# Influence of Ribcage Shape on Thoracic Response of Anthropometrically Correct 5th Percentile Female Finite Element Model

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## 1 Abstract

An anthropometrically correct 5$^{th}$ percentile female FE (THUMSD F05) model was developed based on scanned MRI images (Ghosh *et al.* - 2014). The challenge in development of anthropometrically correct model was to modify existing CAD geometry to meet the requirements of anthropometrically correct surface model. The metrics identified for anthropometric validation were based on 44 dimensional measurements based on CAESER Project. The difficulty existed in modifying internal anatomy of human body to align with the outer surface. This led to modification of ribcage geometry of THUMSD-F05. The developed model was extensively validated for frontal (Kroell & Nahum) and lateral impact (*ISO 9790*) load cases. The model in thoracic region predicted good biofidelity (Biofidelity Rating = 6.95) score in lateral impacts, but, for frontal impact was not good because of lower chest deflections.

One of the principal indicators identified which influences thoracic biofidelity was geometry of ribcage. The geometric assessment of ribcage was conducted based on shape of ribcage to assess chest deflection response. The behaviour of ribcage response was analysed for frontal pendulum impact load cases (Kroell (1971) at 13.23 *m/s &* Nahum (1970) at 4.2 m/s). Investigations suggested that biofidelity of ribcage has strong correlation to geometry of ribcage.

***KEYWORDS** – Human Body Model, Thorax, 5$^{th}$ percentile, Geometry

## 2 Introduction

Small female drivers are always at greater risk of automotive related injuries compared to mid-sized male drivers (Kimpara *et al* 2005). Therefore, to ensure safety of this category of drivers is one of the reasons for developing better restraint systems in vehicles. In the endeavour to provide better safety plenty of advanced restraints systems like beltbags, PRE-SAFE etc. are being developed. Evaluation of these systems through ATD's is difficult and thus, need to develop a finite element human body models exist. Several small female FE human body models exist in research community (Kimpara *et al.*, 2005). However, most of the existing models are based on subject-specific surface data. Ghosh *et al.* (2014) have previously developed THUMSD-F05 anthropometrically correct small female finite element model. This development of model led to modifications in thoracic region of original model. The model was then validated for bio-fidelity based on several tests. The outcome of these tests suggested that THUMSD-F05 predicted chest deflections lesser than those achieved in PMHS tests. Therefore, purpose of this study is to assess influence of geometry on chest deflections for THUMSD-F05.

## 3 Development of anthropometrically correct 5$^{th}$ percentile female FE model

An anthropometrically correct 5$^{th}$ percentile female finite element human body model was developed from a subject specific CAD data existing in open source projects. Three-dimensional surface geometry of a female was created based on MRI data of a female human cadaver with a height of 1543mm (Visible Human Project Data: NIH, USA). Figure 1 illustrates surface geometry of 5$^{th}$ percentile female obtained from NIH database. The derivation of finite element model is discussed in our publication (Ghosh *et al.*, IRCOBI 2014). The finite element model weighs 50 kg and stature of

1524 mm. Figure 2 below illustrates the finite element 5th percentile female referred, henceforth, as THUMSD-F05.

The model comprises of 223563 nodes & 314877 elements. The internal organs in the model are represented as lumped enclosed volumes with masses equivalent to that of the representative organ. The anthropometric correctness of this model was verified based on 44 dimensions measured on the surface of CAD. These measurements were based on research done as a part of Civilian American and European Surface Anthropometry Resource Project (CAESER). Table 1 below gives list of measurements considered for anthropometric validation.

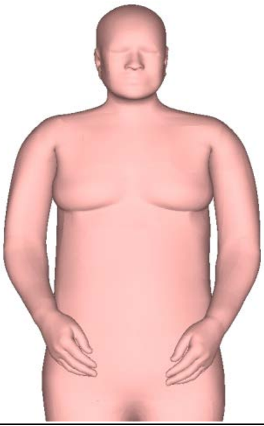


*Figure 1: Surface geometry of 5th percentile female model (Source: NIH database)*

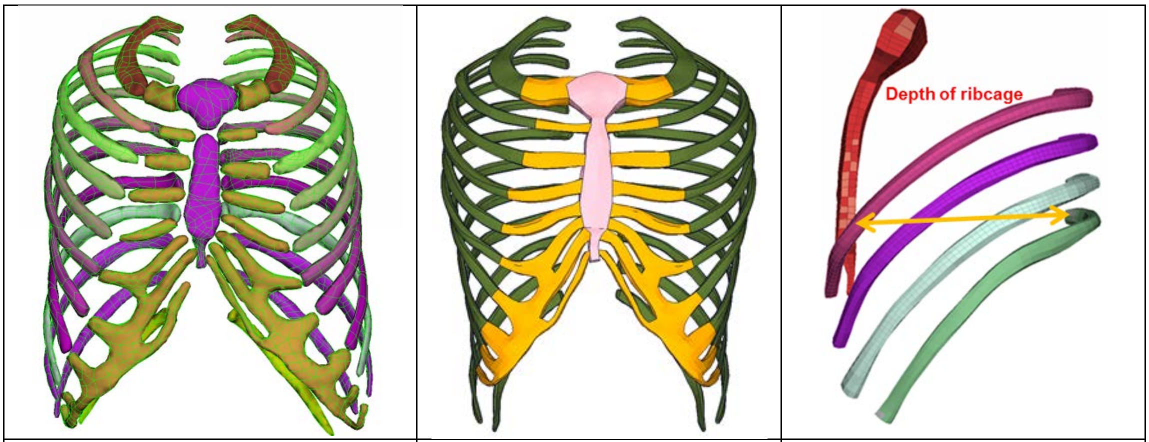
*Figure 2: An oblique view of THUMSD-F05 FE model*

| Number | Measurement | Number | Measurement |
|---|---|---|---|
| 1 | Acromial Height Sitting | 23 | Head Length |
| 2 | Ankle Circumference | 24 | Hip Breadth Sitting |
| 3 | Spine to Shoulder | 25 | Hip Circumference Maximum |
| 4 | Spine to Elbow | 26 | Hip Circumference Max Height |
| 5 | Arm Length Spine to Wrist | 27 | Knee Height |
| 6 | Arm Length Shoulder to Wrist | 28 | Neck Base Circumference |
| 7 | Arm Length Shoulder to Elbow | 29 | Shoulder Breadth |
| 8 | Arm Scye Circumference Scye Circ Over Acromion | 30 | Sitting Height |
| 9 | Bizygomatic Breadth | 31 | Stature |
| 10 | Chest Circumference | 32 | Subscapular Skin fold |
| 11 | Chest Circumference Under Bust | 33 | Thigh Circumference |
| 12 | Buttock Knee Length | 34 | Thigh Circumference Max Sitting |
| 13 | Chest Circumference at Scye | 35 | Thumb Tip Reach |
| 14 | Crotch Height | 36 | TTR1mm |
| 15 | Elbow Height Sitting | 37 | TTR2mm |
| 16 | Eye Height Sitting | 38 | TTR3mm |
| 17 | Face Length | 39 | Triceps Skin fold |
| 18 | Foot Length | 40 | Total Crotch Length |
| 19 | Hand Circumference | 41 | Vertical Trunk Circumference |
| 20 | Hand Length | 42 | Waist Circumference Preferred |
| 21 | Head Breadth | 43 | Waist Front Length |
| 22 | Head Circumference | 44 | Waist Height Preferred |

*Table 1: Anthropometric validation metrics for THUMSD-F05 development (CAESER Report)*

### 3.1 Thorax modification for anthropometric correctness

The thoracic region of THUMSD-F05 was modified from original shape to meet dimensional requirements for chest and waist. The measurements on surface data obtained from Visible Human Database had chest circumference under bust of 927 mm and waist circumference of 921 mm. The dimensional requirement for anthropometric correctness was chest circumference of 690 mm and waist circumference of 634 mm. The modifications conducted in thoracic region to align the model to correct anthropometry were achieved by geometric changes in ribcage. Figure 3 below illustrates differences in ribcage geometry or shape before and after modifications. The depth of chest before and after modifications, however, is same i.e. 118 mm (measured from back of sternum to tip of rib 9).




| *Before Modification* | *After Modification* | *Chest Depth estimation* |
|---|---|---|

*Figure 3: Geometric differences in ribcage of THUMSD-F05 FE model during development for anthropometric correctness*

The ribcage essentially consists of the spine, sternum, costal cartilage & 12 pair of ribs. The modifications to ensure anthropometric validity of model were done on ribs & costal cartilage. The change in geometry of ribs & cartilage led to reduction in total volume inside the ribcage. The representative internal organs were morphed to fit in the volumetric space available in the ribcage. Figure 4 illustrates sectional view of THUMSD-F05 FE model showing representative internal organs.

