IMPLEMENTATION OF NEW RIB MATERIAL MODELS TO A FE-HUMAN BODY MODEL FOR EVALUATION OF THE PRE-SAFE® IMPULSE SIDE RESTRAINT SYSTEM FOR SIDE IMPACT PROTECTION

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ABSTRACT

„Integrated", „Smart" and „Individual" are new characteristics of future safety systems. Furthermore, side crashes are still dominant in terms of high injury risk for car occupants and are predicted to become even more relevant in future. Earlier studies on pre-conditioning the occupant during pre-crash phase have shown the potential to reduce injury risk in such accident scenarios. To evaluate and optimize such advanced safety systems to provide a high safety level for the occupant, finite element human body models were used. Especially integrated safety systems which interact with the occupant in the pre-crash phase require these new and supplementary evaluation tools.

With specific focus on the use case, the thorax and rib material of the FE human body model THUMS-D were modified and validated. Two different rib material properties have been defined for two different age groups, one for the young population and one for the elder population based on quasi static and dynamic 3-point bending test set-up. Furthermore, a damage model for the rib fracture was created and implemented to the THUMS-D model. The validation process of the complete thorax followed pendulum impact standards set by GESAC 2005 and ISO/TR 9790:1999.

Finally the PRE-SAFE® Impulse Side system was evaluated and optimized applying this upgraded THUMS-D model in FE car crash environment.

INTRODUCTION

As a tool for the development and also the assessment of particularly secondary safety systems, dummies have been used over the last 50 years – successively updated in terms of mechanical design, injury criteria and, slightly with respect to "individual" characters (5th female, child dummies, etc.)

As of today, numerical models of these dummies are a common technology. As a next step in the field of numerical simulation, validated human models will be used as a supplemental tool to investigate the biomechanical impact of restraint systems more in detail. Those models offer the opportunity to study effects in body parts that are currently not addressed by common anthropomorphic dummy technology, especially if the pre-crash phase has to be considered.

Analyses of the injury patterns in real crashes reveal that there is still potential to improve loads on the thorax. In order to better understand mechanisms leading to a certain injury risk, a valid representation and characterization of material properties and injury mechanisms in this development tool is necessary to assess and optimize new restraint systems. Especially improvements in the prediction capability for risk of rib fractures in elderly population with THUMS-D motivated the experimental and simulation work, which is described in the following sections. Finally, this modified THUMS-D was used to optimize an advanced pre-crash side protection system.

METHODS

Human Body Model

Mercedes-Benz is already using this integral simulation tool in the standard development process. In this study, a modified THUMS (Total Human Model for Safety) model was used. THUMS (AM50) was originally developed by Toyota Motor Corporation & Toyota Central R&D Labs, Inc. and meanwhile several THUMS base models (AF05, AM50, AM95) and derivatives are released respectively published [1]. The model used within Mercedes–Benz is based on the original THUMS versions V1.X and V3 and was continuously improved on several body parts in recent years and is therefore referred to as “THUMS-D” [2,3].

Experimental work

The entire thorax shape, bone structure and material properties of the ribs are changing over the lifespan. Several studies and research activities were published or initiated in recent years whitin this topic [4, 5]. Almost all authors agree that the stiffness of ribs decrease the older the person is. In other words, the risk for a rib fracture is increasing.

Nevertheless, age specific models which allow also a realistic modeling of a fracture behavior are currently not existing. Therefore, an experimental study was initiated in collaboration with our scientific partner Technical University Graz to investigate and discuss relevant material properties and characteristics of human ribs for the derivation of constitutive laws and fracture modeling under FE code respectively for implemetation to THUMS-D.

1st test phase - 3-point bending – correlation bone density, age and geometrical parameters

Within a first series of experiments to derive biomechanical charcteristics of young and elderly car occupants, force-displacement curves were determined for human ribs in different areas (anterior, lateral and posterior).

Rib samples were obtained from four female and three male Post-Mortem Human Subjects (PMHS) respectively bodies donated for research. One female PMHS was at the age of 32 – the male PMHS was 37 years old. All other subjects in the sample were in age range of 58 – 78 years. In this first series of experiments, the rib samples with a length of approximately 70 mm were taken from the anterior, lateral and posterior region of a rib. For each sample, the geometric dimensions (width, height, curvature height, cross sectional area) and the bone density was determined. Within this study the DXA method (Dual-X-Ray absorptiometry) was applied. It has to be stated, that the DXA method provides an “areal density” (mass / area, e.g g / cm^2) and does not destinguish between cortical and trabecular bone structures.

