TUC Validation Repository

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Load Case Description

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Validation Protocol

Thorax: Isolated Rib under Lateral Loading

Version: V01

Abaqus version provided by: University of Munich (LMU)

Last updated: January 01, 2017

Experimental data provided by: Jason Forman, University of Virginia

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1. General

This document is part of the *validation kit* for the validation of a FE Human Body Model (HBM) against the loading condition specified under 1.1. The *validation kit* is composed of the following parts:

1. FE model of **validation environment**

   The following Abaqus input files contain the validation environment model and are provided as .inp- and .inc-files in Abaqus:

   a. *TUC_THX_RIB_LAT_MAIN.inp*
   b. *TUC_THX_RIB_LAT_MODEL.inc*
   c. *TUC_THX_RIB_LAT_STEP.inc*

   The HBM to be validated needs to be prepared and integrated into the validation environment according to the validation protocol in section 4.

2. Experimental corridors

   The following experimental corridors are provided as excel-files:

   d. *ant&post_ends_cooridor_notscaled_S01.xlsx*
   e. *ant&post_ends_cooridor_notscaled_S02.xlsx*
   f. *ant&post_ends_cooridor_notscaled_S03.xlsx*
   g. *ant&post_ends_cooridor_notscaled_S04.xlsx*
   h. *ant_end_corridor_scaled.xlsx*
   i. *post_end_corridor_scaled.xlsx*

3. Documentation incl. a detailed description of the load case and a validation protocol

1.1 Classification of validation load case

Body region	Thorax
Level	Component
Load case	Dynamic lateral loading of isolated rib
References	Experiments published in: *E del Pozo, M Kinding, C Arregui-Dalmases, J Crandall, S Takayama, S Ejima, K Kamiji, T Yasuki (2011), Structural response and strain patterns of isolated ribs under lateral loading. International Journal of Crashworthiness, Vol 16, No. 2, pp. 169-180.*
Unit system	kg - mm – ms – kN – GPa
Code	Abaqus

1.2 Disclaimer

The validation kit was developed in close cooperation within the THUMS USER COMMUNITY (TUC) research project. Any use of this validation environment shall be entirely at the user's own risk and responsibility. Ludwig-Maximilian University, Adam Opel AG, AUDI AG, Autoliv, BMW AG, Daimler AG, Porsche AG, Toyota Motor Corporation and Volkswagen AG do not assume any responsibility for the validity, accuracy, or applicability of any results obtained from this research model and do not assume any liability or responsibility whatsoever for any damage, claims, injury or loss of any kind that may arise from or in connection with any use of, reference to and/or reliance upon this manual.

Ludwig-Maximilian University, Adam Opel AG, AUDI AG, Autoliv, BMW AG, Daimler AG, Porsche AG, Toyota Motor Corporation and Volkswagen AG ask that the TUC project will be acknowledged under references for any use of this FE model resulting in papers and publications.

2. Short description of experimental setup and selection of configuration

The experimental study of Del Pozo et al. (1) investigated structural and fracture characteristics of individual ribs under lateral loading. Ribs three to seven of three Post Mortem Human Surrogates (PMHS) were extracted, positioned upright and loaded at a loading rate of 1 m/s until fracture of the specimen occurred. Each rib end was thereby potted in polyurethane resin and constrained so that only rotations around one axis (y axis, see figure 1) were possible. Reaction forces were measured by two load cells, one beneath each rib end. Strain gauge measurements at several locations along the rib were taken.

This validation kit provides the FE model of the validation environment, experimental corridors as well as a detailed protocol for the validation of the 5th rib left of any FE Human Body Model (HBM). Three cadaveric specimens were tested in this configuration. Validation reference parameters to be used for the validation of the FE rib are force-displacement-corridors as well as force-strain-corridors.

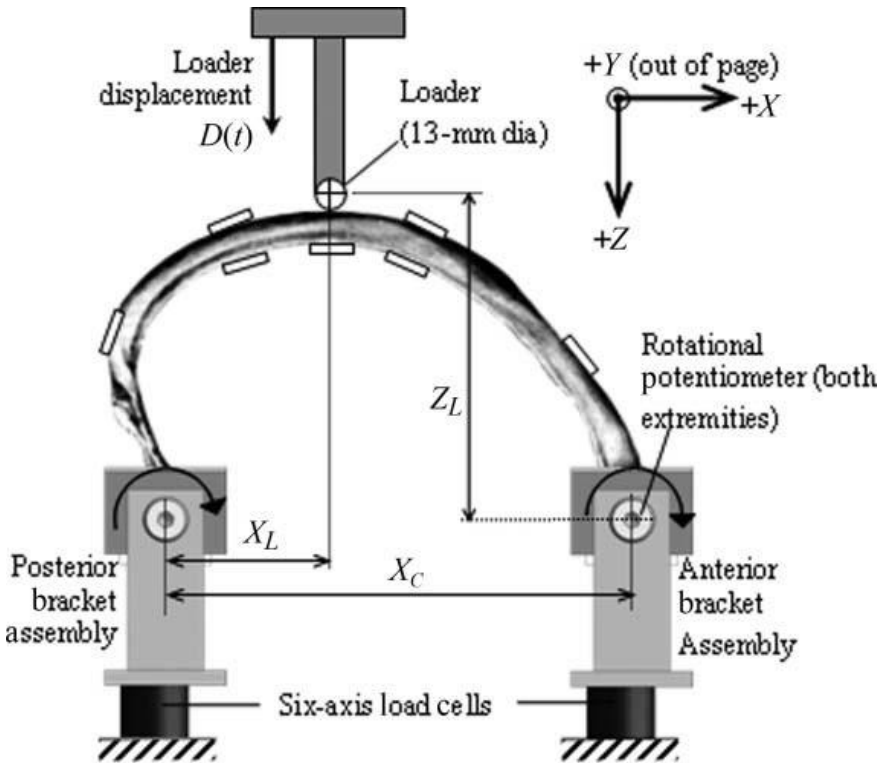

Figure 1 Test apparatus used by Del Pozo et al. (1)

All details on the specimens with regard to age, gender and anthropometric measurements are given in the following table and are illustrated in figure 2.

