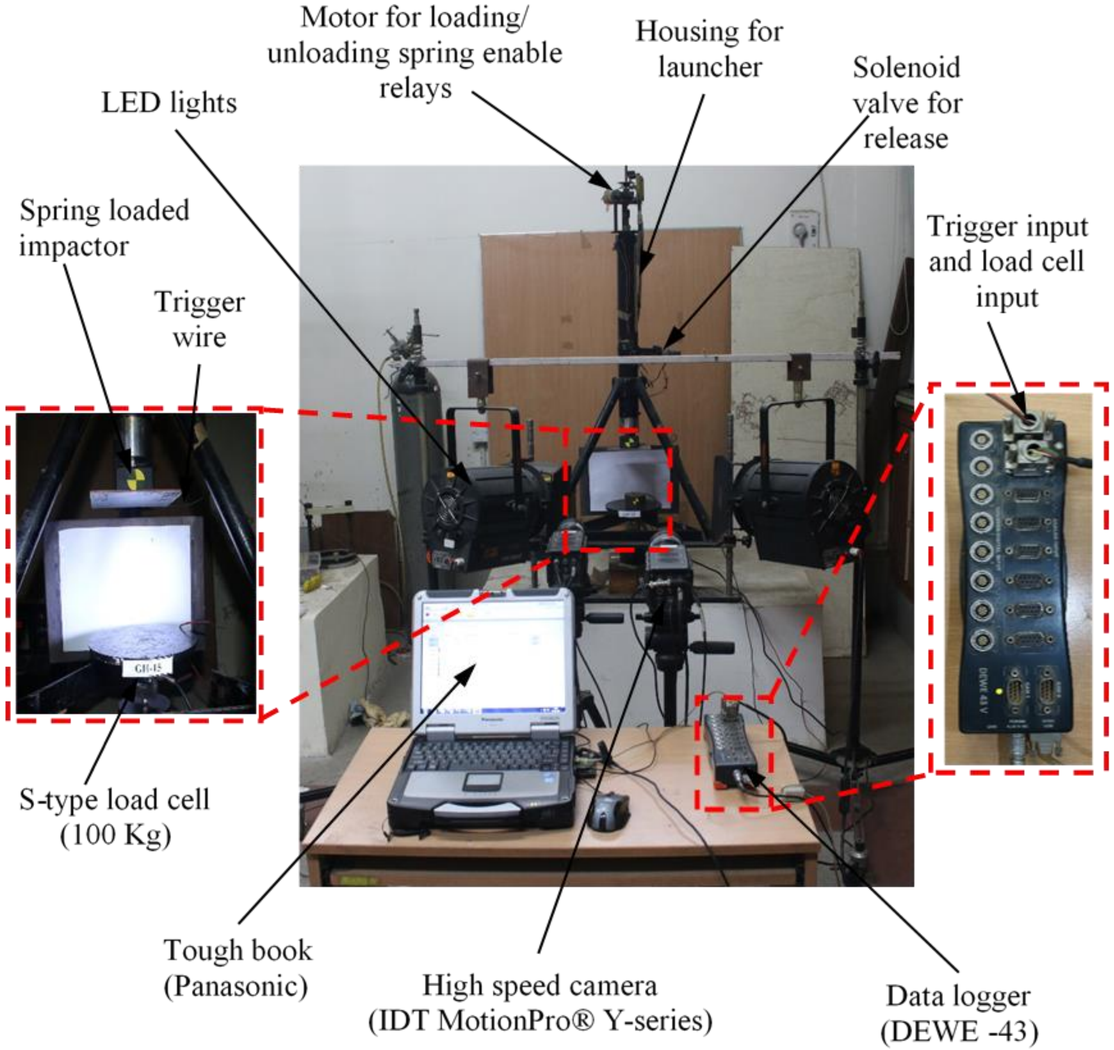
Impact testing



Whole organ measurement and placement of sample for test

- Samples stored in deep freezer at -20°C.
- After thawing, samples kept in saline solution to maintain hydration.
- Average overall organ size : 70 x 50 mm
- Thickness of the organ varies from 23 to 40mm.
- Direction of impact: A-P direction (shown by arrow)