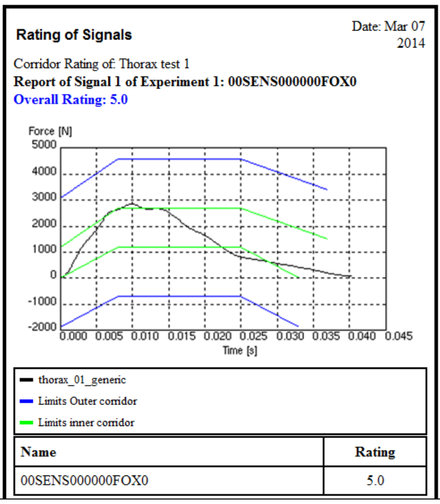
*Figure 4: An oblique sectional view of THUMSD-F05 FE model*

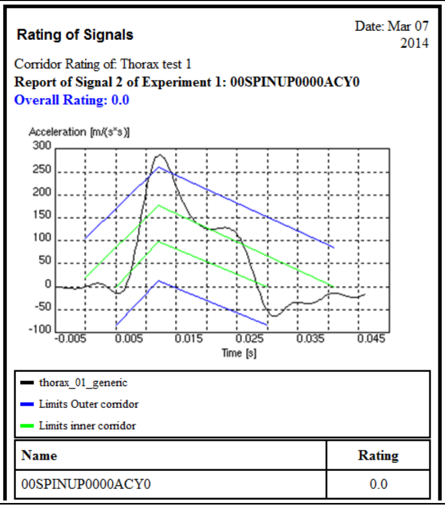
## 4 Validation of anthropometrically correct 5$^{th}$ percentile female FE model

In this study, THUMSD-F05 was validated against some cadaver test data to establish biofidelity of the model. The model was validated for frontal impact cadaver test data conducted by Kroell *et al.* (1971) & Nahum *et al.* (1970) pendulum impact tests. The model was validated for lateral impacts based on tests identified in ISO 9790. The model showed good biofidelity ratings of 6.95. These rating for thoracic region were obtained from ISO rating score. Figure 4 below illustrates the biofidelity rating & results for lateral impact tests for ISO 9790 load cases.

| Thorax | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Boundary | | | Ratings |
| Body Region Test | Impact Condition | $V_{ij}$ | Measurement | $W_{ijk}$ | Lower | Upper | Unit | Test 1 |
| Thorax Test 1 | 4.3 m/s pendulum | 9 | Pendulum Force | 9 | Force Time Corridor | | | 5 |
| | | | | | 1.2 | 2.7 | kN | |
| | | | Peak T4 Y acceleration | 7 | Acceleration Time Corridor | | | 5 |
| | | | | | 10 | 18 | g | |
| Thorax Test 2 | 6.0 m/s pendulum | 9 | Pendulum Force | 9 | Force Time Corridor | | | 10 |
| | | | | | 2.1 | 3.4 | kN | |
| Thorax Test 5 | 6.8 m/s (Heidelberg) rigid sled | 7 | Thorax Plate Force | 8 | Force Time Corridor | | | 10 |
| | | | | | 3.7 | 12.4 | kN | |
| | | | Peak T1 Y acceleration | 7 | 100 | 149 | g | 5 |
| | | | Peak T12 Y acceleration | 7 | 87 | 131 | g | 5 |
| | | | Peak Rib Acceleration | 6 | 78 | 122 | g | 10 |
| Thorax Test 6 | 8.9 m/s (WSU) 23 psi padded sled | 7 | Shoulder+Thoracic Plate Force | 9 | Force Time Corridor | | | 5 |
| | | | | | 4.4 | 6.9 | kN | |
| | | | Peak Lateral Displacement of T12 | 5 | 65 | 88 | mm | 5 |

Pendulum Impact at 4.5 *m/s* with 14 *kg* impactor




Pendulum Impact at 6 *m/s* with 14 *kg* impactor

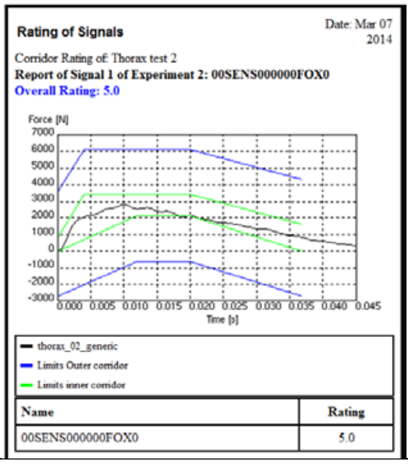



*Figure 4: Biofidelity response of THUMSD-F05 for ISO/TR 9790 impact load cases*

Frontal response of THUMSD-F05 was validated for two tests conducted by Kroell *et al.* (1971) and Nahum *et al* (1970). These tests are discussed in detail by Kimpara *et al.* (2005). Figure 5 & 6 below illustrates force deflection characteristics of thoracic region & kinematics predicted by THUMSD-F05 for frontal pendulum chest impact conducted by Kroell (1971). The response curves highlight that deflection of model is lesser than force deflection response. Similar behaviour was also observed for results predicted for Nahum (1970) impact tests.

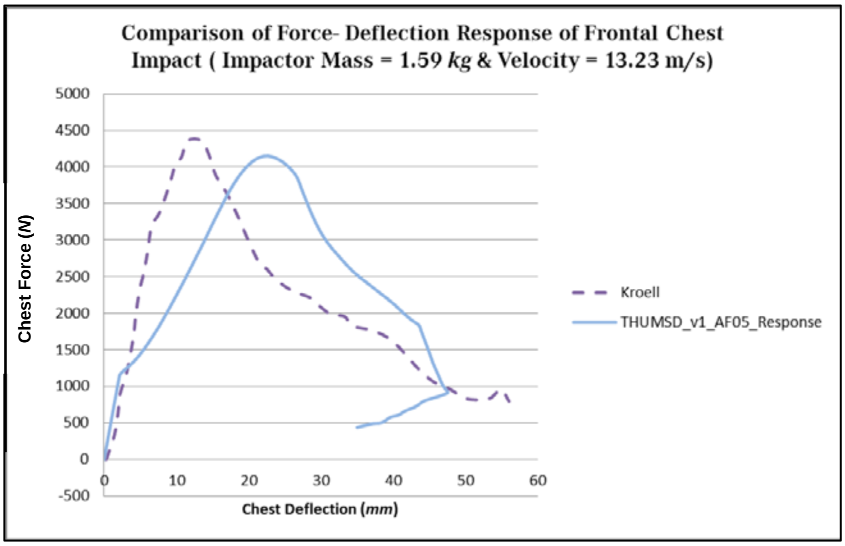
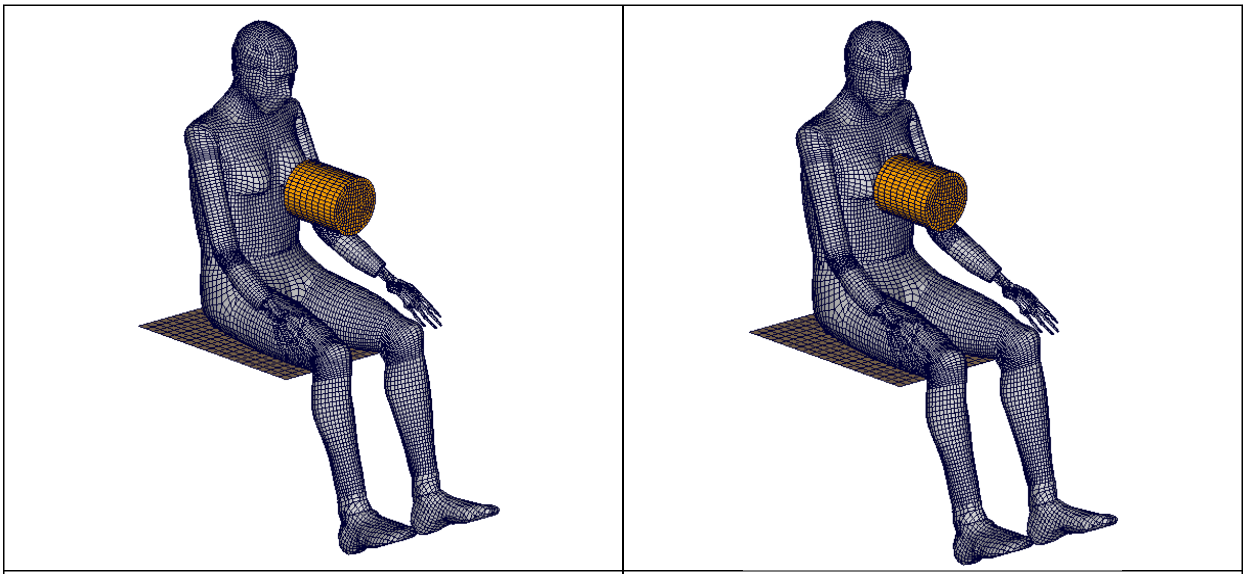
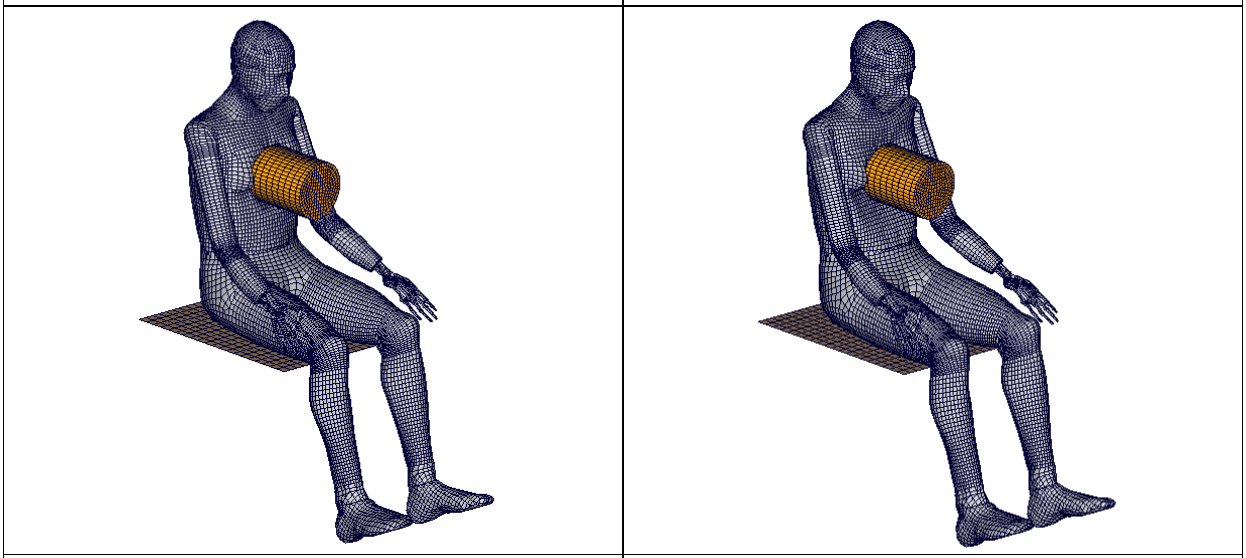



