Viscous criterion and its relation with the projectile-thorax energy interactions

Narasimha M. Thota[1,2*] Jayantha A. Epaarachchi[2] and Kin-Tak Lau[2]

[1] *CAD-CAE Consultants, South Australia, Australia*
[2] *Centre of Excellence in Engineered Fibre Composites, University of Southern Queensland, Toowoomba, Queensland, Australia*

[*]*Corresponding author. Email: tnmurthy@cae-consultants.com.au*

Abstract: Despite many injury criteria to measure thoracic trauma in known engineering parameters, viscous criterion, that is a product of maximum instantaneous velocity of thorax deformation and maximum instantaneous chest compression, has been widely used. Using Lobdell mathematical model of the thorax, Wang [1] has carried out analytical studies and proved that peak viscous response is related to the peak energy storing rate of the thorax and also proved that it does not related to viscosity of the thorax. Authors have carried out a scholastic study by impacting a FE model thorax MTHOTA (Mechanical THOrax for Trauma Assessment), which is fully validated for blunt ballistic impacts, with a foam nose projectile with speeds of 30 – 90 m/s with an increment of 5 m/s. VC$_{max}$ values and projectile – thorax energy interactions were evaluated and presented in this paper. From the outcome of the simulations, relation between maximum stored energy (I_{max}) and the maximum sternal deflection (y_{max}) found to be ($I_{max} \propto y_{max}^{2.06}$) and the relation between rate of maximum stored energy (I'_{max}) and the product of maximum sternal deflection and its time rate ($y_{max} \times y'_{max}$) found to be ($I'_{max} \propto y_{max} \times y'^{0.61}_{max}$). Only the former expression was very well correlated with that obtained from the analytical studies carried out using the Lodbell's mathematical model of the thorax.

Keywords: thoracic injury, blunt ballistic impacts, MTHOTA thorax surrogate, viscous criterion, projectile-thorax interaction.

Introduction

When thorax subjected to blunt impacts such as non-lethal direct impact munitions, solid sports ball impacts, etc., chest wall along with the ribs deform and cause the chest to compress. Compression of the chest, depending upon the speed and mass of the impactor and location of the impact, could cause rib fractures (single rib fracture to life threatening flail chest), lung injuries (lung contusion, pneumothorax and hemothorax). Vital organs protected by the thorax experience viscous and inertial loads when the velocity of chest deformation exceeds certain limit. Viscous and inertial loads, depending upon the magnitude, could cause serious lung and heart injuries. Blunt forces could also cause penetrating injuries as broken ribs can puncture internal organs. Evaluation of blunt thoracic trauma caused by high speed projectiles plays role of paramount importance in development of personal protective equipment for safety during sports activities, development and validation of non-lethal ammunition and validation of the bullet proof vests etc. Many researchers have developed various criteria to evaluate the blunt thoracic trauma and also human tolerance limits in terms of whole body acceleration by Stapp [2] and Eiband [3], Average Spinal Acceleration by Cavanaugh *et al* [4], Force injury by Gadd *et al* [5], Thoracic Trauma Index by Morgan *et al* [6] and Viscous Criterion by Viano *et al* [7]. Some of these researchers used human volunteers and others used human cadavers and anesthetized swine in their experimental studies. Among all the available injury criteria, peak viscous response (VC$_{max}$) has been widely used as a predictor of the blunt thoracic injury risk, which can be calculated using the equation given below.

$$VC_{max} = Max[V(t) \times C(t)] \tag{1}$$

Where,

VC_{max} = Peak viscous response in m/s

$V(t)$ = Instantaneous velocity of the chest compression in m/s

$C(t)$ = Instantaneous chest compression

Though the viscous criterion is widely used, though it was developed by statistical analysis of the experimental data obtained by using biological thorax surrogates (both animals and human cadavers), physical surrogates (anthropomorphic test dummies), the physical meaning of the criterion was unclear. Therefore, using the mathematical model of the thorax developed by Lobdell *et al* [8] , Wang [1] has carried out a study to analyze the fundamental properties of the viscous criterion and proposed four criteria. Of these, only two criteria which relate the stored energy with the deformation and deformation velocity of the thorax were given below.