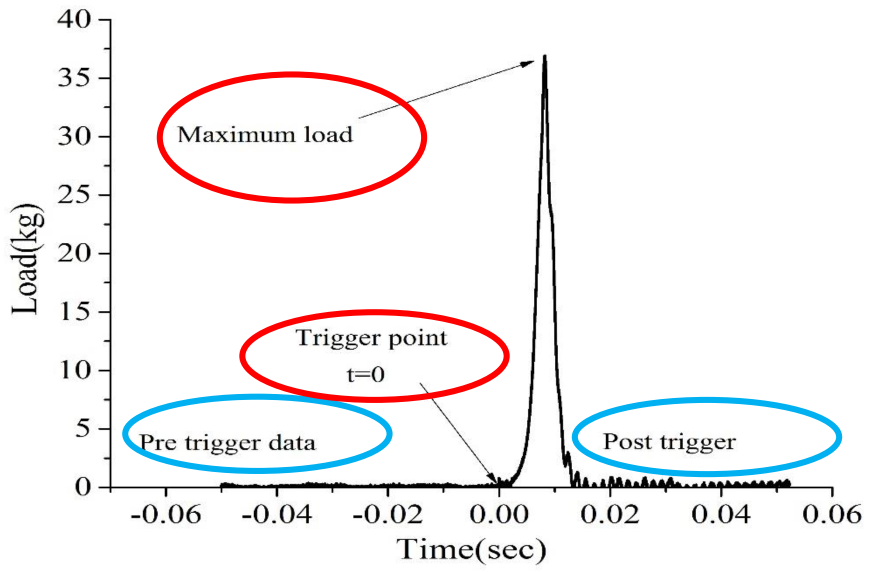
Dynamic test setup

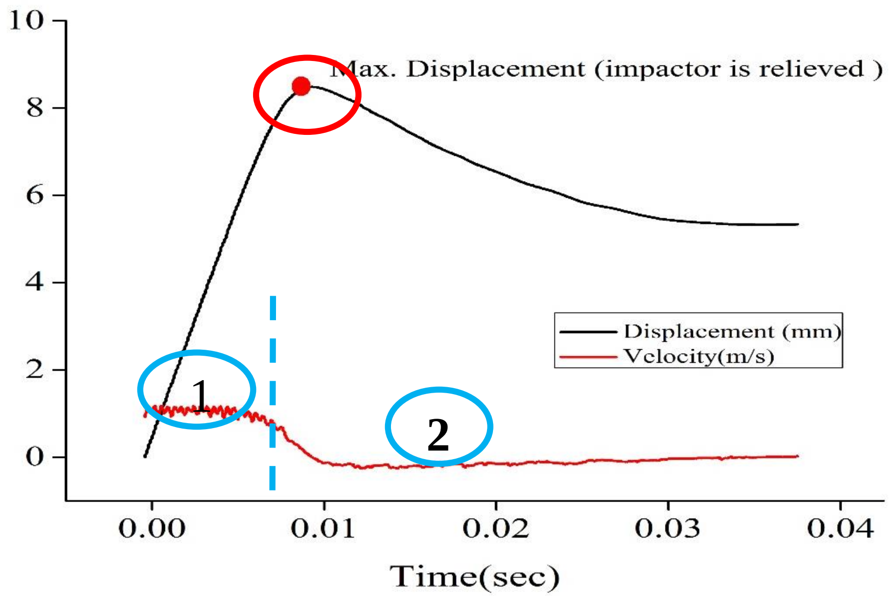


Dynamic compression setup (Impact Gun) mechanical stopper, markers, high- speed camera along with the data acquisition