*Figure 5: Force deflection characteristics for Kroell pendulum impact test (1971)*



| | |
|---|---|
| 0 ms | 5 ms |



| | |
|---|---|
| 10 ms | 15 ms |

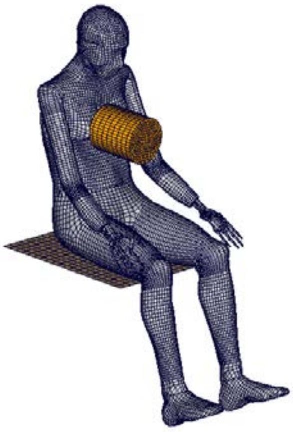
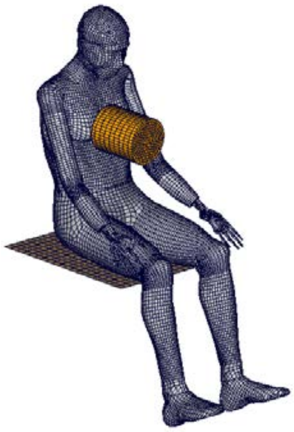
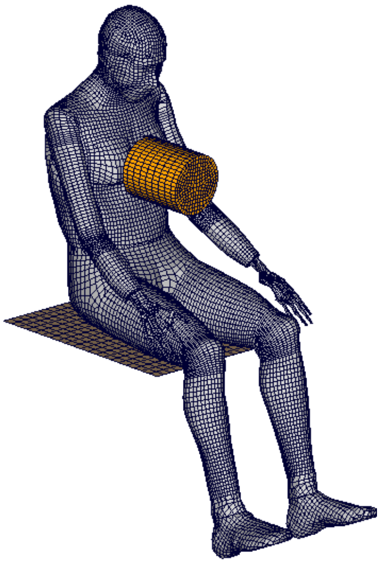
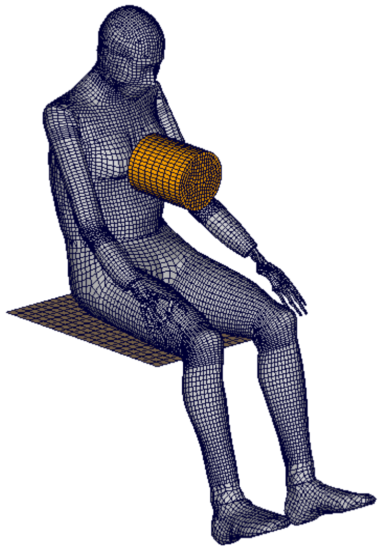
|  |  |
|---|---|
| 20 ms | 25 ms |
|  |  |
| 30 ms | 35 ms |

*Figure 6: Kinematics of THUMSD-F05 predicted by THUMSD-F05 for a 13.23 m/s frontal chest impact with a 1.59 kg pendulum (Kroell pendulum impact test, 1971)*

## 5 Geometric Assessment of Ribcage through pendulum impact tests

The results from pendulum impact tests suggested that for frontal impact configuration chest deflections were lower than those achieved in PMHS response. Lower chest deflections can be associated to multiple factors like material of ribcage, influence of internal organs, geometry of ribcage, connections with surrounding organs etc. In this study, we focussed on evaluating geometric aspects of ribcage due to modifications conducted to anthropometric validity. Therefore, 12 pairs of ribs with cartilage and sternum were isolated from THUMSD-F05. This assembly of ribcage was subjected to frontal pendulum impact test conducted by Kroell (1971) & Nahum (1970). The difference between tests conducted at whole body & ribcage assembly was that motion of ribs was constrained about the spine in all directions Figure 7 & 8 below illustrates the setup of the test.

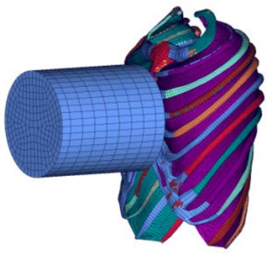


*Figure 7: Pendulum impact deck of ribcage for geometric assessment*

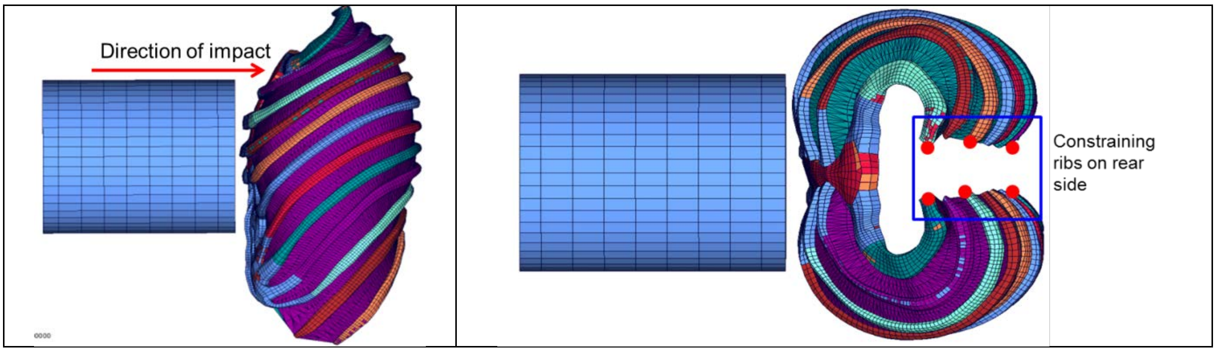
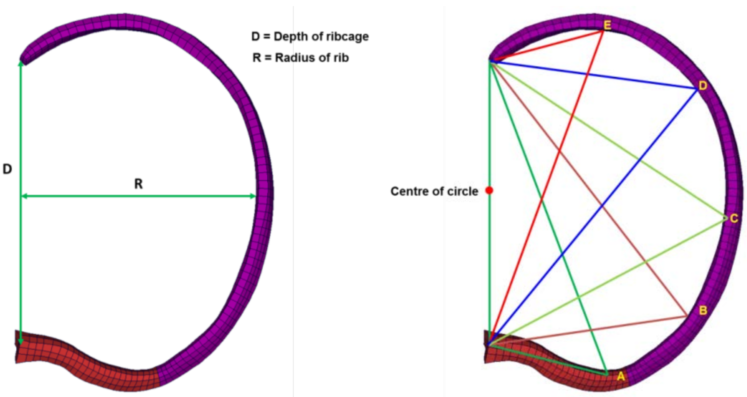



*Figure 8: Geometric assessment set-up*

The ribcage geometry was considered as an ellipse from top view and this is an assumption for further analysis (planar geometry is considered) for analytical calculations. The aspects pertaining to inclination of ribs in frontal plane is neglected in current study. Figure 9 illustrates basic geometrical parameter identified for ribs. The depth of rib is considered from back of sternum to tip of rear end of rib. The radius of rib is considered from mid-point of this depth and projection of the same in lateral direction on the rib. The rib radius was computed based on average value computed based circumscribed circle approach (5 points were identified on rib for computation).