The rib ends were potted in a 30mm x 30mm cylindrical sleeve (aluminum) and then tested in 3-point bending set-up. Quasistatic load was applied in max. 11 cycles (hysteresis mode) starting with 30 N and complete unloading after each cycle. Results were discussed with specific focus on correlation of the geometic parameters, the bone density and age of the PMHS.

The following general findings and correlations were derived in this 1st test series. More details and an extensive discussion of the results could be found in the publication of Tomasch et.al. [6]:

- The bone density (BMD – Bone Mineral Density – g/cm^2) increases from sternum to vertebra region. (within sample a 1.39-fold increase was found on average).
- Ribs from younger PMHS showing 1.8 times higher density compared with rib samples from elderly persons on average.

- Gender specific differences are also observed: Measured bone density of male ribs were consistently higher compared with density of female ribs – but both sexes showing comparable increase of bone density values from sternum to vertebra.
- The height and cross sectional area of the ribs also increases from anterior to posterior. These parameters decrease with age.
- Rib samples from young, male PMHS could withstand approximately three times higher loads compared to rib samples from elderly, female persons.
- All tested specimen (young and elderly) showed a distinctive post-cracking behavior. Force remains on more or less constant level until load was reduced (approximately up to fourfold of the displacement of failure load).

2nd test phase - 3-point bending for failure modelling and dynamic impactor testing

28 middle ribs (mainly 3 – 6, partly 2 and 10-11) were obtained from four female PMHS. Three of them between ages of 59 and 65 – one 32 years old. Within the second series of experiments, the quasi-static 3-point bending test set-up was slightly modified with regard to the length (now approximately 100 mm) of the rib specimen and its support condition (now clamped firmly). The main focus of these experiments and especially of the further processing of the results was among the determination of the material properties on the faithful reproduction of the behavior at rupture and also the observed post-cracking mechanism of rib bones.

For the quasi-static test set-up the movement speed was 100 mm/min with a total displacement range of 30mm to generate a loading on the rib until fracture. The force vs. deflection curve was collected and the test itself was recorded by a camera.

The force-deflection diagram in Figure 1 shows typical behavior of elder and younger rib specimen. In principle the main characteristics of the curves are comparable with the 1st test phase. The rib bone shows a kind of elastic stiffness at the beginning of test. The curves of the younger rib specimen are consistently steeper and therefore indicate higher stiffness. Also in this test series rib samples from younger PMHS show failure at approximately three times higher load level compared with the sample from the elderly. Similar post-cracking behavior was observed in both tests.

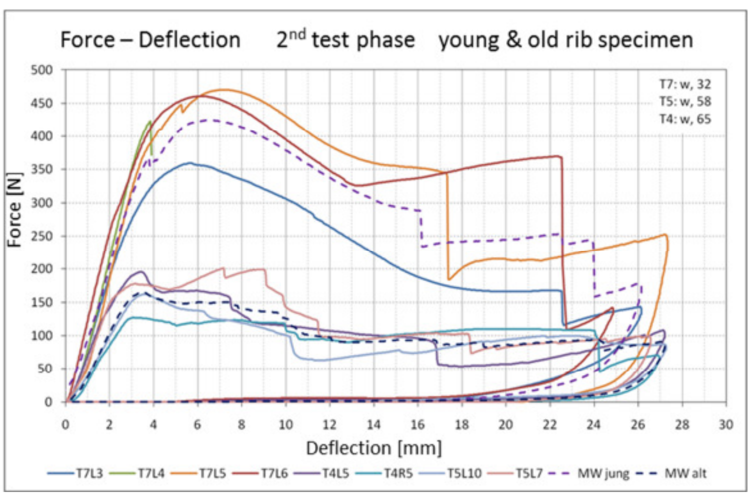

Figure 1: Typical Force-Deflection of elder and younger rib specimen observed in this load case.