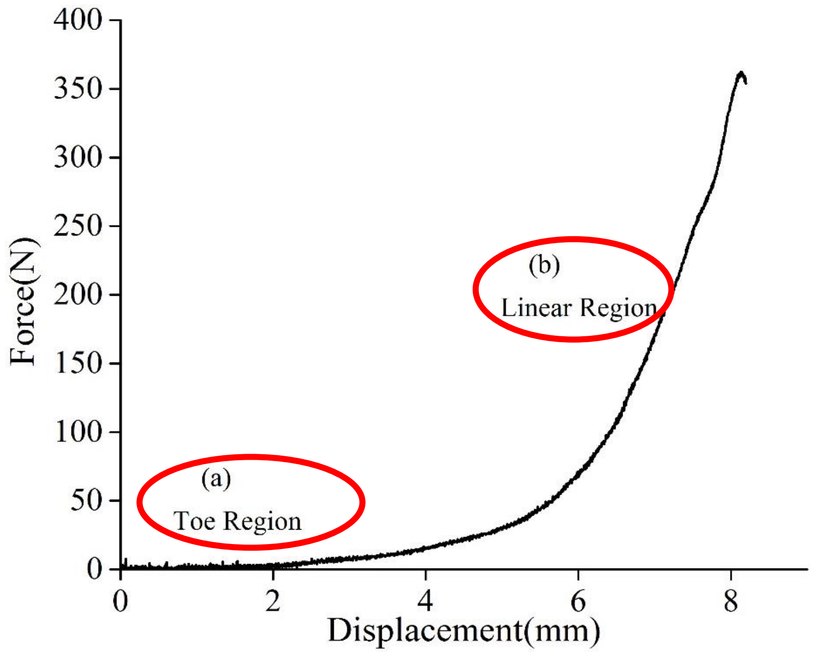
- Spring loaded launcher mechanism used in impact gun .
- Velocity regulated by the compression of spring
- Video recorded at 20,000 frames per sec.
- Data recorded at 2,00000 sample/second.
- 100 kg S type load measured the impact load
- Trigger system is used to synchronize the load and displacement data.

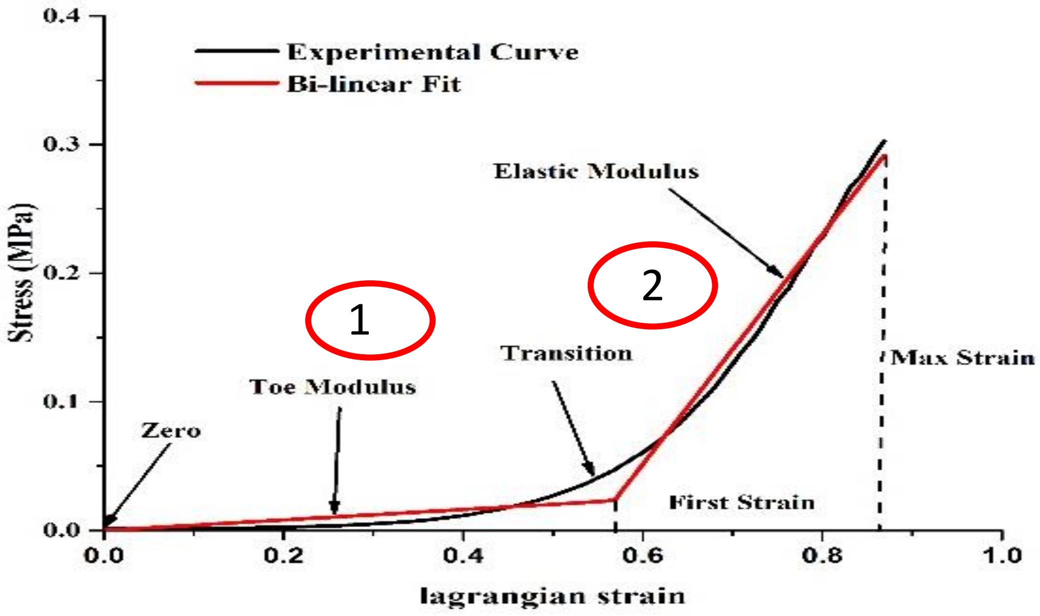
Data obtained from experiments





- Load time data is recorded as 50ms pre trigger and 50ms post trigger.
- The start time, t = 0, taken as the point where the load starts increasing
- Deformation of the tissue and impactor velocity calculated from video.
- Deformation of the tissue increases until impactor get relieved.
- Region 1 shows constant tissue velocity
- Once impactor relieved velocity drop to zero region 2