(a) (b)

*Figure 9: Parameters for rib geometry & method of calculation of rib radius*

In this study, the ribcage is dealt as a curved beam and influence of geometry is analysed based on the bending moment formulations. These equations are primarily valid for static loading conditions but since, influence is analysed at global scale.

$\sigma_b = M_b \times P$ (1)

where

$M_b$ = *Bending Moment*

*P = Geometric parameter function*

$\sigma_b$ = *Bending Stress*

$P = \frac{y}{A \times e \times (R_n - y)}$ (2)

where

A = Cross sectional area of rib

e = Eccentricity between centroidal and neutral axis ($e = R - R_n$)

R = Radius of centroidal axis

$R_n$ = Radius of neutral axis

y = Distance of fibre from neutral axis

For circular cross section of rib,

$R_n = \frac{\left(\sqrt{R_o} + \sqrt{R_i}\right)^2}{4}$ (3)

$R = R_i + \frac{d}{2}$ (4)

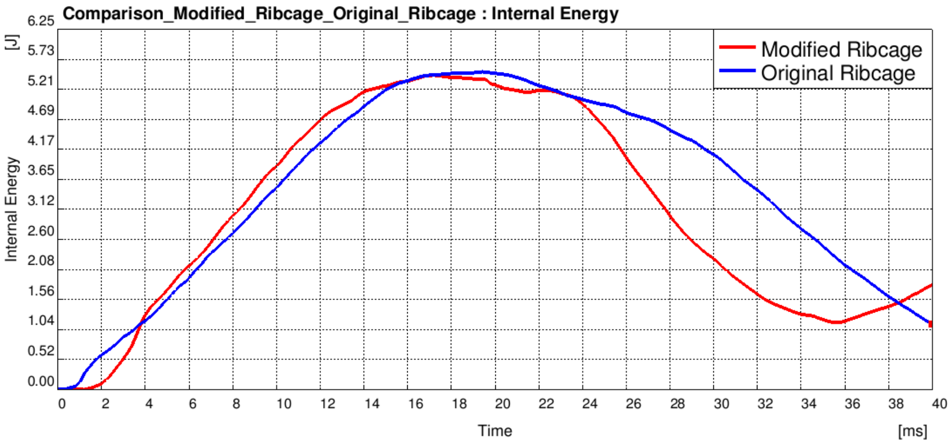
Considering $R = x_0 \times d$ where $x_0$ (amplification factor) (5)

Substituting equations 5 in 4 gives $R_i$ as a function of $x_0$ and similarly $R_o$ can be obtained as function of $x_0$ which is inversely proportional in nature. Substituting all parameters as a function of $x_0$ in equation 2 leads to $P = f(x_o)$.

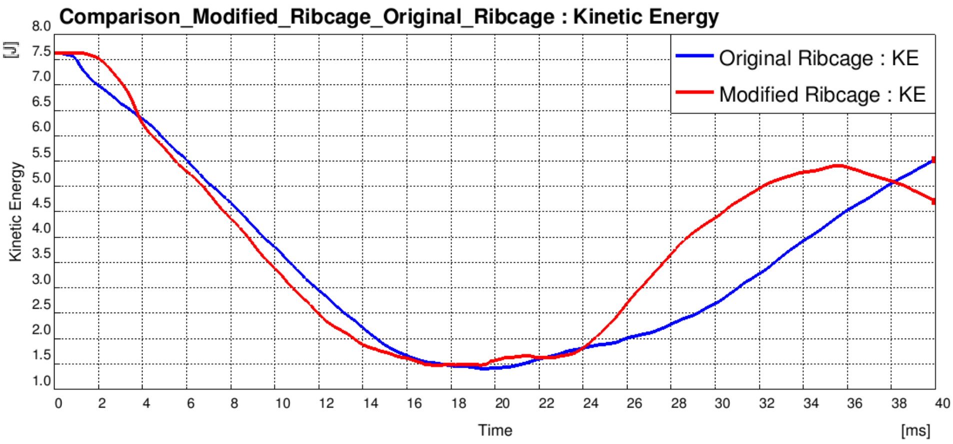
$$S_{yt} = \sigma_b + \sigma_t \quad (6)$$

Considering $\sigma_t = 0$, $S_{yt} = \sigma_b$ ➔for ensuring yield stress is constant increase in $M_b$ would be obtained for lower value of geometric parameter function. Therefore, for ribcage with smaller $x_o$ would lead to lower allowable $M_b$.
where
$S_{yt}$= *Yield stress of material*

This is evident from figure 13 below where bending moments across section for modified ribcage (lower $x_o$) are lower compared to original ribcage. Similar trend is observed for frontal pendulum conducted by Nahum (1970) as observed in figures 15, 16 & 17. Figure 13 & 14 illustrates the sectional forces & bending moments in mid-section of modified and original ribs for frontal pendulum impact as per Kroell (1971). Figure 10 (a) & (b) depicts internal energy & kinetic energy variation with time for Kroell test case (v=13.23 & impactor mass=1.59 kg). It is observed that kinetic energy & internal energy for both cases are same before 24 ms. In both cases, peak chest deflections are also achieved before 24 ms as shown in figure 11. Therefore, comparing both model configurations (original ribcage & modified ribcage) seems reasonable. Energy balance suggests that lower chest deflections should lead to higher contact forces. This complements with observations made on contact forces between impactor and ribcage as shown in Figure 12.




(a)




(b)

*Figure 10: Kinetic Energy & Internal Energy for ribcage assessment for Kroell test setup (v=13.23 m/s & mass = 1.59 kg)*

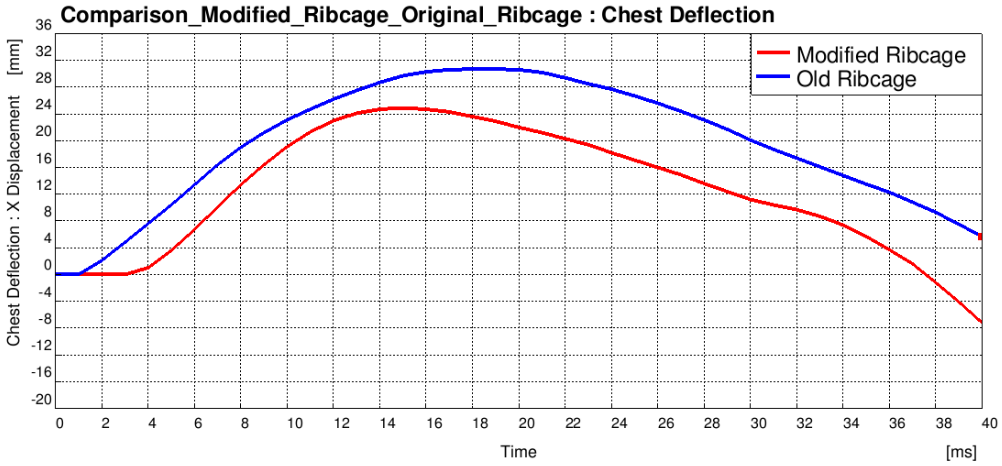



*Figure 11: Chest Deflection for ribcage assessment for Kroell test setup (v=13.23 m/s & mass = 1.59 kg)*