The findings of the 2nd series of experiments (quasi-static) could be summarized as follows:

- Rib specimen with similar dimensions showing quite comparable elastic behavior – this applies for rib sample from younger and elderly.
- Rib samples from young PMHS (female) withstand approximately two to three times higher loads compared to rib samples from elderly (female) .
- Stiffness (elastic curve section) of younger ribs is significantly higher

The material model validated against this quasi-static testing was also assessed under dynamic loading conditions. Focus of this study was to confirm the material model and parameters for the elastic behavior on the one hand and for fracture on the other hand. For this, a DOE (Design Of Experiment) study was carried out based on FE-Simulation of the dynamic 3-point bending test set-up. The fracture or no-fracture behavior of a rib specimen was predicted for a certain combination of test parameters such as impactor mass and velocity. The rib samples were as well potted on both ends and clamped firmly in a test rig. The results were finally plotted into the DOE diagram and correlate well (final material properties) with the predicted behavior. Nevertheless, it has to be stated, that for this additional dynamic study only ribs from the elderly (59), female PMHS were available.

Rib material model and failure modelling of rib fracture

The results respectively force-deflection curves from mainly the second test series were now discussed to be transferred into a constitutive law and finally a material description to be used within the LS-Dyna code. As already described in previous paragraph, the rib bone shows an elastic stiffness at the beginning of test (Figure 2). At the end of the elastic material behavior the rib starts to get locally deformed while the test curve shows an elasto-plastic material behavior attended with a material hardening. At this point the bone starts to get a fibrous fracture at the force application point followed by an extension of the fracture along the rib in the closer area. The test curve shows a continuous elasto-plastic fracture behavior with steady reduction of the stiffness.

To regulate the elastic range of a response curve (section a in figure 2), the Young's modulus as contributing factor has to be adjusted to the test results in terms of the Hooke's law. The parameters to control the adjustment of non-linear hardening in the elastic-plastic range (section b in figure 2) are the effective plastic strain values (EPS) and the corresponding yield stress (ES). The third part of the response curve (section c in figure 2) shows an elastic-plastic behavior combined with a softening of the bone. This softening is now realized and controlled by a modulated failure flag in the material properties which limits the maximum plastic strain at 6.8% and conduct elements deletion of the shell elements (cortical bone). It has to be noted, that the threshold respectively failure flag of 6.8% is strictly model dependant. In case of any modification in mesh or use in other models, this threshold is not valid and has to be refined against the original test data. The material properties of the cortical rib bone are defined in MAT_24 similar to the current THUMS-D v3.2 but with different parameter values. One of the most essential adjustments was the change of the Young's modulus from 18 GPa to 3.5 GPa (Young Rib Material) and 1.5 GPa (Old Rib Material). Also the definition of the trabecular bone has been changed from MAT_12 to MAT_1 what is defined as elastic material behavior.