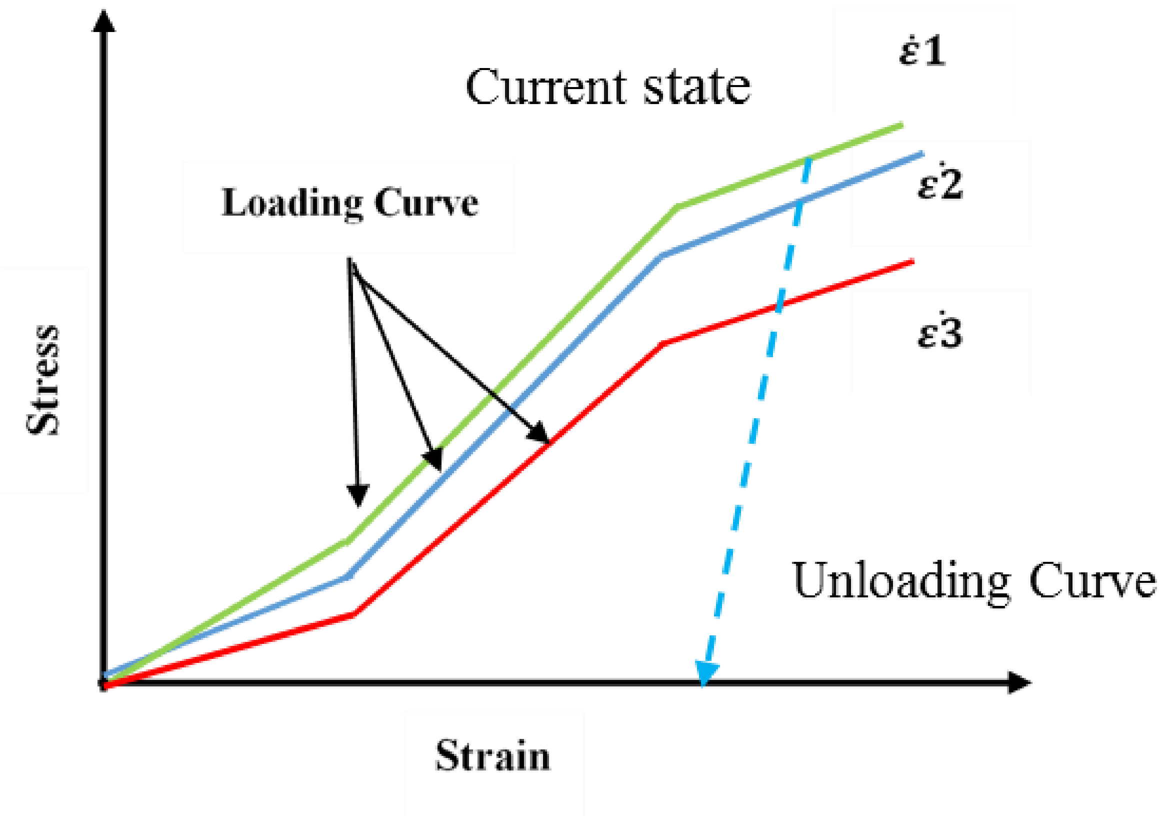
- Force displacement curve plotted from recorded force and displacement data

- Two regions are observed in force displacement data - non linear behavior seen
  - Region (a): low load deformation and
  - linear region (b) which bears maximum load

- Bi-linear strain rate dependent model has been used to capture nonlinear behavior of tissue.
- Toe region characterized by
  - Toe modulus and max toe strain
- Second region characterized by:
  - Elastic Modulus & Max strain
- All parameters taken to vary with strain rate