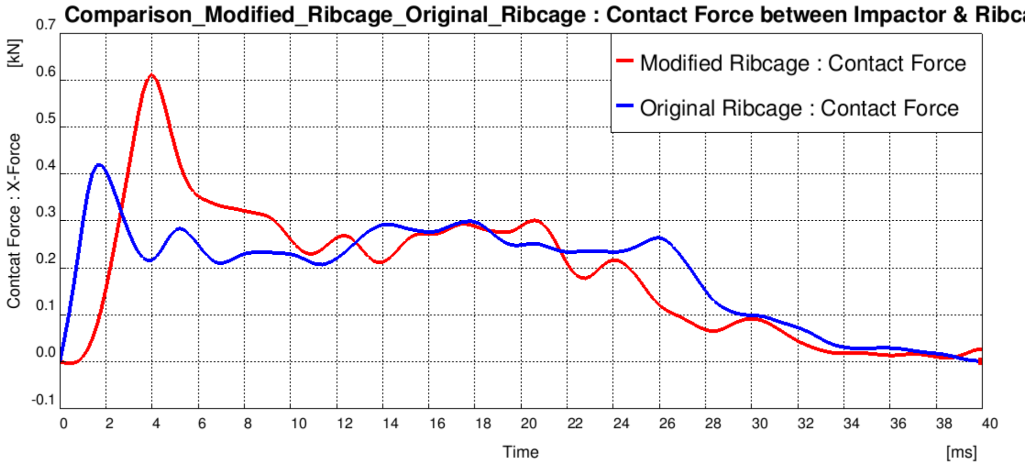
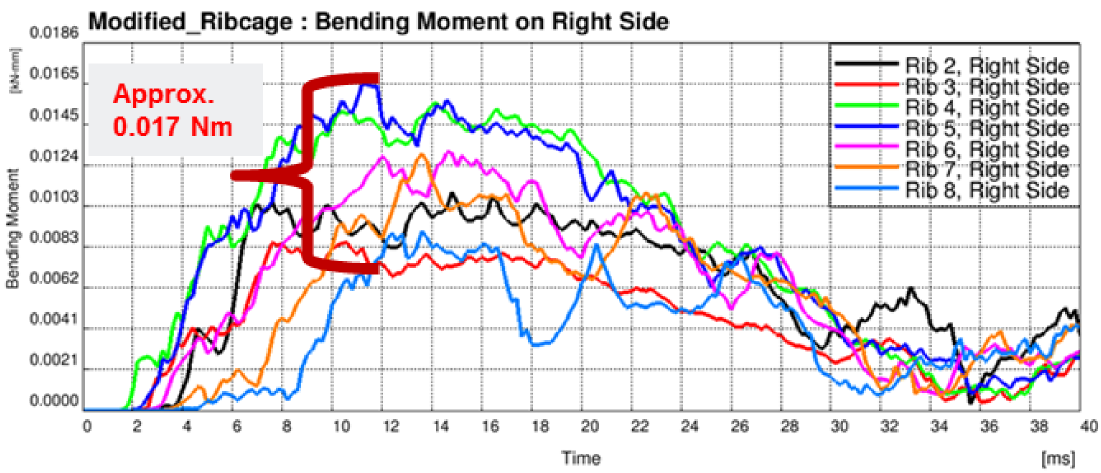
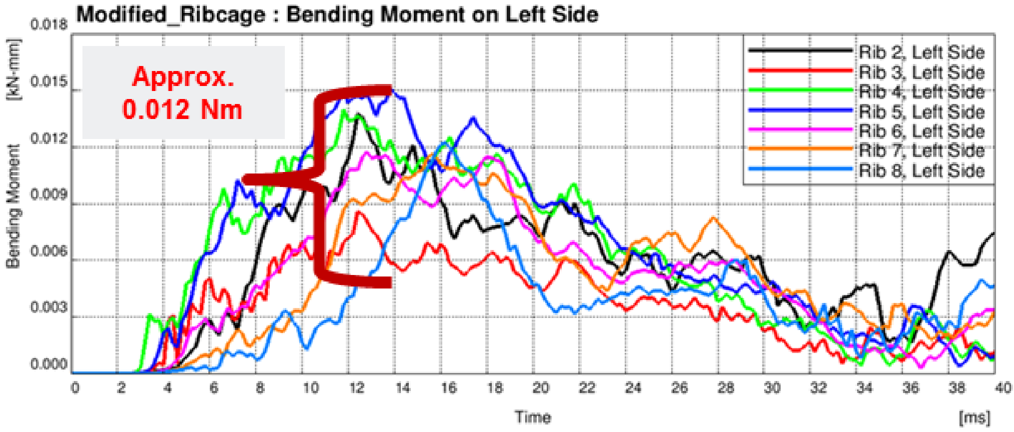


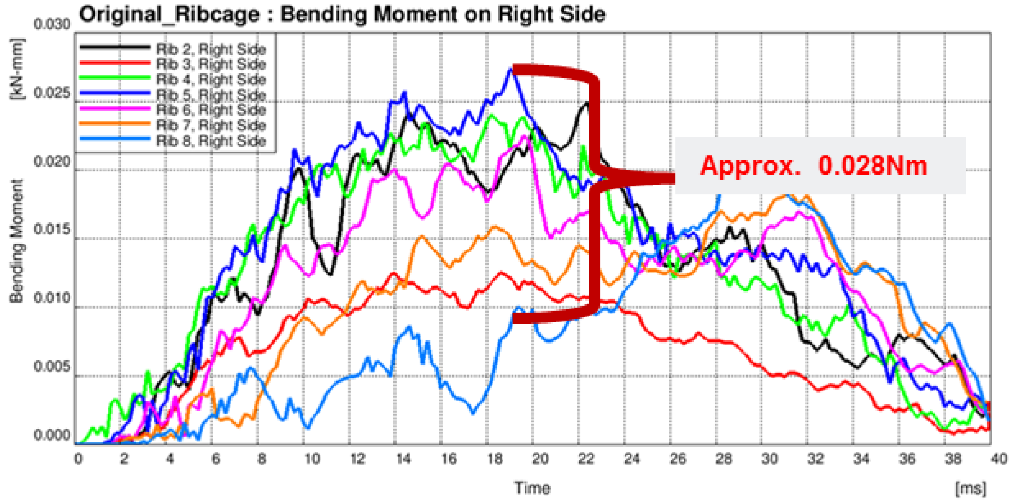

*Figure 12: Contact Force for ribcage assessment for Kroell test setup (v=13.23 m/s & mass = 1.59 kg)*