			Rib dimensions [mm]			Strain locations [mm]		Initial position [mm]		
Subject	age	gender	D_0	L_0	L_1	L_2	L_3	X_C	X_L	Z_L
468	67	Male	208	314	171	65	50	210	70.9	94.5
473	54	Male	194	304	166	63	46	189	56.2	92.8
480	71	Male	216	333	171	166	57	210	75.2	99.1

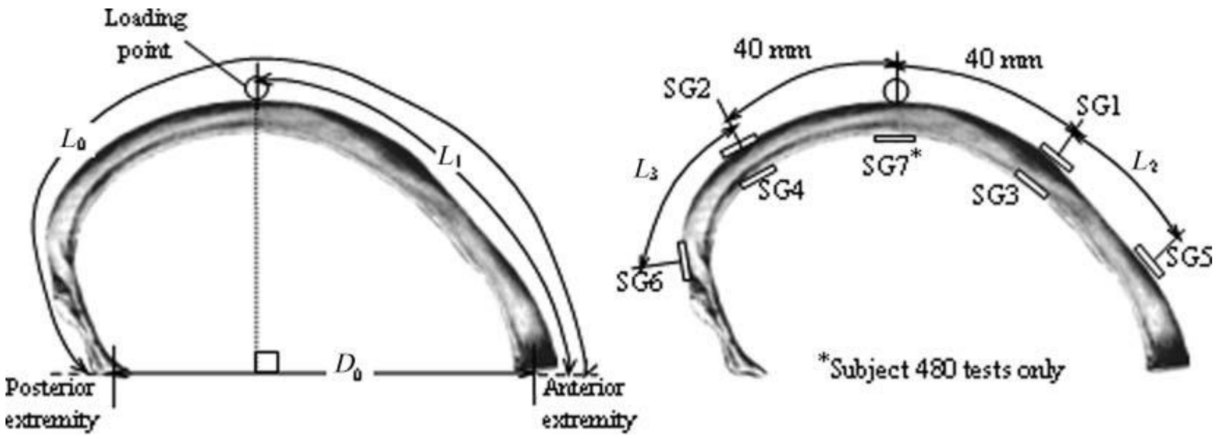

Figure 2 Rib dimension definitions and strain gage locations (1)

3. Description of the Validation Environment

In this section the validation environment, i.e. the numerical model of the experimental setup excluding the HBM to be validated, is described by providing an overview of the keywords used in the above mentioned input decks: *TUC_THX_RIB_LAT_MAIN.inp, TUC_THX_RIB_LAT_MODEL.inc* and *TUC_THX_RIB_LAT_STEP.inc*. The protocol of section 4 describes how a human body model needs to be processed to be integrated in and validated with this environment FE model.

3.1 *TUC_THX_RIB_LAT_MAIN.inp* - main file

Keyword	Explanation	
*INCLUDE	**Included files are:** • *TUC_THX_RIB_LAT_MODEL.inc* • *TUC_THX_RIB_LAT_STEP.inc* • *[HBM.inc]*	**Include**

3.2 *TUC_THX_RIB_LAT_MODEL.inc* – Model data

Keyword	Explanation	
*ELEMENT	**Impactor** • ELSET=IMPACTOR • TYPE=C3D8R • Diameter: Ø = 13 mm • Length: l = 30mm	**Impactor**
*SOLID SECTION *SECTION CONTROLS	**Impactor** • ELSET=IMPACTOR • Element ID range: 656-1039 • Node ID range: 1-537	
*MATERIAL *DENSITY *ELASTIC	**Impactor** • NAME=IMPACTOR • density: ρ = 2.700e-006 kg/mm3 • Young's modulus: E = 70 GPa • Poisson's ratio: ν = 0.35 •	
*RIGID BODY	**Impactor** • REF NODE=1285249 • POSITION=CENTER OF MASS	
*INITIAL CONDITIONS	**Initial velocity definition** • NSET=INITIAL_VELOCITY • TYPE=VELOCITY • Initial velocity in global z-direction: 1 m/s	**Initial Conditions**
*SURFACE	**Surface definition for rib-impactor interface** • ELSET=CORTICAL_RIB • TYPE=ELEMENT	**Surface**

3.3 *TUC_THX_RIB_LAT_STEP.inc* – Boundary Conditions

The following boundary conditions, constraints and output parameters are defined in the validation environment.

Keyword	Explanation	
*STEP *DYNAMIC, EXPLICIT	• Termination time = 25 ms	
*CONTACT PAIR *FRICTION *SURFACE INTERACTION	**Surface definition for rib-impactor interface** • Sliding contact between rib (cortical bone part/slave) and impactor (master) • CPSET=RIB_IMPACTOR	**Contact**
*BOUNDARY, TYPE=VELOCITY	To apply a constant velocity of 1m/s to the impactor in z-direction	**BCs**

*RIGID BODY	To account for specimen potting
	• Anterior rib end
	  o REF NODE=1285250
	  o TIE NSET=RN2;ANTERIOR
	• Posterior rib end
	  o REF NODE=1285251
	  o TIE NSET=RN3;POSTERIOR
		Potting

*CONNECTOR SECTION *ORIENTATION *BOUNDARY	Revolute joint defined at anterior and posterior rib ends • ELSET=CS1;ANTERIOR (anterior rib end) • ELSET=CS2;POSTERIOR (posterior rib end)	**Joints**
*BOUNDARY	To constrain nodes with IDs 1001 and 2001 in all global translational and rotational directions	**Constraint**
*OUTPUT, FIELD	**Binary output** • INTERVAL = 1.0 ms • VARIABLE=PRESELECT	**Output**
*OUTPUT, HISTORY *CONTACT OUTPUT *ELEMENT OUTPUT *ENERGY OUTPUT	**Time history output** • INTERVAL = 0.1 ms • Joint reaction forces • Impactor displacement • Element output for strain measurements • Contact Forces • Global output	

Control cards delivered with the HBM itself are to be used. Termination time only is defined.