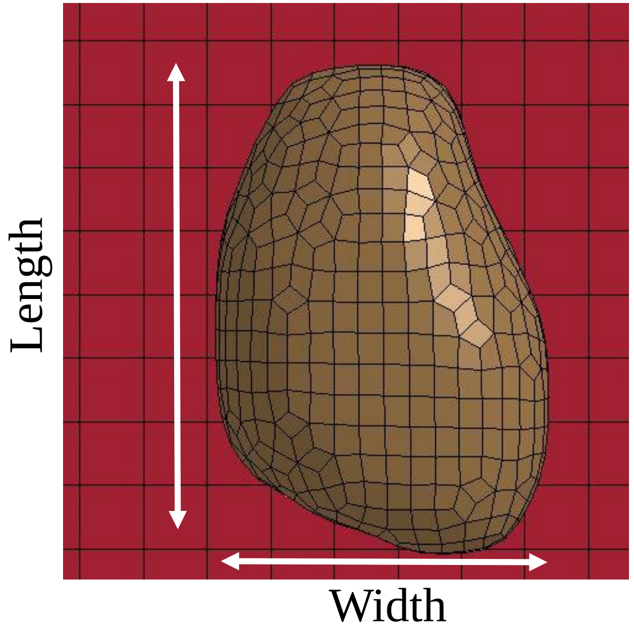
- The region of interest is the second region 2 in which injury as well as energy absorption happen

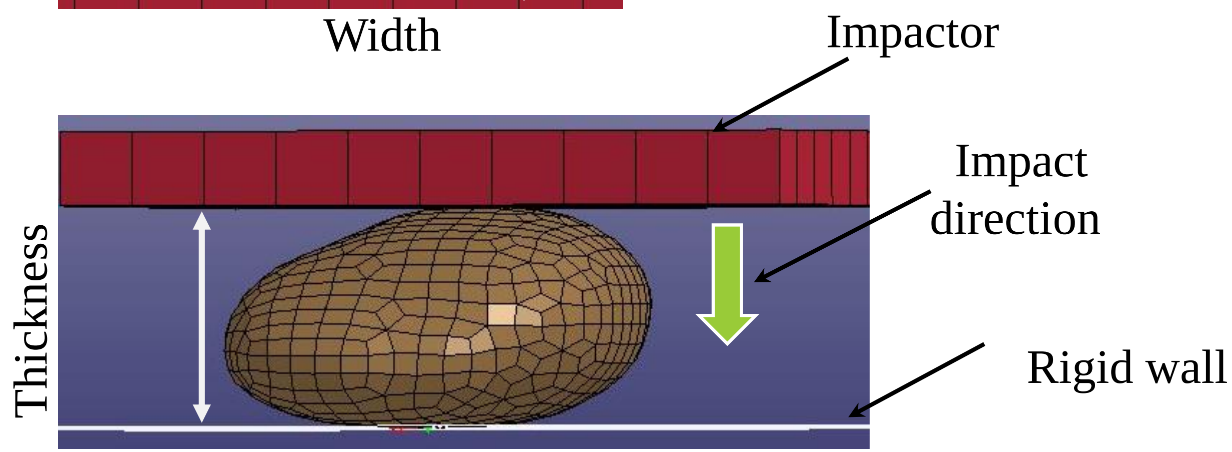
Flow chart for strain rate dependent material model



- A series of stress strain loading curves at different strain rates, i.e. up to 400/s is given as input.
- On the basis of current effective strain and strain rate, material parameter taken from these curves
- Cumulative stress updated at the end of each time step.