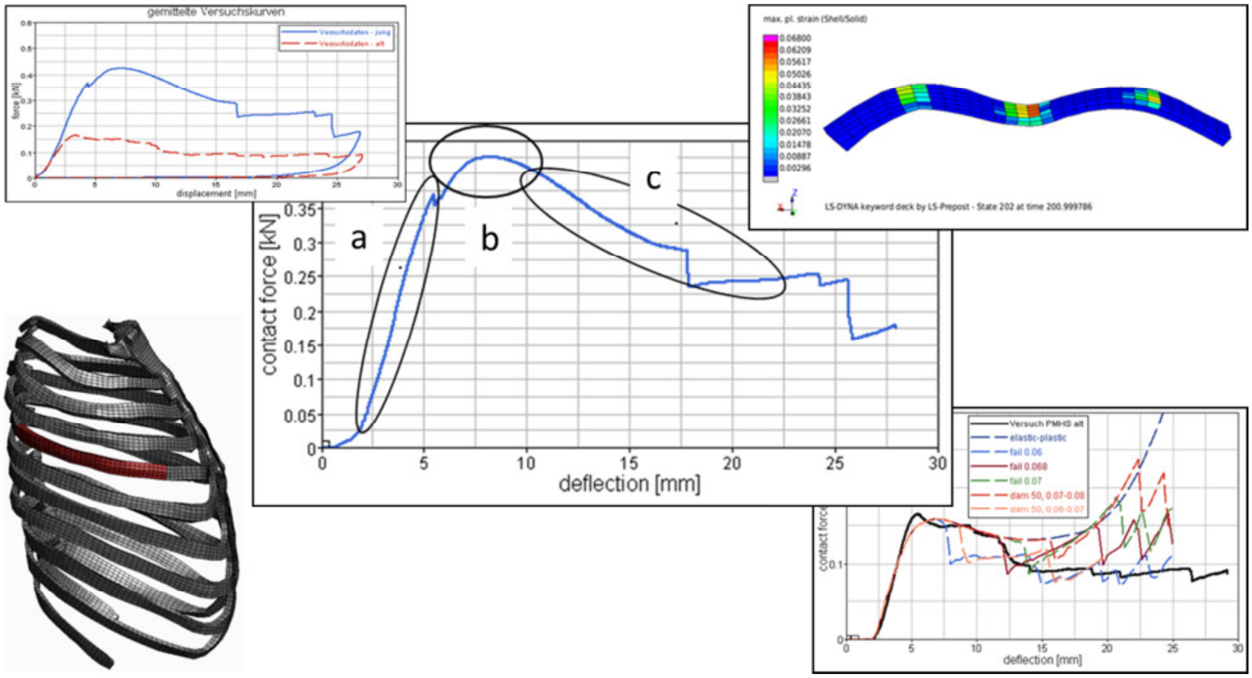

Figure 2: Rib material model and failure modelling of rib fracture – Top Left: averaged test data of elder and younger rib specimen – Centre: characterization of test curve segments; elastic (a), elastic-plastic/hardening (b), elastic-plastic/softening (c) – Bottom Right: determination of damage parameter.

Validation against GESAC 2005 & ISO/TR 9790

The validation of the complete THUMS-D with new rib materials comprises the frontal pendulum impact tests defined by GESAC 2005 [7] and the lateral and oblique-lateral pendulum impact tests defined by ISO/TR 9790 [8].

The study on fracture mechanism showed a significant difference between the Young Rib Material (NRy) and the Old Rib Material (NRo) in terms of material behavior and predicted risk of rib fractures. The NRy performs considerably more elastic than the NRo what reflects the embrittled bone material of the elderly population. A comparison with the Number of Fractured Ribs (NFR), documented in ISO/TR 9790 for lateral, low speed oblique-lateral and high speed oblique-lateral PMHS tests shows a good correlation to the predicted rib fractures given by simulations with NRy and NRo (Figure 3).

- The NFR in 4.3 m/s lateral impact PMHS tests have a range of 0 to 7. The model with NRy predicts no risk on any rib while NRo predicts a risk on 6 ribs including 2 of them with a high fracture risk.
- For the low speed oblique-lateral impact tests on PMHS showing 0 to 2 fractured ribs on impact side and 0 fractured ribs on the opposite side. THUMS-D with NRy predicts a relatively low risk for 1 rib on impact side. The model with NRo predicts 6 ribs with a risk thereof 2 to 3 with an advanced risk.
- The high speed oblique-lateral impact tests on PMHS showing 2 to 7 fractured ribs on impact side and 0 to 3 on the opposite side. The model with NRy predicts 6 ribs thereof 2 with advanced risk on the impact side. The model with NRo predicts 8 ribs thereof 6 multiple and 4 with critical risk on the impact side, additional 1 rib with an advanced risk on the opposite side.