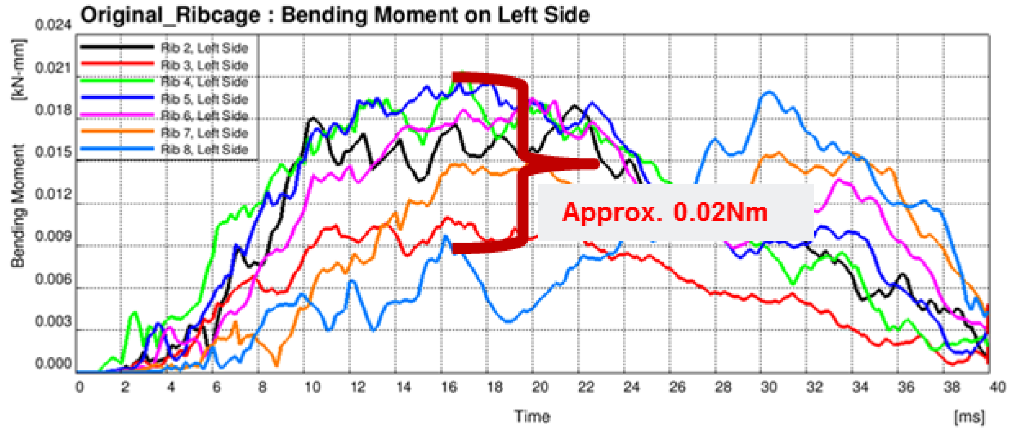

*(a)*




*(b)*

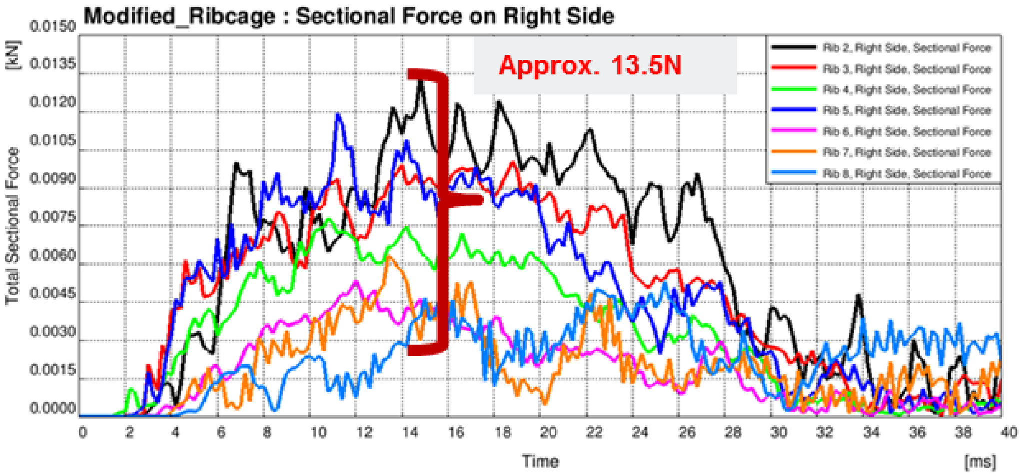



*(c)*

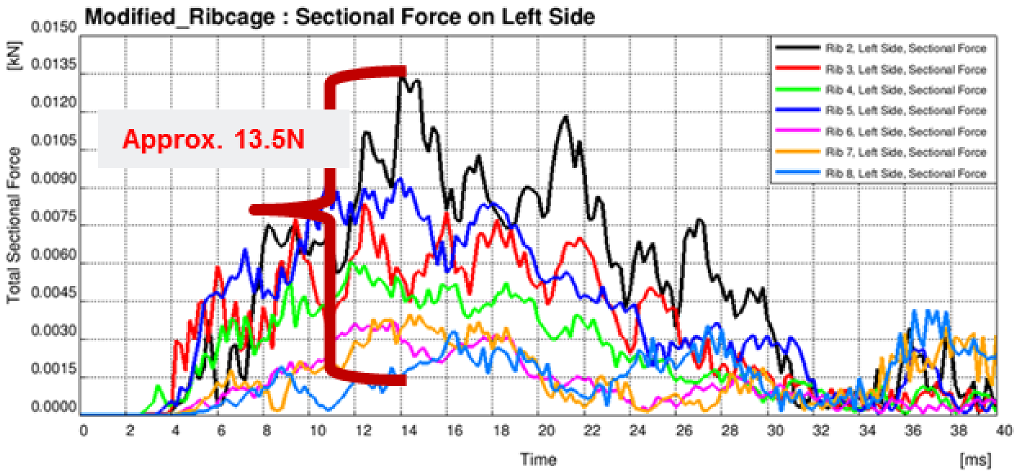



*(d)*

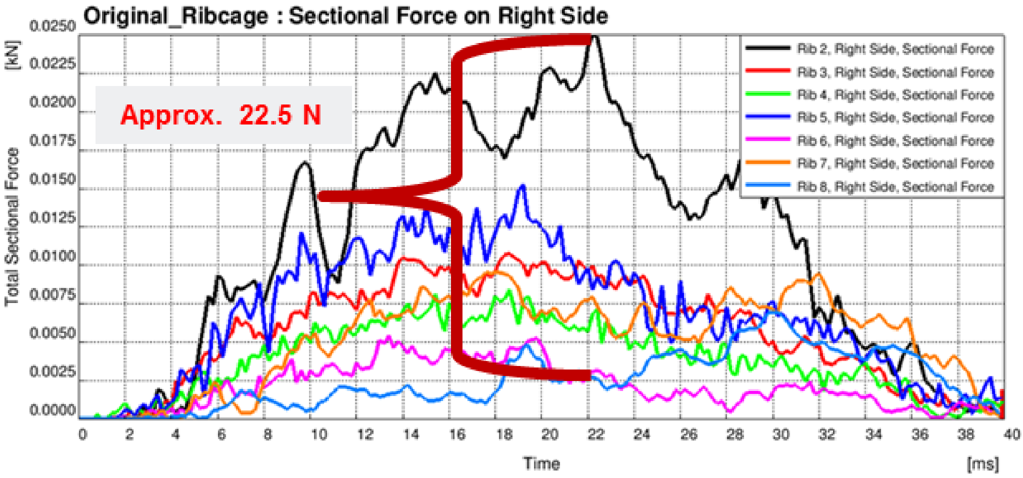
*Figure 13: Sectional bending moment distribution at mid-section for ribcage assessment for Kroell test setup (v=13.23 m/s & mass = 1.59 kg)*


Modified_Ribcage : Sectional Force on Right Side
Approx. 13.5N
Rib 2, Right Side, Sectional Force
Rib 3, Right Side, Sectional Force
Rib 4, Right Side, Sectional Force
Rib 5, Right Side, Sectional Force
Rib 6, Right Side, Sectional Force
Rib 7, Right Side, Sectional Force
Rib 8, Right Side, Sectional Force
Total Sectional Force
[kN]
Time
[ms]

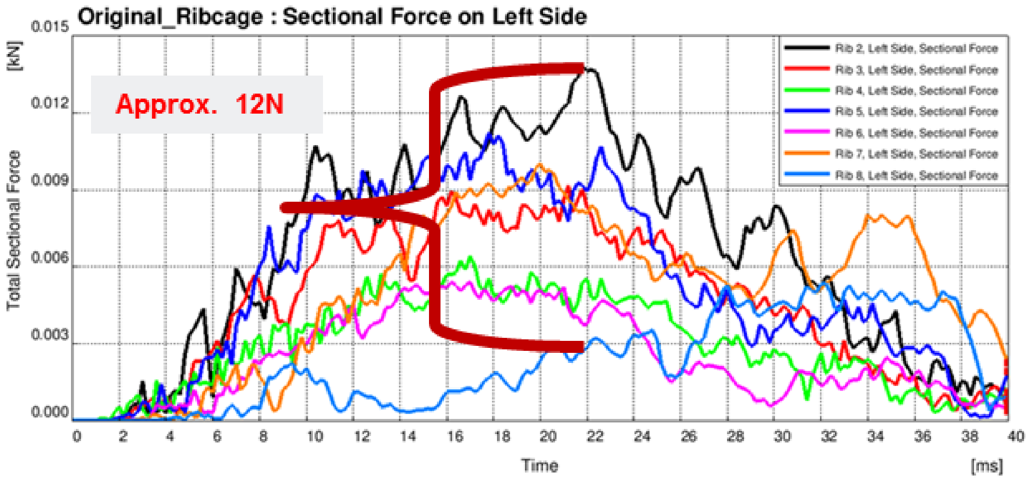
*(a)*


Modified_Ribcage : Sectional Force on Left Side
Approx. 13.5N
Rib 2, Left Side, Sectional Force
Rib 3, Left Side, Sectional Force
Rib 4, Left Side, Sectional Force
Rib 5, Left Side, Sectional Force
Rib 6, Left Side, Sectional Force
Rib 7, Left Side, Sectional Force
Rib 8, Left Side, Sectional Force
Total Sectional Force
[kN]
Time
[ms]

*(b)*


Original_Ribcage : Sectional Force on Right Side
Approx. 22.5 N
Rib 2, Right Side, Sectional Force
Rib 3, Right Side, Sectional Force
Rib 4, Right Side, Sectional Force
Rib 5, Right Side, Sectional Force
Rib 6, Right Side, Sectional Force
Rib 7, Right Side, Sectional Force
Rib 8, Right Side, Sectional Force
Total Sectional Force
[kN]
Time
[ms]

*(c)*




*(d)*

*Figure 14: Sectional force distribution at mid-section for ribcage assessment for Kroell test setup (v=13.23 m/s & mass = 1.59 kg)*

## 6 Summary

THUMSD-F05 finite element model meets requirements of anthropometric correctness. The anthropometric correctness was achieved based on statistical data available in CAESER project. However, modifications to achieve correct anthropometry led to changes in geometry of ribcage. The development of model is discussed previously by Ghosh *et al.* (2014). The model was validated for bio-fidelity based on ISO 9790 (lateral impacts, sled & pendulum impacts) & pendulum impacts for frontal. The model shows good bio-fidelity for lateral impacts (Bio-fidelity Score=6.95). The bio-fidelity for frontal impacts was reasonable because lower chest deflections were predicted by THUMSD-F05. Therefore, geometric assessment of ribcage was undertaken where a constrained ribcage was subjected to pendulum impacts as per Kroell (1971) & Nahum (1970) test conditions.

The study treats ribcage as a curved beam based on which a geometric parameter function was identified. This parameter is realized for characterization of ribcage and theory is proposed which to understand the importance of this parameter to rib deflections. Results suggest that increasing geometric parameter function (P) leads to increasing bending moments in rib cross-section. This is evident from bending moments predicted by FE model with modified and original ribcage geometry.

There are many limitations in terms of theory of bending and also related to geometry of ribcage which still have to be researched to develop better confidence in the proposed theory.

## 7 Literature

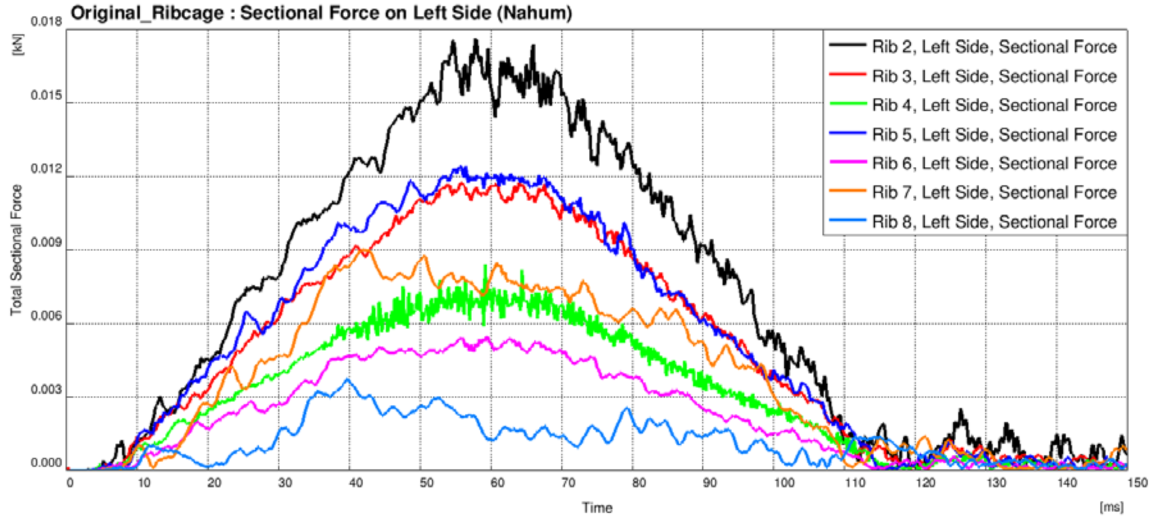

[1] Kimpara ,H *et al.*: " Development of a Three-Dimensional Finite Element Chest Model for the 5th Percentile Female", Stapp Car Crash Journal, 2005, 251-269

[2] Ghosh, P *et al.*: "Deriving anthropometrically-correct 5th percentile female from subject-specific female CAD model", IRCOBI, 2014, 477-478