FE modelling of the whole organ and setup of dynamic compression test





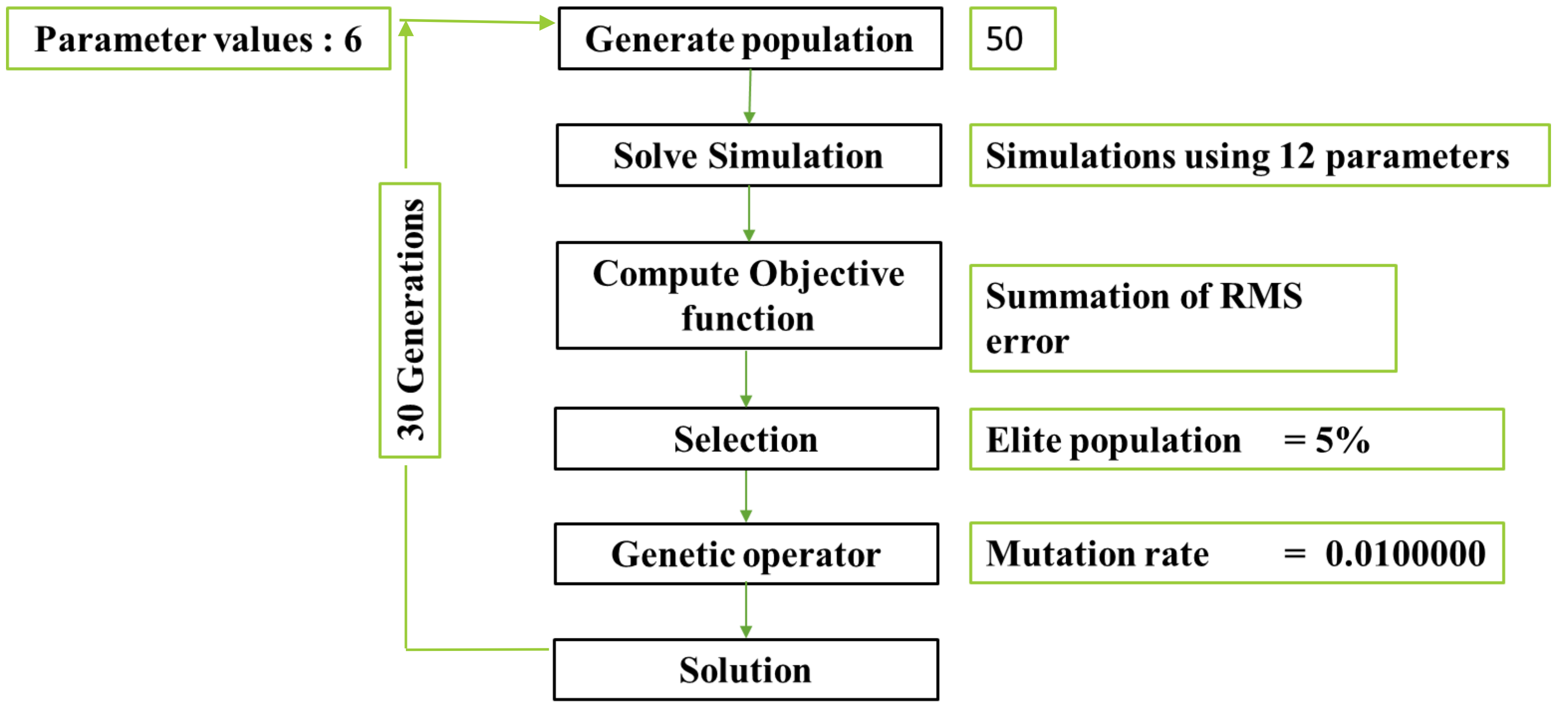
Isometric view of dynamic compression test

- Finite element model description
  Finite element mesh : Ls dyna pre post
  Element type : Eight node solid element
  FEM analysis : LS-DYNA solver in UMAT

- Scaled (as per anthropometric dimension of samples) finite element of heart used for simulation

- Material parameters (E_1, E_2, ε_1 and ε_2 at different strain rates) obtained from inverse FE characterization using GA based optimization

Optimization process flow for genetic algorithm



Schematic diagram of material parameter estimation procedure using GA

- 6 independent parameters at four different strain is input
- In each iteration GA generates population as input.
- Each family of input parameter is solved with ls dyna executable.
- Fitness /objective function is calculated for further.
- Selection process and genetic operator has been used to generate new population of input parameter for next generation.