4. Validation Protocol

The following validation protocol is a step-by-step procedure to safeguard a credible validation of any HBM this validation environment is used for. The protocol is composed of three parts containing the following information:

1. **Pre-processing**
   In section 4.1 it is described how the human model needs to be prepared and positioned in the above described validation environment and what other adaptions need to be done to meet the specifications in the reference paper.
2. **Solution**
   Chosen control parameters, hardware and solver version are listed in section 4.2.
3. **Post-processing**
   Section 4.3 describes how experimental data were prepared and how simulation results need to be processed to guarantee a reasonable validation.

It is envisaged that the following protocol can be applied to any HBM which is to be validated against the above mentioned loading condition. However, the provided FE model of the validation environment was setup with **THUMS^{TM} TUC AM50 Version 3.0**.

4.1 PRE-PROCESSING

This section describes how the human model needs to be prepared and positioned in the above described validation environment and what other adaptions need to be done to meet the specifications in the reference paper.

Note: THUMS™ AM50 Version 4.01 (LS-Dyna) was used to illustrate the positioning process.

4.1.1 Isolation, Positioning and Integration of the Human Body Model

The following steps are to be taken to prepare and position the HBM in the above described validation environment to meet the specifications in the reference paper. It is recommended to put all HBM relevant keywords in an additional Abaqus include file and reference the include file in the main file.

1. **Isolation of validation-relevant components**

The HBM needs to be prepared according to the specimen preparations done in the experimental study and described under 2. To extract the 5th rib of the left side, the following parts are to be isolated from the HBM:

- Cortical bone of 5th rib from the left side of the HBM
- Trabecular bone of 5th rib from the left side of the HBM

All other parts are not relevant for modelling the above mentioned loading condition and are to be deleted including corresponding material, property, set, group, etc. definitions.

2. **Positioning of the isolated rib in the validation environment**

To correctly position the isolated rib in the validation environment, the following steps need to be taken.

a. Definition of loading point

First, the *loading point* is to be defined on the external surface of the rib. It is defined as the point on the external surface of the rib furthest from the axis extending between anterior and posterior extremities as can be seen in Figure 3.

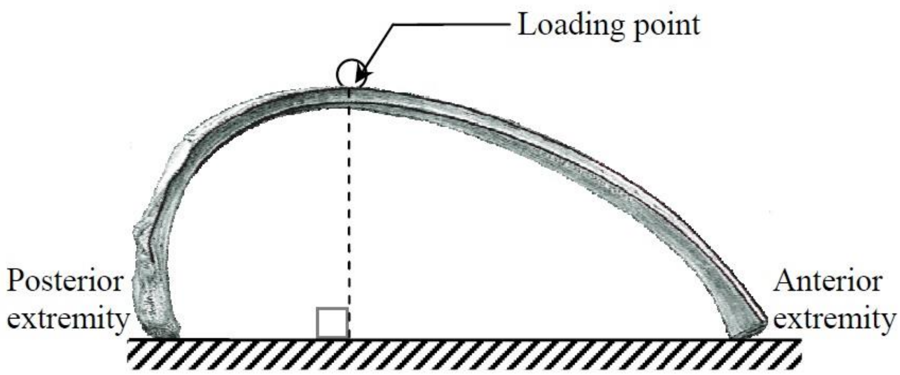

Figure 3 Loading point definition

b. <u>Translation</u>

To facilitate the positioning process a temporary node in the middle of the distance between the centres of the anterior and posterior rib end needs to be created. Location of all nodes can be seen in Figure 4.

The whole rib is then to be translated in a way that the temporary node coincides with the origin of the global coordinate system.

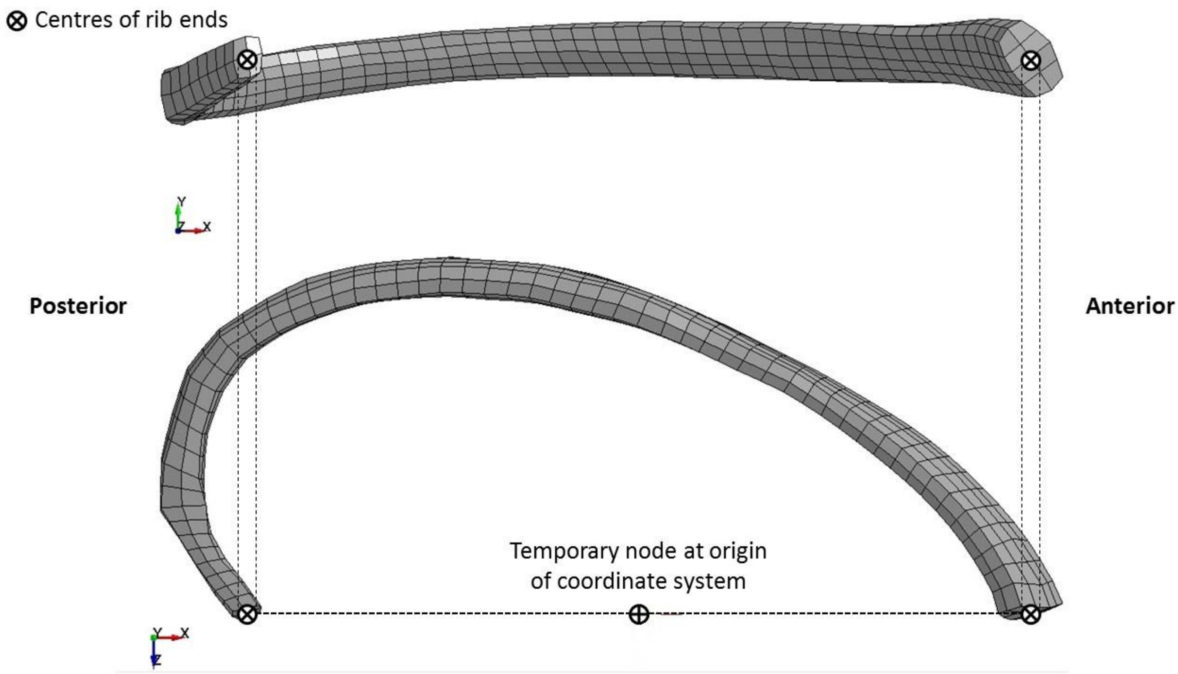

Figure 4 Centres of rib ends and temporary node at origin of coordinate system

c. <u>Rotations</u>

Next, the rib is to be rotated to match the following:

i. X axis (its positive direction) of the global coordinate system points from the posterior rib end to the anterior rib end
ii. Z axis (its positive direction) of the global coordinate system points from the lateral side of the rib to the medial side
iii. Z coordinate (in the global coordinate system) of the centres of the anterior and posterior rib end is zero
iv. The centres of the anterior and posterior rib end as well as the loading point are in the same major plane which is located parallel to the ZX plane and which can be seen in figure 5.

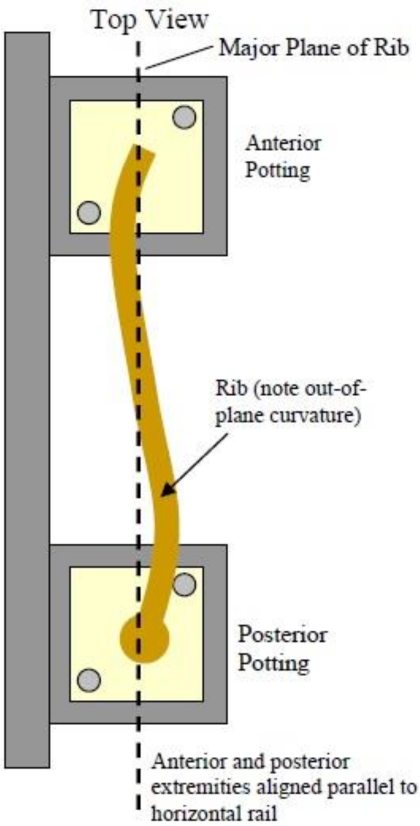

Figure 5 Major plane of rib

4.1.2 Constraints

The following constraints already defined in the model or step include file need to be adapted depending on the HBM used.

a. <u>Potting</u>

To account for the specimen potting of the anterior and posterior rib end, several rows of elements are to be set rigid (Figure 6). Being measured from the ends up to 20 mm along the rib curvature the rib extremities were potted (measurements based on CT data). The nodes of the concerned elements at the anterior rib end are to be added to node set NSET = ANTERIOR_RIB_END, the nodes of the posterior rib end to node set NSET = POSTERIOR_RIB_END. Both node sets (as TIE NSET) are referenced in the rigid bodies with reference nodes REF NODE = 1285250 (anterior rib end) and REF NODE = 1285251 (posterior rib end).

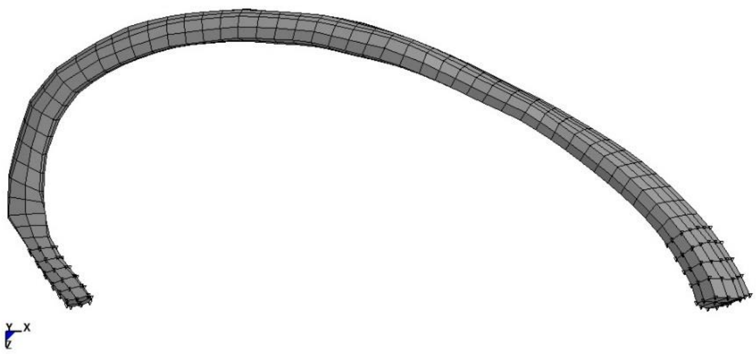

Figure 6 Node selection for rigid body definition at rib ends

b. Joints

Two revolute joints were defined at the anterior and posterior rib ends, respectively, to allow rotations about the y-axis only. The nodal coordinates of the coincident node pairs (for the anterior rib end: 1000/1001; for the posterior rib end: 2000/2001) as well as the coordinate systems (*ORIENTATION; NAME = ANTERIOR_CS: for anterior rib end; *ORIENTATION; NAME = POSTERIOR_CS: for posterior rib end) are to be updated to meet the following specification:

1. The axis of each of the two defined revolute joints is to be parallel to the y-axis of the global coordinate system.
2. Based on measurements approximated from CT data, the nodes defining the axes of the revolute joints are to be chosen so that:
   a. the axes are located parallel to the global y-axis,
   b. they lie within a distance of ±3 mm (along the rib curvature) from the rib end (cf. Figure 7) and
   c. their X coordinates coincide (approximately) with the centre of each rib end.

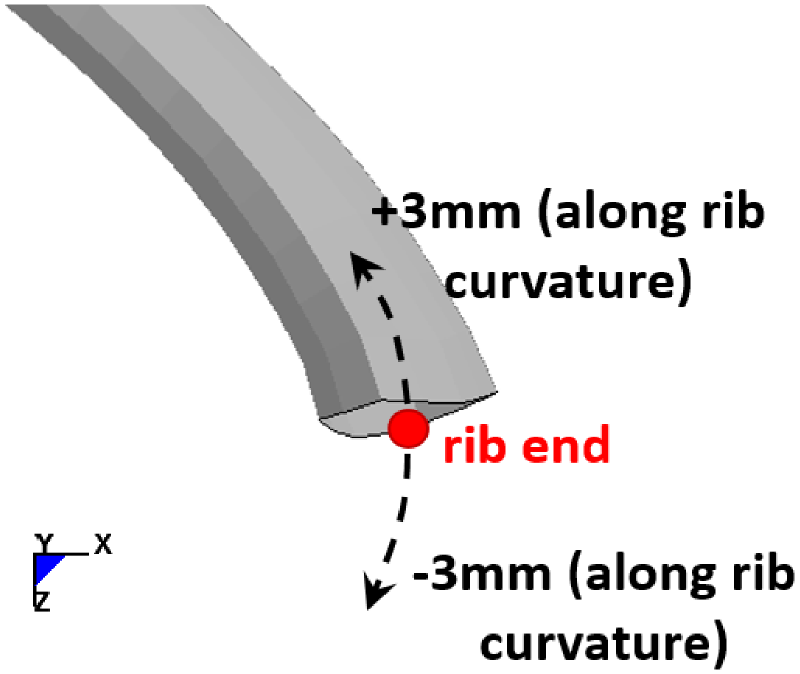

Figure 7 Range for the position of the axis of rotation with regard to the rib end