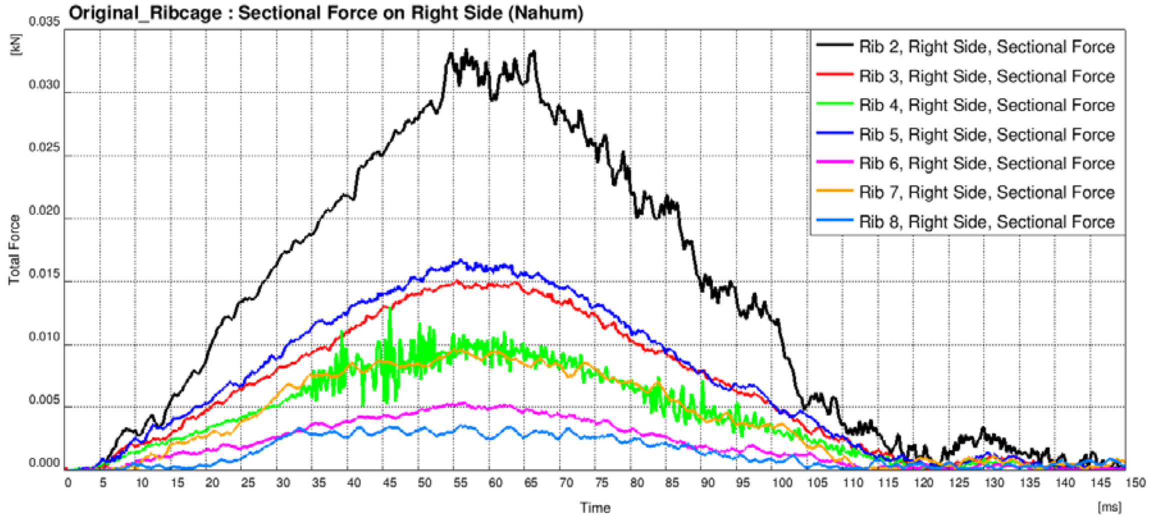
[3] ISO/TR 9790:"Road Vehicles – Anthropomorphic side impact dummy – Lateral impact response requirements to assess the bio-fidelity of the dummy ", 1990, 15-16

[4] Robinette, K *et al.*: "Civilian American and European Surface Anthropometry Resource (CAESER) Final Report, Volume I: Summary", SAE, 2002, 20-45

## 8 Annexure: Predicted results for Pendulum Impact Test as per Nahum (1970)




*(a)*

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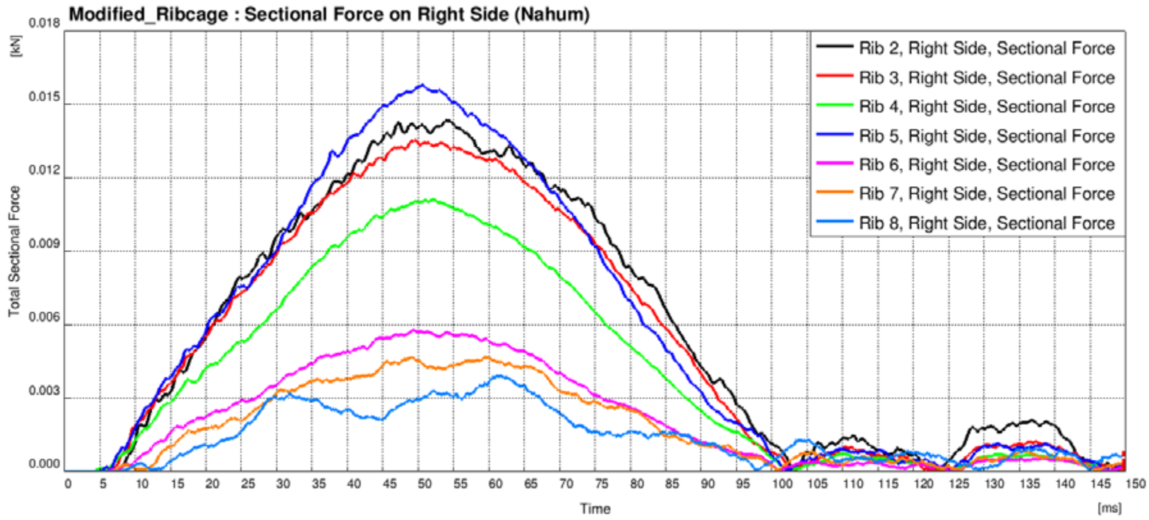
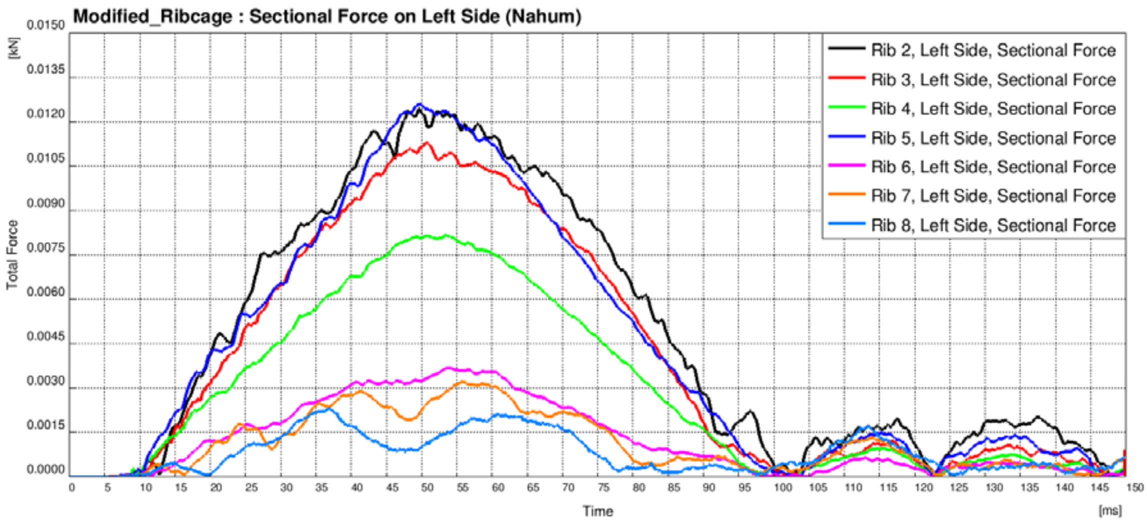
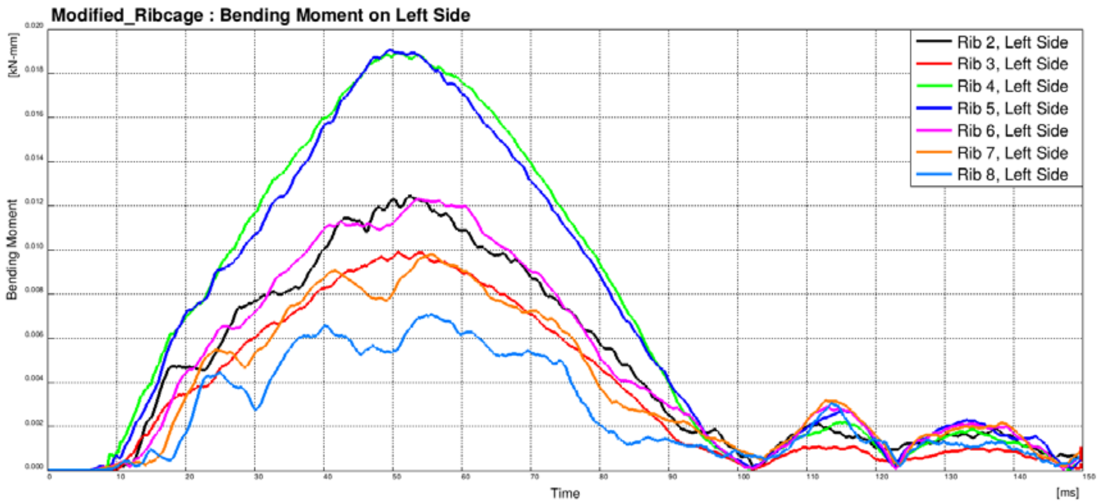