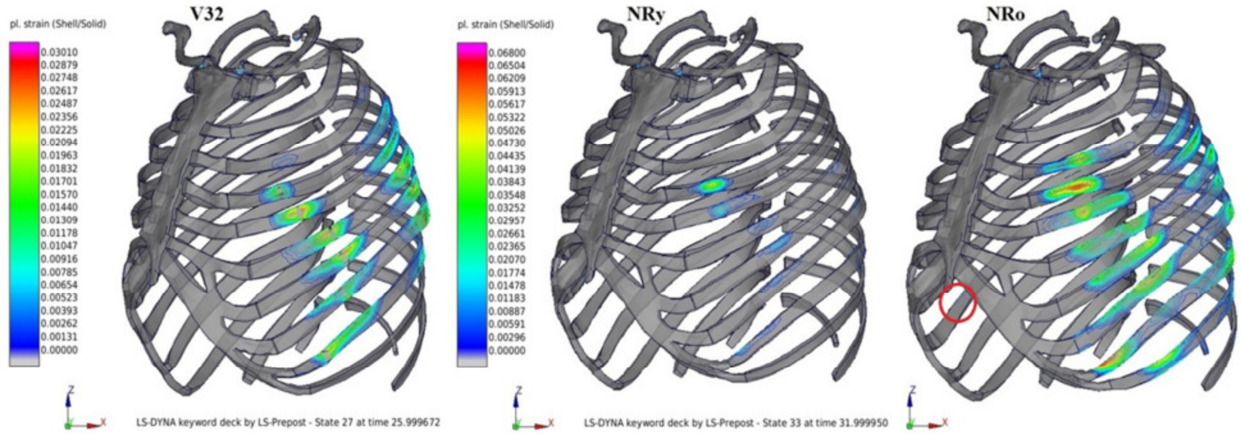

Figure 3: Fringe plots / results ISO/TR 9790 load case oblique pendulum impact 6.7 m/s; plastic strains; From left: Rib material original THUMS-D (V32), Young rib material (NRy), Old rib material (NRo).

Discussion

Two new rib material models and properties, for younger population (NRy) and for elder population (NRo), were defined for the use with LS-Dyna code based on human rib specimen tests by TU Graz. With reference to the pendulum impact results for validation, NRy and NRo are showing an improved chest response of the entire THUMS-D. The outcome of this is an improved but still amendable chest response on frontal pendulum impacts, an acceptable performance on lateral pendulum impacts and a good performance in the oblique-lateral impact tests which motivated finally the application within the loadcase and system development which will be presented in the following paragraphs.

Nevertheless, it is important to note, that several limitations arise from the biomechanical testing and modelling. The biomechanical test data is limited to three elderly female and two elderly male PMHS. The data for the younger population is just based on one male and one female subject. Within the modelling and validation part no change of the thorax shape and its changes over lifespan was realised. Also the modeled fracture mechanism just reflects the results of the 3-point bending test set-up.

APPLICATION PRE-SAFE® IMPULSE SIDE:

In this chapter, the newly validated Human Body Model will be used for the development of a new generation of integral safety restraint systems: PRE-SAFE® Impulse Side.

System description PRE-SAFE® Impulse Side

Theory PRE-SAFE® Impulse Side is the very first of a new generation of pre-impacting restraint systems whose field of action will be extended prior to the collision thanks to the integration of active and passive safety [9].

The specifics of the vehicle structure in a lateral impact make it necessary to use all the available space to reduce the loads to the occupants. Structural measures, the right material choice and the use of tailored side impact restraint systems like side airbags or curtain airbags describe the state of the art protection measures. But what if there were more space available to take efficient mitigation countermeasures without increasing the car body dimensions? That is the idea of PRE-SAFE® Impulse Side.

The new PRE-SAFE® Impulse Side restraint system aims at creating more space between occupant and car interior/structure only when needed i.e. right before a crash event occurs. As a result, the side airbag could better deploy, the contact with the intruding structure might occur later, so that more crash energy could be dissipated by the vehicle structure deformation before the gap between structure and airbag is being closed.

But PRE-SAFE® Impulse Side is not only increasing the space between occupant and side structure. Indeed, PRE-SAFE® Impulse Side also actively pre-accelerates the occupant toward the center of the car. As a result, the occupant has already been set in motion when the collision begins, in other words the relative velocity between occupant and intruding structure has been reduced.

Maximizing the distance and reducing the relative velocity between occupant and intruding structure can significantly reduce the occupant loads especially in the thorax region.

Functional implementation Inflating a specifically designed air bladder in the seat rest side bolster creates the impulse needed to move the occupant. The activation time has to be precisely calculated using information of the car surroundings gathered by camera and/or radar sensors [9].

Through the light impulse, the occupant is being moved towards the center of the vehicle prior to the predicted impact (Figure 4).