4.1.3 Impactor

The impactor needs to be positioned to match the following:

1. The longitudinal axis of the impactor is to be parallel to the rotational axes of the extremities and therefore also to the y axis.
2. The centre of the impactor longitudinally coincides approximately with the major plane of the rib.
3. The centre of the impactor cross-section should be positioned above the loading point node at time t = 0.

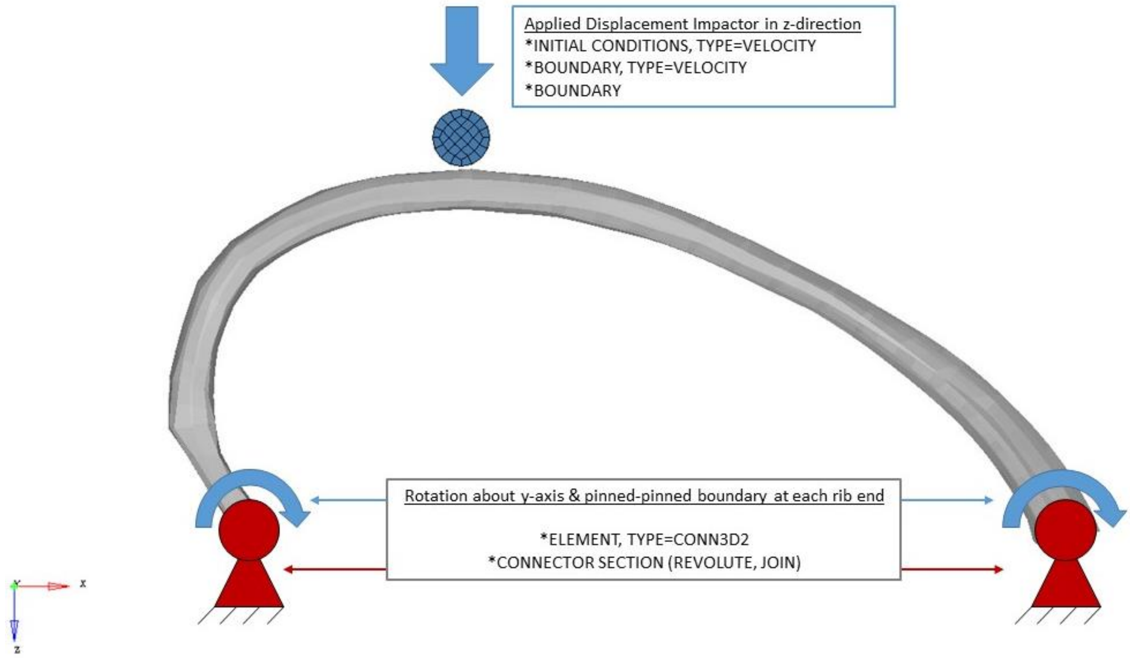

Figure 8 Model overview

4.1.4 Further adaptions

A sliding contact (CPSET=RIB_IMPACTOR) is defined between the impactor (master) and the cortical bone of the rib (slave). The surface definition of the cortical bone of the rib needs to be updated. Therefore, all non-rigid shell elements of the cortical bone are to be added to element set ELSET=CORTICAL_RIB.

In the experiments no sliding between the impactor and the rib was observed. To maintain the non-sliding condition in the computational model a friction coefficient (not measured in the tests) needs to be defined in the contact. The sliding condition can be mesh dependent – i.e. for a different element size different values of the friction coefficient can prevent the impactor from sliding along the rib. Therefore, the value of the friction coefficient needs to be chosen such that the non-sliding condition is maintained throughout the entire simulation. The user might need to run several simulations to determine the appropriate value and check how different values influence the output forces/strains. The goal is to find a value which will prevent the impactor from sliding and a small change in the friction will not change the output results in a noticeable way.

4.1.5 Definition of output parameters

The binary and time history output is defined in the step include file *TUC_THX_RIB_LAT_STEP.inc.* The following model-relevant step is to be taken.

To account for the strain gauge measurements at the four locations SG1, SG2, SG3 and SG4, four elements of the cortical bone of the rib located approximately ±40 mm off the loading point (along the rib curvature) on the lateral and medial side of the rib, respectively, are to be added to the element set ELSET=STRAIN_MEASUREMENT.