GA formulation

The objective function of the problem is to minimize the root mean square difference between experimental and finite element forces response shown below.

$$f(X)=\text{RMS error} = \sqrt{\frac{\sum_{i=1}^{N}\left[\frac{F_{exp}-F_{sim}}{\max F_{exp}}\right]^2}{N}}$$

Where

F_{exp} = Experimental Force time value, F_{sim} = Simulation force time value, N= no of data points

Minimize *f*(*X*)

For

$E_{2\_imin} < E_{2\_i} < E_{2\_imax}$ *(E_{2_i} elastic modulus at strain rate i)*

$\varepsilon_{t\_min} < \varepsilon_t < \varepsilon_{t\_max}$ *($\varepsilon_{t\_}$ – toe strain for all strain rate)*

$v_{min} < v < v_{min}$ *(v - Poisson ratio)*

Where i = 0.001/s, 100/s, 200/s, 400/s

Subjected to constraints

$E_{2\_0.001/s} - E_{2\_100/s} \leq 0$

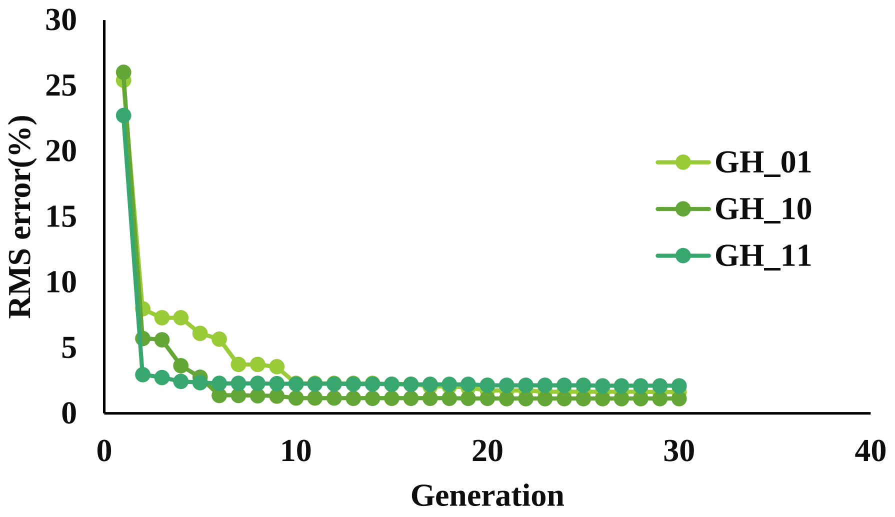
$E_{2\_100/s} - E_{2\_200/s} \leq 0$

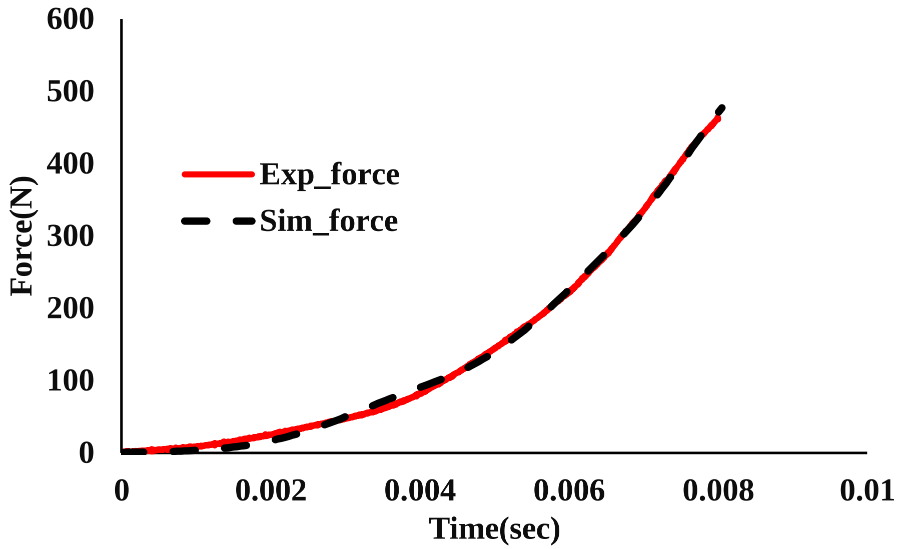
$E_{2\_200/s} - E_{2\_400/s} \leq 0$

GA input parameters

Description of function	**Value(units)**
Number of generation	30
Population Size	50
Number of real coded variable	6
Mutation rate	0.01
Random seed	1
Distribution index	5
Hybrid algorithm	Hooke-Jeeves
Elite population(%)	5
Variables iterated	$E_{2\_.001/s}$, $E_{2\_100/s,}$ $E_{2\_200/s,}$ $E_{2\_400/s,}$ ε, ν
Lower and upper bound of $E_{2\_0.001/s}$ (Mpa)	$(E_{2\_0.001/s})_{min}$=0.002, $(E_{2\_0.001/s})_{max}$=10
Lower and upper bound of $E_{2\_100/s}$ (Mpa)	$(E_{2\_100/s})_{min}$=0.002, $(E_{2\_100/s})_{max}$=20
Lower and upper bound of $E_{2\_200/s}$ (Mpa)	$(E_{2\_200/s})_{min}$=0.002, $(E_{2\_200/s})_{max}$=30