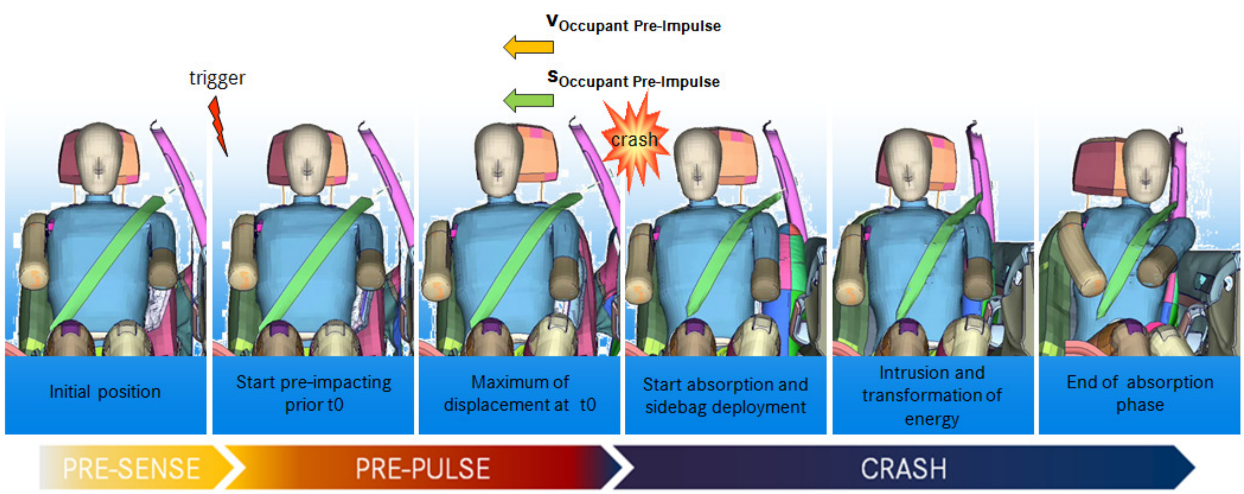

Figure 4: PRE-SAFE® Impulse Side way of action

PRE-SAFE® Impulse Side safeguarding

In contrast to traditional irreversible restraint systems, the deployment decision for the PRE- SAFE® Impulse Side bladder is based on situation analysis of the vehicle surroundings before crash. As a result, there is a minimal chance of system activation remaining even though the collision could be avoided in the last moment. Therefore, the system characteristics were designed to meet the conflicting targets of both providing the required impulse to the occupant and being gentle enough in the deployment not to harm anyone.

The safeguarding assessment of the system was done by simulating a static deployment of PRE-SAFE® Impulse Side using THUMS-D with modified rib material representing elderly persons. After triggering PRE-SAFE® Impulse Side, the HBM displacement as well as rib compression, stress and strain were measured (Figure 5).