- Stored Energy Criterion (SEC), according to which maximum stored energy is proportional to the square of maximum deflection of the thorax.

$$Maximum\ stored\ energy = I_{max} = y_{max}^2 \qquad (2)$$

- Energy Storing Rate Criterion (ESRC), according to which maximum rate of stored energy $\propto$ the product of maximum deflection and its time rate.

$$Rate\ of\ maximum\ stored\ energy = I'_{max} = y_{max} \times y'_{max} \qquad (3)$$

Authors have carried out a scholastic study by impacting a fully validated thorax surrogate (MTHOTA) for blunt ballistic applications with a typical blunt projectile with impact speeds from 30 – 90 m/s (with an increment of 5 m/s). From the simulation output, deflection and its time rate and theirs relation with the peak stored energy, peak viscous response and energy interactions of the projectile and thorax, etc. were elicited and presented in this paper.

2. Methodology

In order to study the impactor – thorax interaction, MTHOTA surrogate was subjected to impacts of a typical blunt projectile. As the topic of interest is not the performance of the projectile, a typical projectile with PVC base and stiff closed cell thermo-plastic foam nose was considered as the impactor.

2.1 MTHOTA FE model surrogate

A simple in construction and easy to set up, FE model of the thoracic surrogate (MTHOTA) which was fully validated by correlating its biomechanical responses with those obtained from the cadaveric experiments conducted by Bir [9] for the similar blunt ballistic impacts. FE model of the MTHOTA and its cross-section were shown in the Figure 1.
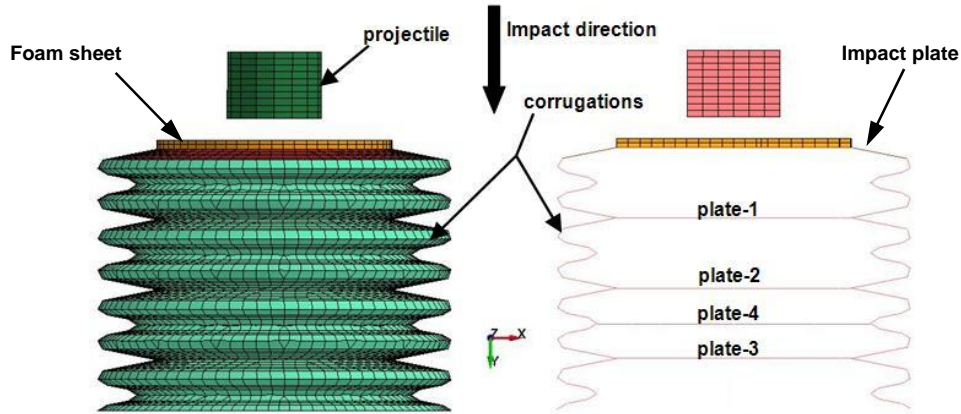

Figure 1: FE model of the MTHOTA and its cross-section. Adapted from Thota *et al* [10]

Using MTHOTA surrogate, VC$_{max}$ values were calculated using the equation (1) and appropriate scaling factor and dummy constant, as shown below.

$$VC_{max} = S \times \left(\frac{y_{max}}{D}\right) \times \left(\frac{y_{max}}{T}\right) \qquad (4)$$

Where,

VC_{max} = Peak viscous response or viscous criterion in m/s

S = Scaling factor = 0.366

y_{max} = Peak deflection of the impact plate in mm

D = Dummy constant = 110 in mm

T = Time at which deflection of the impact plate is maximum

FE model thorax surrogate MTHOTA facilitates fairly accurate prediction of the blunt thoracic trauma due to ballistic impacts and the surrogate has been tested for many case studies published by reputed military research organizations and Universities. Complete details of the construction, FE model, material models, material data and validation of MTHOTA surrogate could be found in the research work published by Thota *et al* [10] and Thota *et al* [11]. Throughout the study presented in this paper, MTHOTA has been used as the surrogate.