Lower and upper bound of $E_{2\_400/s}$ (Mpa)	$(E_{2\_400/s})_{min}$=0.002, $(E_{2\_400/s})_{max}$=50
Lower and upper bound of ε_t	$(\varepsilon_t)_{min}$=0.01, $(\varepsilon_t)_{max}$=0.60
Lower and upper bound of ν(Poisson ratio)	$(\nu)_{min}$=0.35, $(\nu)_{max}$=0.499

Inverse characterization





- Root mean square value convergence plot for the optimization of whole organ (heart) for 30generation
- Optimized force time response for typical heart sample

Modulus (Mpa)				Strain		Poisson ratio	RMS
$E_{2-0.001/s}$	$E_{2-100/s}$	$E_{2-200/s}$	$E_{2-400/s}$	ε_1	ε_2	ν	
3.326±2.08	7.561±4.64	15.055±5.65	33.209±9.48	0.33±0.11	0.80	0.44±0.04	2.23±1.88

Optimized strain rate dependent material parameters

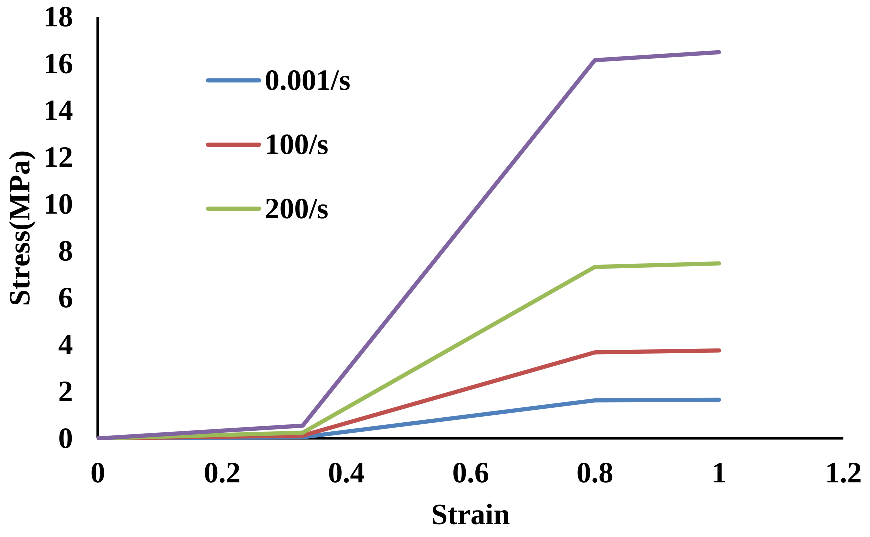
Summary

- The heart tissue modeled using bi-linear strain rate dependent model for compressive impact lading.

- Genetic algorithm based optimization in conjunction with FE simulation was used to tune material parameters by inverse mapping.

- Material model implemented using a user defined routing in ls-dyna

- Average modulus parameter obtained at 0.001/s, 100/s, 200/s and 400/s is 3.33 MPa, 7.56 MPa, 15.06 MPa and 33.21 MPa respectively.



- Input stress strain loading curve at varying strain rate

Limitation and future scope

- Behavior of the tissue is assumed to be bi-linear isotropic
- Unloading behavior has not been investigated
- Regional variation, age and other variations effects is not included
- Specimen were tested in their passive state i.e. no muscle activation there.
- Future Scope : Using the strain rate dependent user material model in HBM to predict the injury.

Thank you