*(c)*

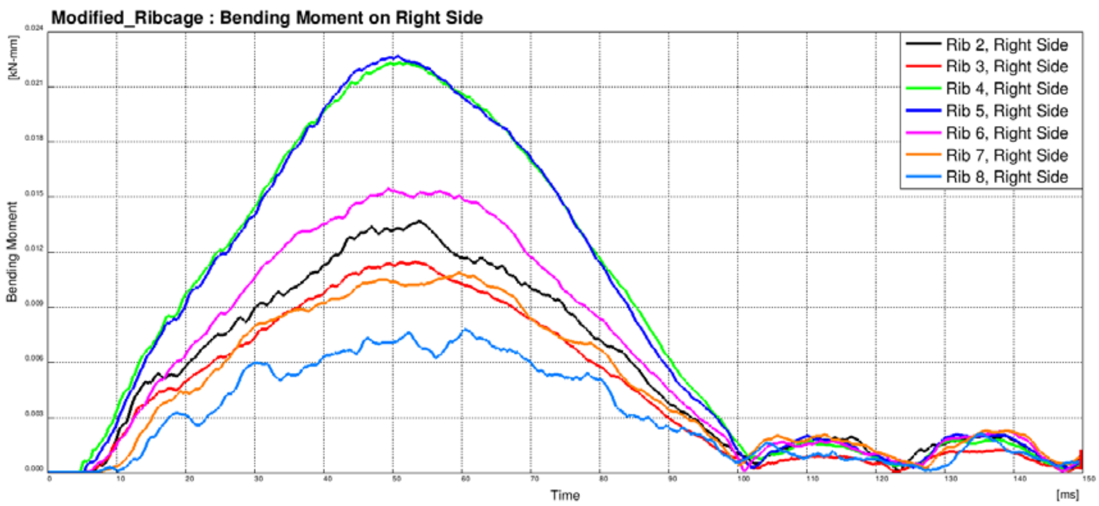



*(d)*

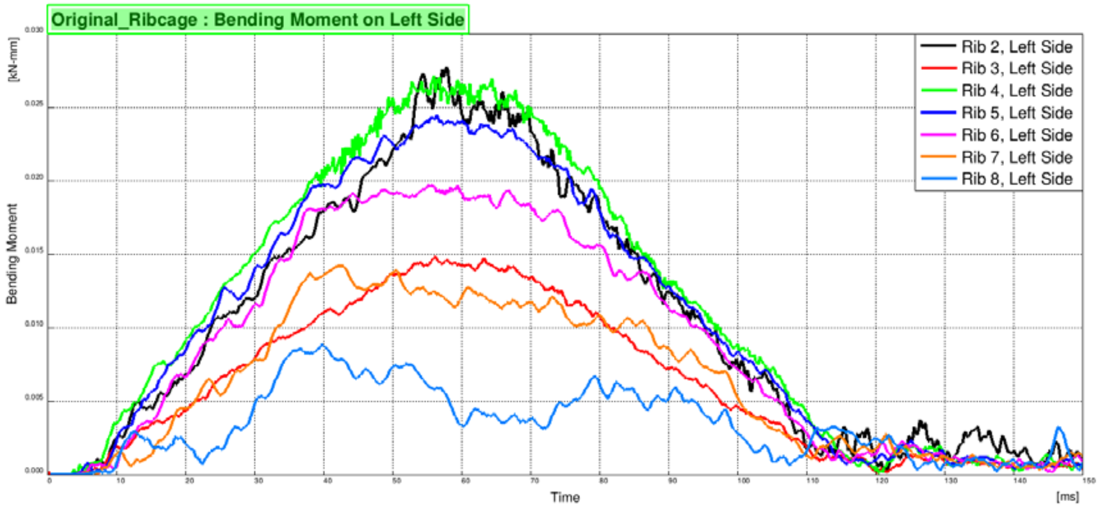
*Figure 15: Sectional force distribution at mid-section for ribcage assessment for Nahum test setup (v=4.92 m/s & mass = 19.3 kg)*



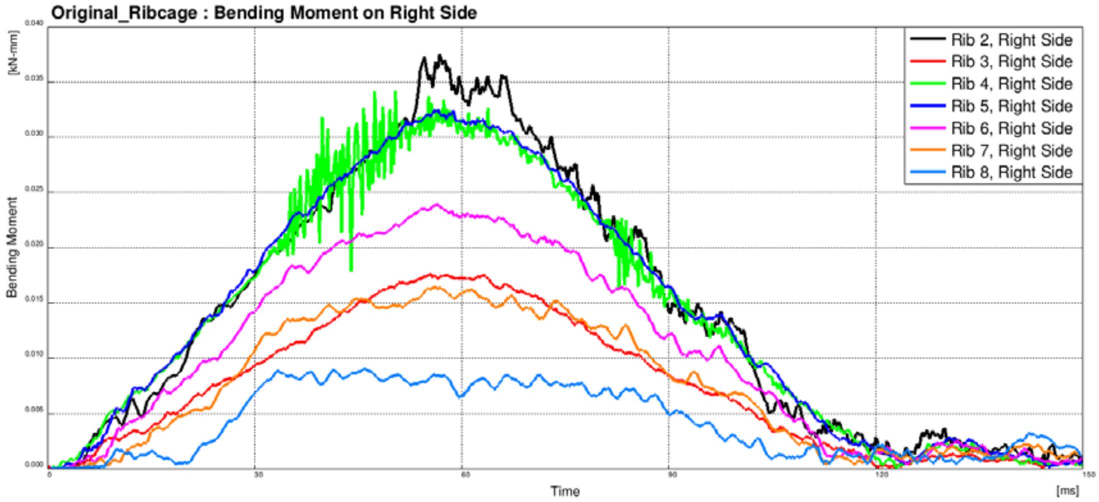

*(a)*




*(b)*

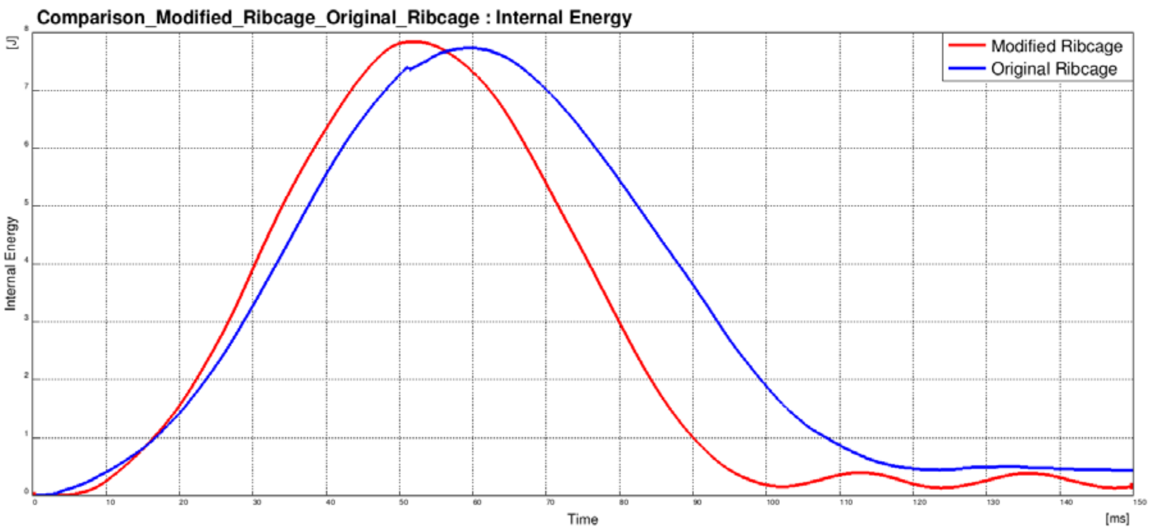



*(c)*

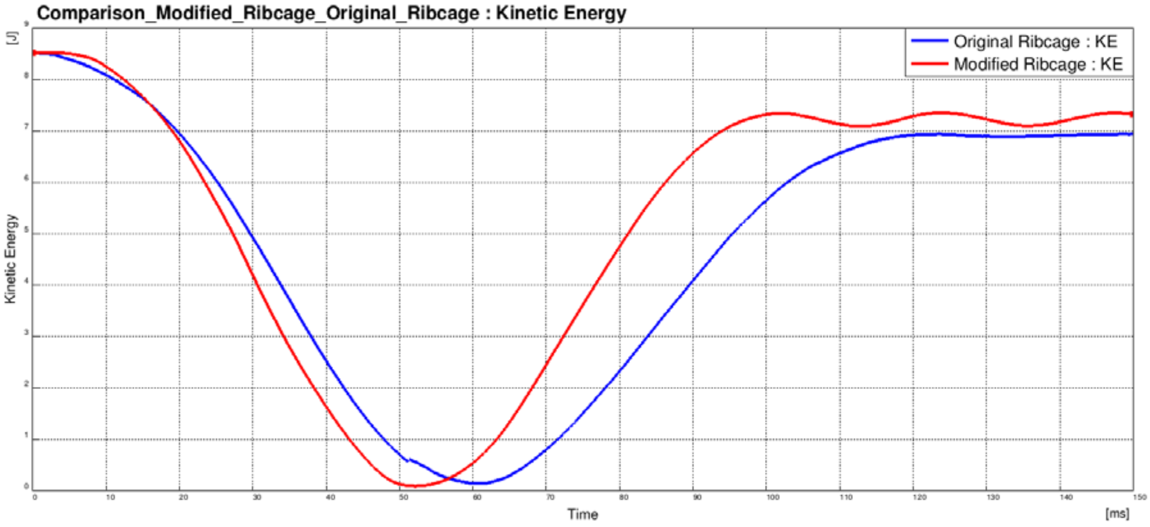



*(d)*

*Figure 16: Sectional bending moment distribution at mid-section for ribcage assessment for Nahum test setup (v=4.92 m/s & mass = 19.3 kg)*




*(a)*




*(b)*

*Figure 17: Kinetic Energy & Internal Energy for ribcage assessment for Nahum test setup (v=4.92 m/s & mass = 19.3 kg)*