2.2 Details of the impactor

Though the present study is only concerned with the projectile – thorax interaction, energy stored by the thorax and its relation with the other measurable physical quantities such as deformation and the velocity of deformation, a typical projectile with PVC base and stiff foam nose (XM 1006) was considered as the impactor. Dimensions of the projectile were taken from the research work published by Lyon [12]. One of the 16 foam materials data (experimentally obtained by the present authors) was used for the nose. Projectile used in the present study was as shown in the Figure 2.
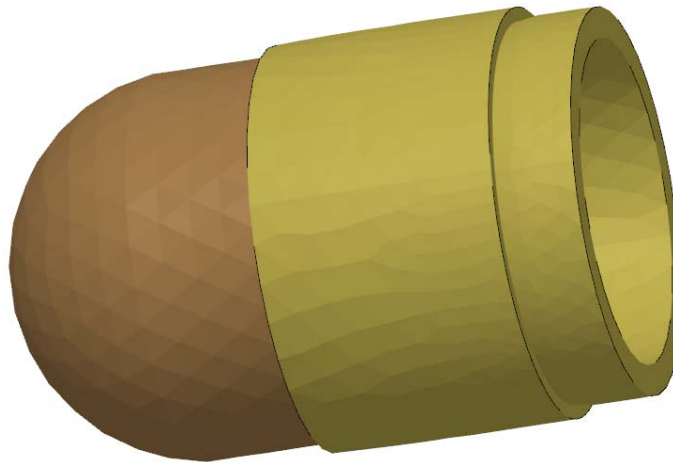

Figure 2: Typical projectile with PVC base and foam nose used in the study

MTHOTA was subjected to the projectile impacts with 13 impact speeds (30 – 90 m/s, with an increment of 5 m/s) in virtual testing environment. From the outcome of the non-linear dynamic transient FE simulations, projectile – thorax energy interactions, force–time response, deflection–time response and VCmax were elicited and presented in the paper. Peak stored energy, peak rate of the stored energy and their relation with peak deflection and its rate were also elicited and presented.