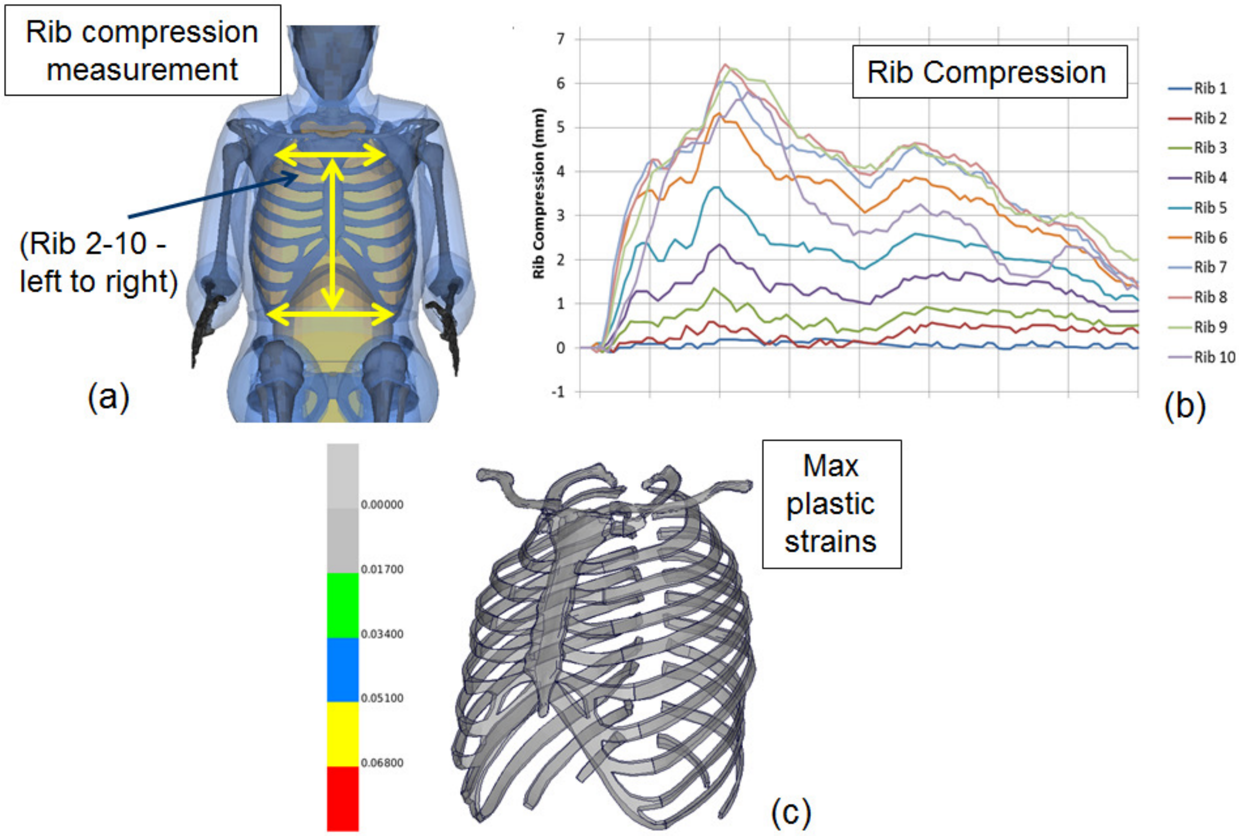

Figure 5: Definition of relative rib compression (a) relative rib compression measurement (b) and fringe plot of plastic strains(c) of the ribs

The rib compression is evaluated by monitoring the relative displacement of two outer nodes of each rib as shown in Fig. 5a. Fig. 5b shows the highest compression which takes place at the lower ribs (7, 8, 9) exactly at the height of the PRE-SAFE® Impulse Side air bladder. As can be seen on the diagram, the maximal compression does not exceed 6,5mm. Analysis of the maximal rib strains shows almost no plastic strains (c). As the fracture limit of the rib model is set to 6,8% plastic strain, the THUMS-D model is not predicting any fracture risk by an activation of PRE-SAFE® Impulse Side.

Dynamic Results

After having assessed the safeguarding of the system in a given static case, the following section describes its protection potential in a barrier load case using a full scale car crash simulation model. HBM was used to configure the system by determining the optimal time to deploy – frequently referred to as ttf (time to fire). The baseline simulation model was built using a carline achieving very good results in both European and US side crash ratings. The simulation was run with THUMS-D model with newly validated rib material (NRo).

In full scale vehicle crash tests using side impact dummy, the PRE-SAFE® Impulse Side system has already shown the potential to reduce the measurements of the rib cage significantly with up to 20-30% decreased rib deflection values. The goal of the following CAE activity was to confirm this result using HBM. It is commonly accepted that absolute values of measurements obtained by anthropomorphic test devices cannot be directly compared to calculation results derived from HBMs. In addition to the rib compression, maximal plastic strains of the ribs were estimated in order to assess the risk of rib fracture in a lateral collision with and without PRE-SAFE® Impulse Side. The results concerning rib compression and thorax strains are plotted in Fig. 6.