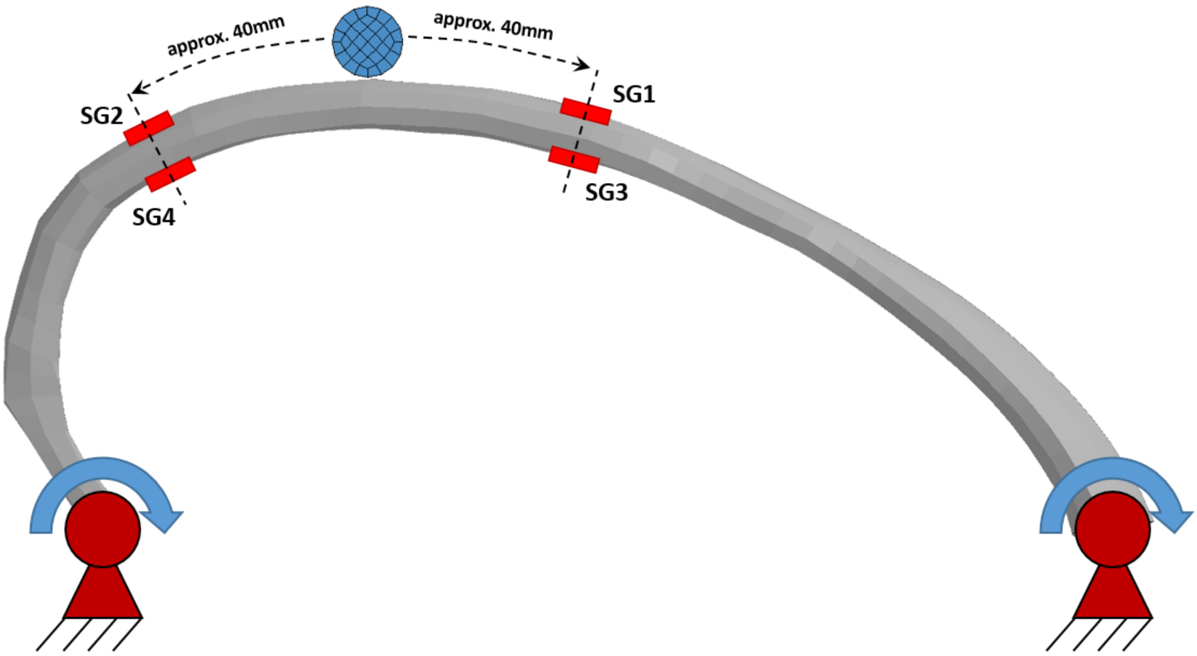

Figure 9 Strain gauge (SG) locations

4.2 SOLUTION

The following solver and hardware was used to setup and run the validation model with THUMS™ TUC AM50 Version 3.0.

Hardware	Intel® Xeon®E5645, 2.4GHz, 4 cores, Intel Corporation
Solver	Abaqus 6.12

4.3 POST-PROCESSING

4.3.1 Model check

Before comparing the model response against the experimental corridors, the user should check first:

a. That the forces on the impactor (read as the forces in x-, y- and z-direction, respectively, from contact between the impactor and the rib) are the same as the sum of the forces in x-, y- and z-direction, respectively, from the rib ends (read as joint forces)
b. If mass scaling is used, the system added mass is less than 1% of its physical mass
c. That the energy ratio remains close to 1 throughout the entire simulation
d. That hourglass energy is less than 5% of the peak internal energy
e. That sliding energy is positive (due to friction, if used), NOT negative due to initial penetrations in contact
f. That the total energy of the system is similar, in terms of the shape of its time-history curve, to the time-history curve of the external work put into the system
g. That the kinetic energy is substantially lower that the total energy of the system

4.3.2 Data Processing

It is suggested to use a moving average (in the time domain) for the joint reaction forces and strains to reduce numerical noise from the output. Before building the response curves, the user needs to make sure, though, that by using the moving average, the force and strain response will not be altered in a way that the processed data will not be corresponding to the model behaviour anymore.

4.3.3 Corridors

For the purpose of validating a HBM against the above mentioned loading condition six response corridors (Figures 10 to 15), i.e. two force-displacement and four force-strain corridors, were created based on the experimental test data. Each corridor consists of two main parts:

- (before fracture) response corridor marked in black, following the experimental test curves, built using the ellipse-based method described in detail by Ash et. al, 2012
- fracture (occurrence) corridor marked in red, built as a simple ±1 standard deviation (SD) rectangular corridor. SD for the corridor was calculated in both directions (either for force and displacement or for force and strain). The average force and loader displacement (or strain), at which the fracture occurred, were calculated, based on the fracture values recorded on the experimental tests.