3. Results and discussion

At first, the surrogate MTHOTA was subjected to normal impact (direction of the impact is perpendicular to the impact plate) with the projectile with compressible nose with an impact speed of 30 m/s, in the virtual testing environment. States of the projectile and the thorax during the impact time and deflection – time response elicited from the outcome of the simulations were as shown in the Figure 3 and Figure 4 respectively.
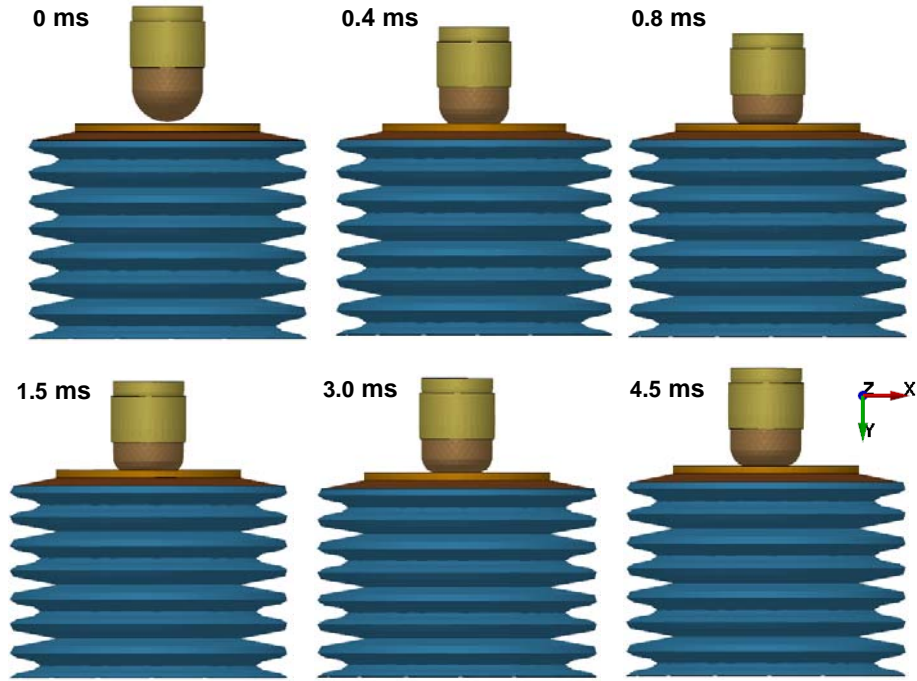
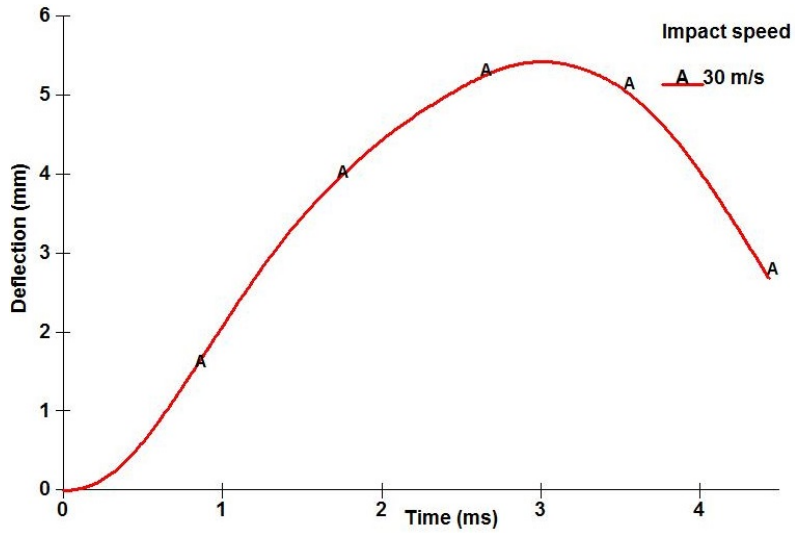**Figure 3:** Stages of the projectile and the thorax during the impact

Figure 4: Deflection – time response of the MTHOTA when subjected to projectile impact with 30 m/s speed. (Evaluated from the time histories of impact plate nodes)