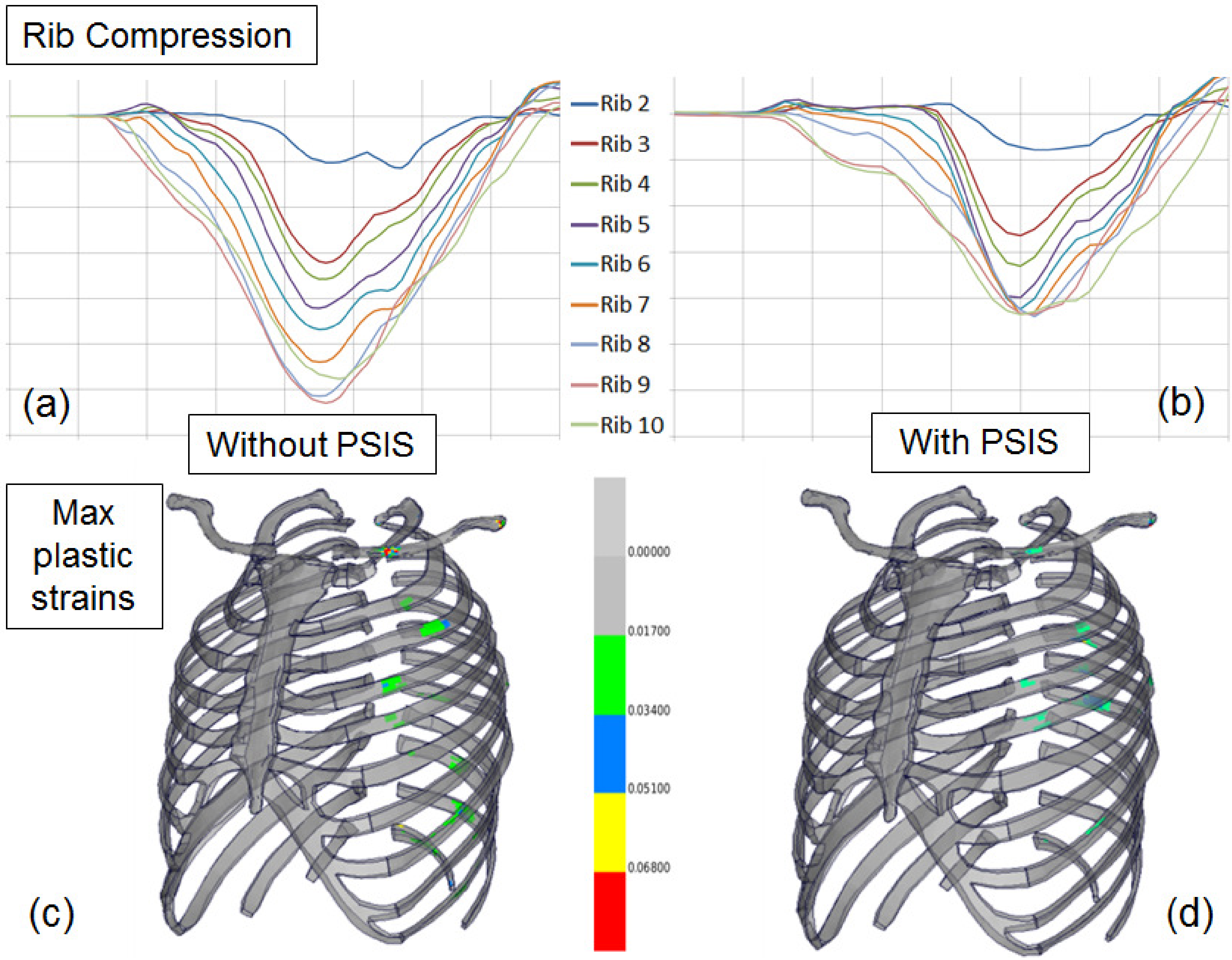

Figure 6: Rib compression measurement without (a) and with PRE-SAFE® Impulse Side (PSIS) (b), maximum plastic strains without (c) and with (d) PSIS.

The calculated rib compression shows a significant reduction of the thorax load when the PRE-SAFE® Impulse Side system is used, especially for ribs situated directly next to the air bladder. An average reduction of the rib compression by 20% was achieved.

As stated earlier in the paper, the new rib material was implemented with a failure flag when plastic strain exceeds 6,8%. Using this limit, the simulation without PRE-SAFE® Impulse Side indicates a possible rib fracture (red flag on Fig. 6c). A reduction of the calculated maximal plastic strain can be achieved while triggering PRE-SAFE® Impulse Side. Maximal plastic strain is not exceeding 4%, leading to a significant decrease of the rib fracture risk when PRE-SAFE® Impulse Side is used.

CONCLUSIONS

It is challenging to verify the effects and to show the whole potential of advanced restraint systems with traditional CAE tools. Therefore, the methodology shown in this paper was developed to assess the effects of a new generation of pre-impacting restraint systems. Regarding safeguarding and system optimization, a newly validated HBM with improved prediction capability for risk of rib fractures in elderly population was used to assess the PRE-SAFE Impulse Side system. The use of this new THUMS-D was important toward the development of the system showing that it remains harmless in case of unmotivated activation. Furthermore, the optimal triggering time of the PRE-SAFE® Impulse Side System, found using anthropomorphic test devices, has been confirmed by HBM simulations. In the investigated load case, both hardware tests and HBM simulations show a significant reduction of thorax load by using PRE-SAFE® Impulse Side.

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