1. **<u>Force-displacement corridor for anterior rib end</u>**

   ➔ Provided in excel format in file *ant_end_corridor_scaled.xlsx*

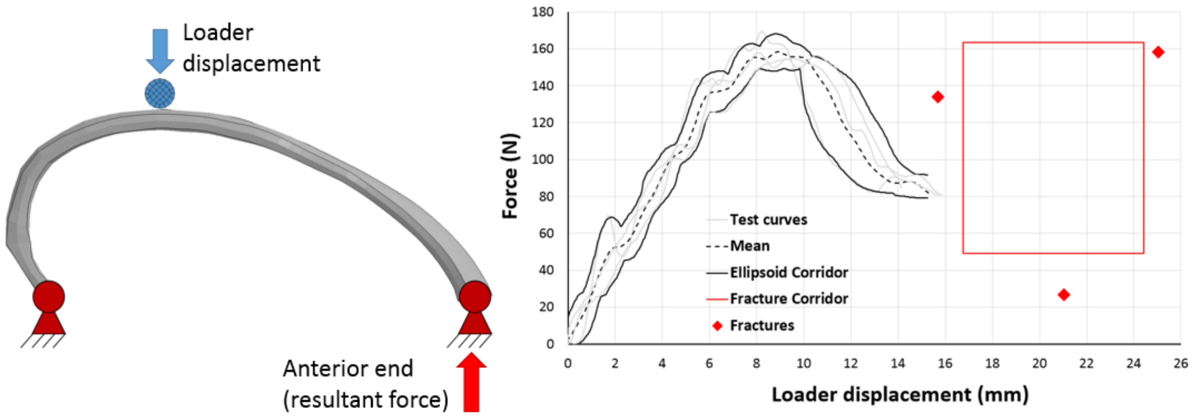

Figure 10 Force-displacement corridor for the anterior rib end

2. **Force-displacement corridor for posterior rib end**

➔ Provided in excel format in file *post_end_corridor_notscaled.xlsx*

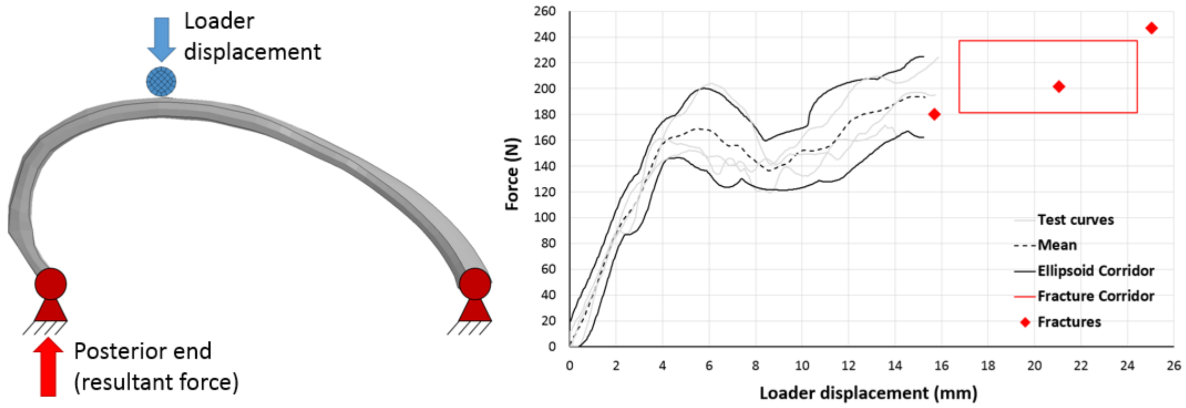

Figure 11 Force-displacement corridor for the posterior rib end

3. **Force-strain corridor for strain gauge 1**

➔ Provided in excel format in file *ant&post_ends_cooridor_notscaled_S01.xlsx*

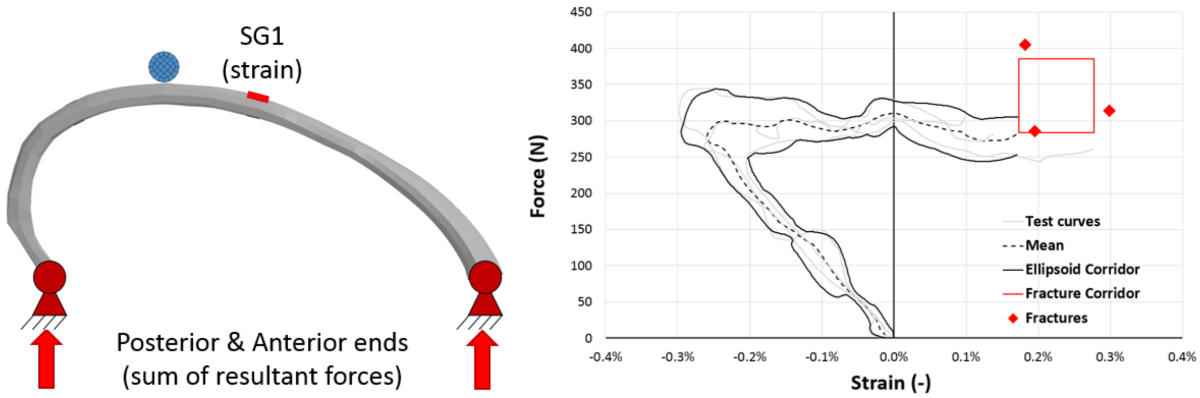

Figure 12 Force-strain corridor for strain gauge 1 (SG1)

4. Force-strain corridor for strain gauge 2

➔ Provided in excel format in file *ant&post_ends_cooridor_notscaled_S02.xlsx*

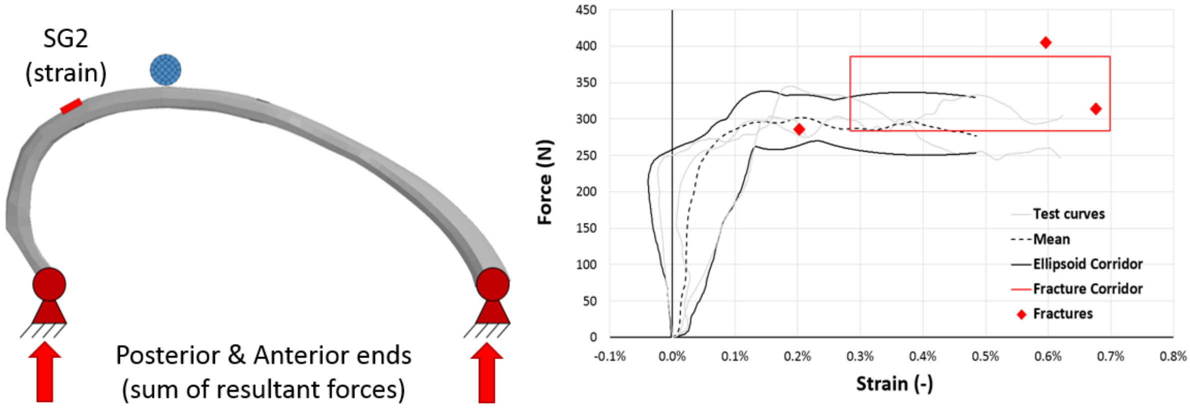

Figure 13 Force-strain corridor for strain gauge 2 (SG2)

5. Force-strain corridor for strain gauge 3

➔ Provided in excel format in file *ant&post_ends_cooridor_notscaled_S03.xlsx*

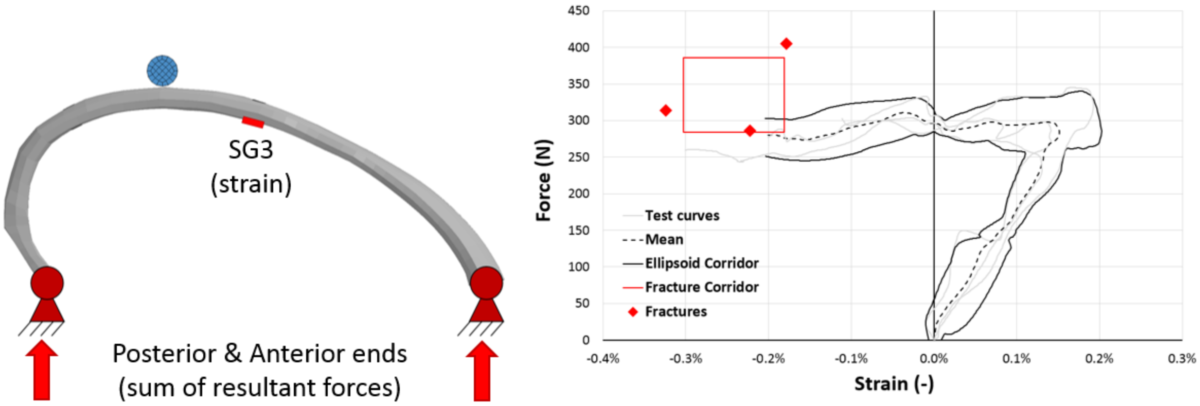

Figure 14 Force-strain corridor for strain gauge 3 (SG3)