Kinetic energy of the projectile and the thorax during the impact was as shown in the Figure 5. Internal energy and Total energy of the MTHOTA during the impact were as shown in the Figure 6 and Figure 7 respectively.
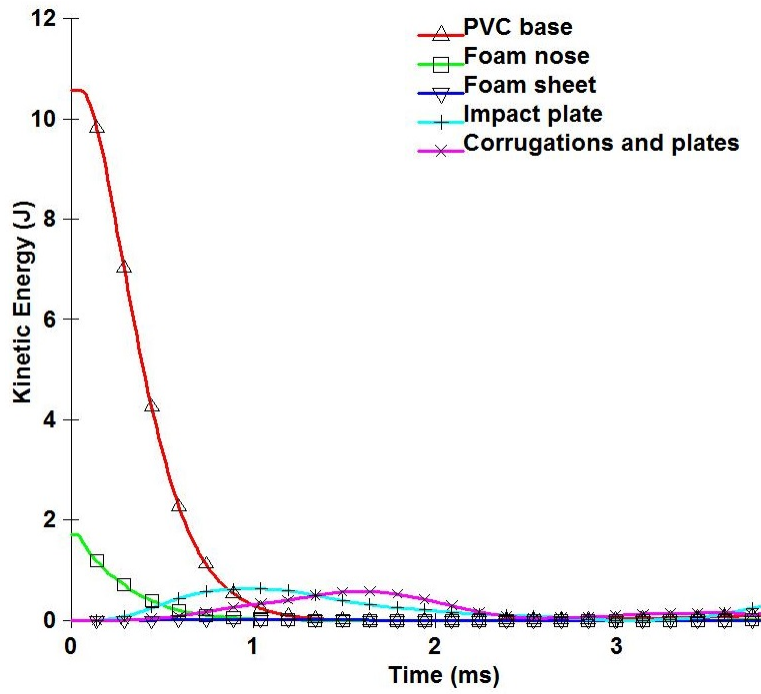
Figure 5: Kinetic energy of the projectile and the thorax during the impact (speed of the impact was 30 m/s)
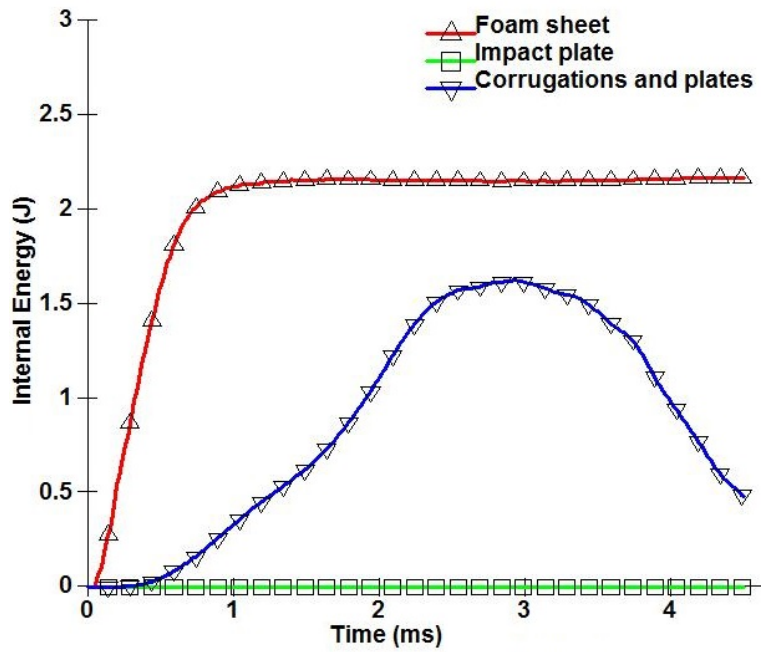

Figure 6: Internal energy of the thorax during the impact (speed of the impact 30 m/s)
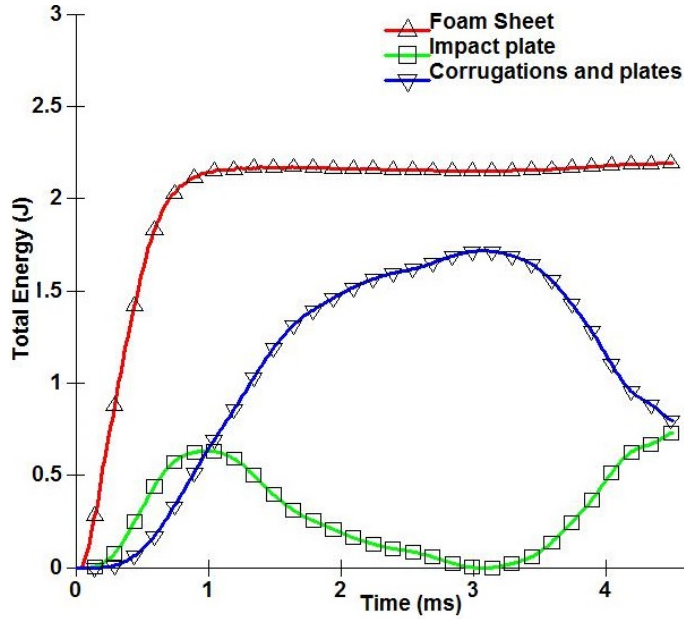
Figure 7: Total energy of the thorax during the impact (speed of the impact 30 m/s)

Similarly, deflection response, internal energy and total energy of the thorax surrogate during the impact for all other impact cases were elicited. Peak deflection (y_{max}), peak rate of deformation (y'_{max}), peak energy stored (peak internal energy or I_{max}) and its rate (I'_{max}), peak viscous response (VC_{max}) were evaluated and given in the Table 1.

Table 1: Peak internal energy and its rate, peak deformation and its rate MTHOTA

Impact speed	y_{max}	y'_{max}	$y_{max} \cdot y'_{max}$	I_{max}	I'_{max}	VC_{max} Equation (4)
30.00	3.65	1.11	4.05	3.78	1.30	0.03
35.00	4.26	1.30	5.53	4.95	1.70	0.04
40.00	4.83	1.37	6.62	6.30	2.17	0.05
45.00	5.25	1.50	7.89	7.89	2.90	0.06
50.00	5.27	1.45	7.65	9.76	3.37	0.06
55.00	5.01	3.48	17.44	11.76	3.68	0.13
60.00	5.58	3.88	21.63	13.60	4.12	0.16
65.00	6.18	4.29	26.52	16.05	4.64	0.19
70.00	6.85	4.75	32.54	18.60	5.39	0.23
75.00	7.56	5.21	39.39	21.20	5.97	0.28
80.00	8.31	5.65	46.99	24.00	6.67	0.34
85.00	9.14	6.09	55.70	27.10	7.36	0.40
90.00	10.3	5.19	53.64	30.60	8.38	0.39

Peak internal energy of the thorax surrogate versus peak deflection, rate of peak internal energy versus product of the peak deflection and its time rate were plotted and were as shown in the Figure 8 and Figure 9 respectively.
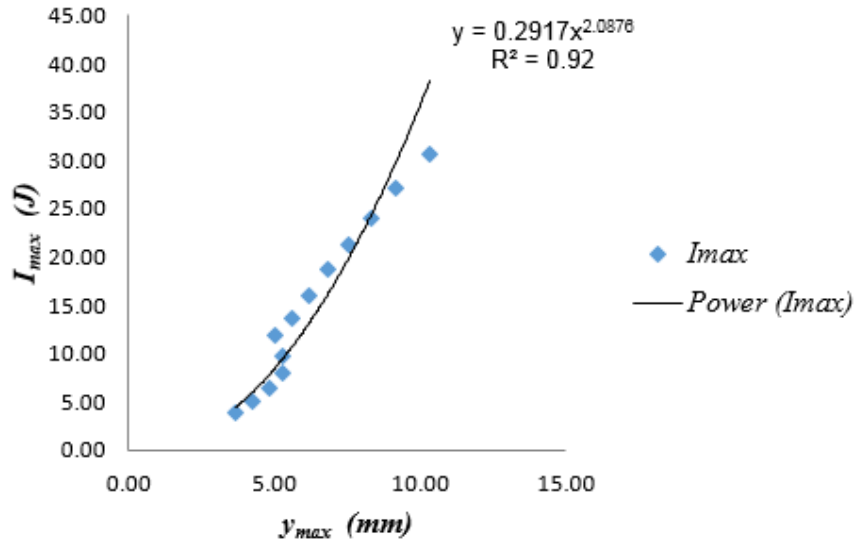
Figure 8: Peak stored energy of the surrogate and its relation with the peak deflection
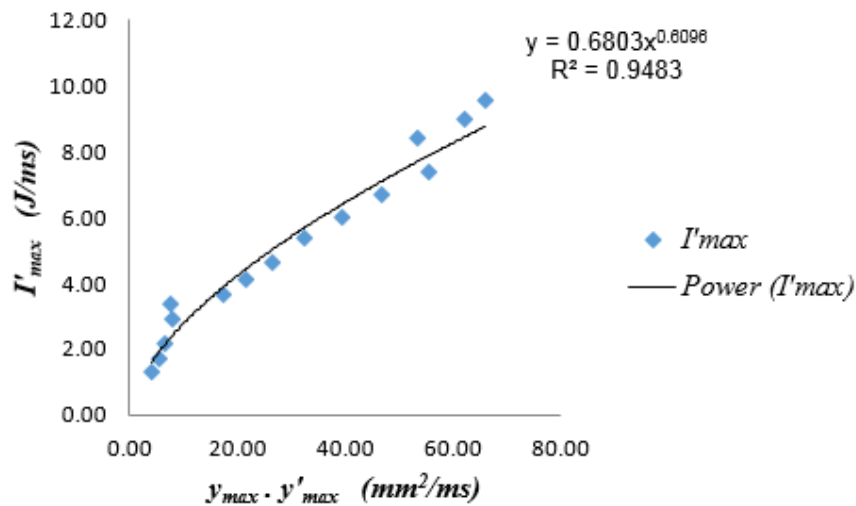