6. Force-strain corridor for strain gauge 4

➔ Provided in excel format in file *ant&post_ends_cooridor_notscaled_S04.xlsx*

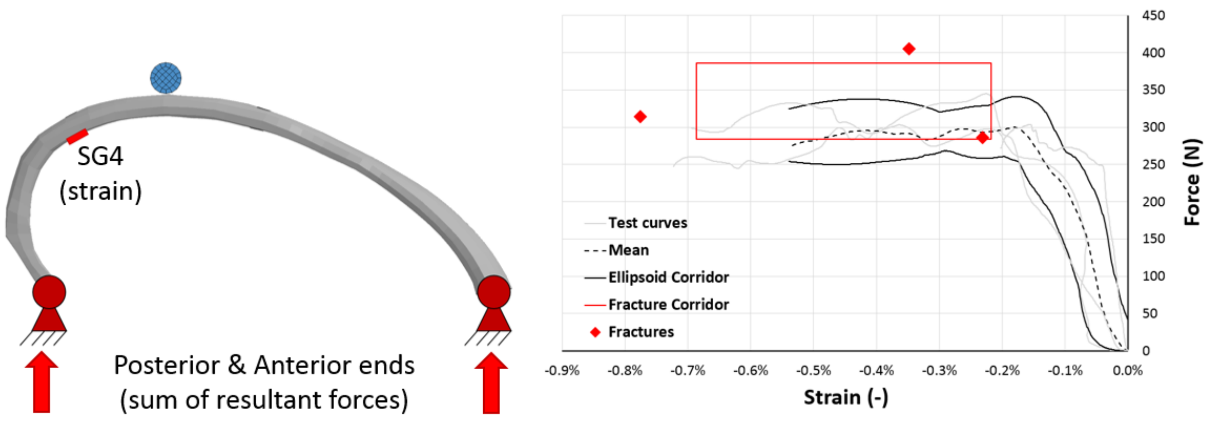

Figure 15 Force-strain corridor for strain gauge 4 (SG4)

4.3.4 Model validation

1. **General**

Achieving the model response fitting the given corridors using simple material models may be a challenge. The user should focus on parts of the corridors applicable to the goals of the modelling task. For example, if the model is intended to capture the linear response of the rib under limited deformation, then it may be adequate to consider only the first 6mm of the force-displacement corridors. If the user wants to model the rib response under large deformation, including material and geometric nonlinearities after the first force peak, all six corridors (throughout their entire length) should be considered as the goal response.

2. **Strain measurements**

In the experiments the following strain gauges were used:

- Model CEA-06-062UW- 350, Vishay Micro-Measurements
- Length - Active 0.062" (1.57mm)
- Length - Overall Pattern 0.220" (5.59mm)
- Length - Overall 0.31" (7.9mm)
- Width - Active 0.120" (3.05mm)
- Width - Overall Pattern 0.120" (3.05mm)
- Width - Overall 0.19" (4.8mm)

Strain measurements in the Finite Element Method are mesh-dependent. It means that for a different element size different values of strain can be calculated at the same rib location. It is crucial that the element size used in the model is as close as it is possible to the size of a physical strain gauge (its active part) used on a test. For the purpose of this load case scenario, measurements from four different locations along the rib (Figure 9) were used to plot the model response against different force-strain corridors (Figures 12 to 15). As the strain gauges were attached to the medial and lateral side of the rib, it is up to the user to utilize the strains from the outermost shell element surface, and in the correct direction (along the rib curvature). To do so, the user needs to identify the axes of the element local coordinate system for the elements identified as the numerical strain gauges, and confirm that one of the local axes is closely aligned with the rib curvilinear abscissa. Strains in this direction should be used to build the force-strain response curves. The normal vector of the element will indicate the element's outermost surface.

It is strongly suggested for the user to run a sensitivity study with elements (±1 or 2 elements) closer/further away from the impact point, to investigate the variability in strain measurements as a function of the distance from the initial contact location between the impactor and the rib.

The sum of the resultant reaction forces at both rib ends are to be plotted against the obtained strains projected to the element's surface.

3. Reaction forces

Resultant reaction forces at the anterior and posterior rib end are measured as reaction forces (RF-Reaction Force, MAG) in the nodes with ID 1001 (anterior rib end) and 2001 (posterior rib end) and are to be plotted against the impactor displacement measured by nodal time-history (*NODE OUTPUT, NSET=IMPACTOR_DISPLACEMENT). After being processed according to section 3.3.2 the plot can then be compared to the relevant corridors (Figures 10 and 11).

5. References

1. E del Pozo, M Kinding, C Arregui-Dalmases, J Crandall, S Takayama, S Ejima, K Kamiji, T Yasuki (2011), Structural response and strain patterns of isolated ribs under lateral loading. International Journal of Crashworthiness, Vol 16, No. 2, pp. 169-180.
2. Ash, J.H., Lessley, D.J., Forman, J.L., Zhang, Q., Shaw, C.G., Crandall, J.R., 2012. Whole-body kinematics: response corridors for restrained PMHS in frontal impacts. In: Proceedings of the International Conference on the Biomechanics of Impact (IRCOBI).