Figure 9: Peak energy storage rate and its relation with the product of peak deflection and its time rate

The plot of peak energy stored in the surrogate and the peak deformation, after power law curve fitting, yielded $I_{max} \propto y_{max}^{2.06}$. Power law fitting of the plot of peak energy storing rate versus the product of the peak deformation and peak deformation velocity has yielded $I'_{max} \propto y_{max} \times y_{max}^{0.61}$. From the Equation (2) and (3), it is evident that the former equation is very well correlated and the latter is not correlated with the those obtained from the analytical studies carried out by Wang [1] using the Lobdell's mathematical model of the thorax.

It is important to note that thorax response is viscous only if $3 \leq$ deformation velocity of the thorax ≤ 30. From the Table 1, for all impact speeds less than 50 m/s the deformation velocity is less than 3 m/s. Therefore, peak internal energy of the thorax surrogate versus peak deflection, rate of peak internal energy versus product of the peak deflection and its time rate were replotted and were as shown in the Figure 10 and Figure 11 respectively.
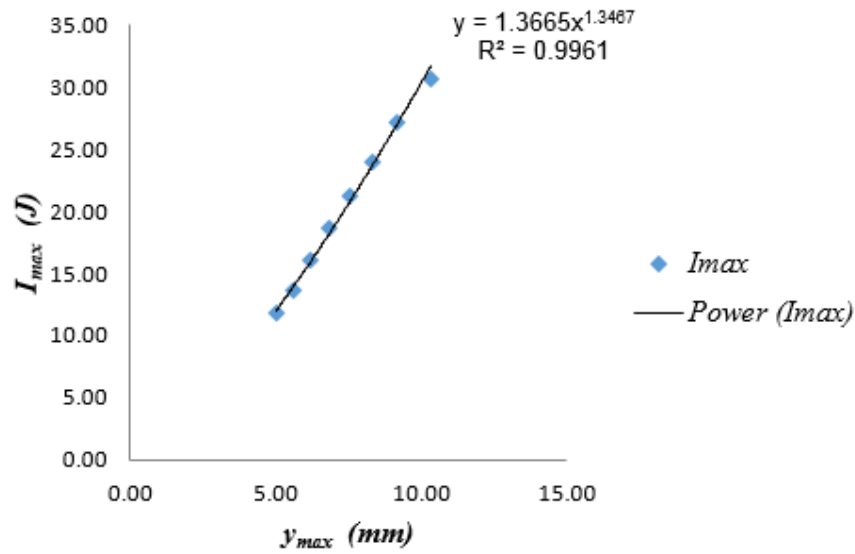
Figure 10: Peak stored energy of the surrogate and its relation with the peak deflection (only for the impact speeds from 55 – 90 m/s)
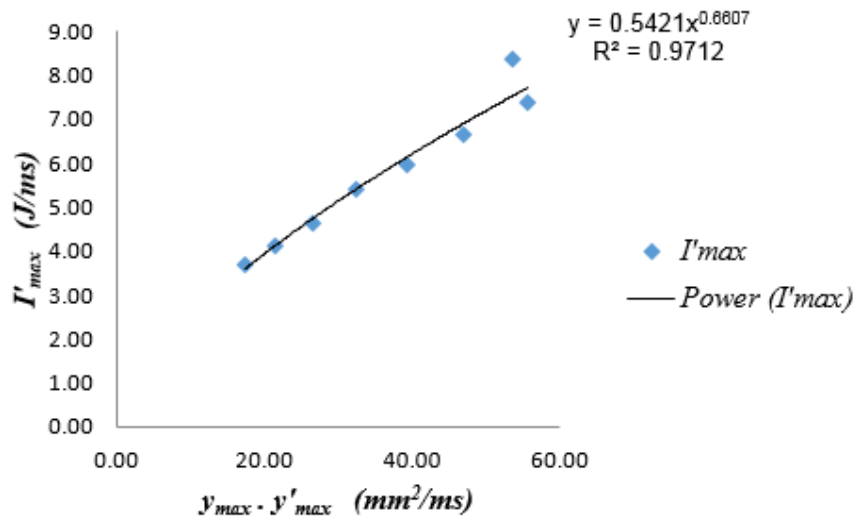

Figure 11: Peak energy storage rate and its relation with the product of peak deflection and its time rate (only for the impacts speeds from 55 – 90 m/s)

The plot of peak energy stored in the surrogate and the peak deformation (Figure 10), after power law curve fitting, yielded $I_{max} \propto y_{max}^{1.35}$. The plot of rate of peak energy stored versus the product of the peak deformation and peak deformation velocity (Figure 11), after power law curve fitting, produced $I'_{max} \propto y_{max} \times y_{max}^{0.66}$. Both relations developed for 'stored energy criterion' and 'energy storing rate criterion' for MTHOTA were not correlated with those obtained for Lodbell's mathematical model.

4. Conclusion and recommendations for the future work

FE model thorax surrogate (MTHOTA) was subjected to a blunt projectile impacts with the speed of 30 – 90 m/s (with an increment of 5 m/s) and Stored Energy Criterion and Energy Stored Rate Criterion were developed and the following conclusions were made from the outcome of the simulations.

- Stored Energy Criterion has yielded $I_{max} = y_{max}^{2.06}$ and Energy Stored Rate Criterion has yielded $I'_{max} = y_{max} \times y'^{0.61}_{max}$ (For complete range of impact speeds considered for the study)

- Stored Energy Criterion yielded $I_{max} = y_{max}^{1.35}$ and Energy Stored Rate Criterion yielded $I'_{max} = y_{max} \times y'^{0.66}_{max}$ (For 3 m/s $\leq y'_{max} \leq 30$ m/s)

It is very crucial to note that force – deflection response of the Lobdell's mathematical model (one dimensional lumped mass model) was correlated with the biomechanical response corridors which were pertinent to the frontal impacts of the vehicular occupant, developed by Kroell *et al* [13] and Kroell *et al* [14]. Bir [9] has developed biomechanical response corridors (force – time, deflection – time and force – deflection) of the human thorax by subjecting thoraces of human cadavers to impacts pertinent to the blunt ballistics. Biomechanical responses obtained using the Lobdell's mathematical model for the similar impact condition were found to be not correlated with biomechanical response corridors developed by Bir [9], which means that the Lobdell's model is not suitable for the evaluation of the thoracic trauma due to blunt ballistic impacts. Whereas, FE model of the thorax surrogate used in the study (MTHOTA) has been fully validated such a way that biomechanical responses, peak viscous responses obtained using MTHOTA would correlate with cadaveric test data for similar impact conditions. This explains the discrepancies in the results obtained from MTHOTA when compared with analytical expressions obtained using the Lobdell's mathematical model. It is important to verify whether the equations obtained using MTHOTA $[I_{max} = y_{max}^{1.35}$ and $y_{max} \times y'^{0.66}_{max}$ (when 3 m/s $\leq y'_{max}$ ≤ 30 m/s)] were projectile specific or applicable to all blunt projectile impacts. Therefore, authors aim to further investigate the validity of the criteria obtained using MTHOTA with other projectile impacts such as baseball, wooden baton projectile etc.

Acknowledgements

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