

Improving comfort simulations of sleeping mattresses for IKEA

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DEPARTMENT OF DESIGN SCIENCES
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MASTER THESIS



Improving comfort simulations of sleeping mattresses for IKEA

Using finite element methods in LS-Dyna

Joel Elinder
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Abstract

It is beneficial for a furniture company like IKEA to objectively and accurately evaluate what makes a mattress comfortable. But what defines comfort? IKEA currently investigates mattress comfort through extensive real-life user testing. Through which, six parameters of comfort have been identified. By measuring these parameters, one can get an idea of how comfortable a particular person will find a particular mattress. These parameters are a convenient tool in product development since they allow mattresses of different designs to be compared objectively. However, the mattress specific parameter values' procurement requires user testing, which is an inherently slow process that creates a bottleneck in the product development cycle. To reduce this bottleneck, IKEA wants to use computer-simulations. By combining computer models of the human body with models of a mattress, full-scale so-called finite element (FE) simulations can be run. However, IKEA's current computer models are neither accurate nor efficient, which is what this thesis aims to address. In this thesis, a major increase in accuracy and a 10x increase in efficiency has been achieved through fine-tuning of the computer models and certain simplifications made to the computerized model of the human body. The results of this thesis are computer models and methodology, which are usable in all future similar comfort simulations. If utilized correctly, the product developers now have a tool to accurately and efficiently establish whether or not a mattress is likely to be comfortable, without the need for extensive user testing.

Keywords: LS-Dyna simulations, optimizing explicit finite element analysis, simulated compressive testing, human soft tissue material models, mass scaling, hyperelastic materials, material validation

Sammanfattning

Ett kommersiellt möbelföretag som IKEA har av förklarliga skäl ett stort intresse i att både objektivt och tillförlitligt avgöra om en madrass är komfortabel eller inte. Men hur definierar man komfort? I nuläget utvärderar IKEA detta med hjälp av användartester. I användartesterna har IKEA identifierat sex stycken komfortparametrar, med hjälp av vilka de kan få en objektiv initial uppfattning om huruvida en person av viss kroppstyp kommer att tycka en madrass är bekväm eller inte. Men, då insamlingen av madrassspecifika parametervärden sker via tidskrävande användartester, uppstår här en flaskhals i utvecklingscykeln. För att reducera denna flaskhals vill IKEA därför använda sig av finita elementmetoden (FEM), en analysmetod där interaktionen mellan datormodeller av människa och madrass kan simuleras. Här ligger fokus för denna uppsats, då IKEAs nuvarande modeller av människa och madrass varken är tillförlitliga eller effektiva. Genom utvärdering och en efterföljande rationalisering av IKEAs modeller har jag lyckats öka både tillförlitlighet i modellerna och effektiviteten i metoden. Simuleringarna överensstämmer nu bättre med verkligheten och kräver endast en tiondel av datorkraften. De slutsatser och metoder som har etablerats under arbetets gång är generella inom ämnet, och är därför applicerbara på alla framtida snarlika komfortsimuleringar. Med hjälp av dessa förbättringar har IKEAs produktutvecklare nu erhållit ett fungerande verktyg, som effektivt och tillförlitligt hjälper dem att avgöra om en madrass är komfortabel eller inte, utan att behöva genomföra tidskrävande användartester.

Nyckelord: LS-Dyna simuleringar, optimering av explicit finit elementanalys, kompressionstest, materialmodell av mänsklig vävnad, hyperelastiska material, materialmodeller, masskalning

Preface/Acknowledgements

Summer is coming, it is the end of May and the white lilacs are blooming. In a lot of ways May represents beginnings, the blackbirds find their mates, the beech and chestnut trees outside IKDC are in full bloom, they stand firm, almost like masts on a ship touting large green sails, ready to take us out on the pleasantly blue summer seas. But for me, May, and the writing of this last preface, is somewhat bittersweet. I am happy that the work on my thesis is done. I am pleased with the results. But while working on something as large, as intensely, and alone (although I have sat alongside my fellow classmates), it is impossible not to weave part of yourself into the work. While the thesis can't be considered a self-portrait by any means, it could be regarded as an extra toe, or a particularly fancy-looking haircut. As we can learn from looking at ourselves, a thesis is never perfect, it is good enough. The finishing of this report represents the end of my time here at LTH, and while it symbolises the beginning of many new things, it is the end for some. A deep dive into finite element analysis is a fitting end, a big red bow-tie to put on top, of a masters degree in mechanical engineering. As the study of it, includes almost the entire vat of technical knowledge within. Looking back over these five years at LTH, and out across the fluorescent-lit dental office waiting room-esque office, where I have been working for the majority of the last five months, I am hit with an odd sense of nostalgia, an inevitable almost existential resignation, asking myself: *What now?*

Big thanks to my mom, Liselotte Schäfer Elinder, for your extensive proof-reading. Thank you Praveen Kulkarni at IKEA for your friendliness, interest, and technical support. Finally, thank you Ingrid Svensson, my supervisor, for proof reading and helping me get the project started.

Lund, 06-2020
Joel Elinder

Contents

1	Introduction	1
1.1	Overview of the finite element method (FEM)	3
1.2	Limitation of timestep in FEM	6
1.2.1	Massively parallel processing (MPP) and decomposition	7
1.3	(Dis)comfort according to IKEA	9
1.3.1	Measuring comfort	9
2	Purpose of master thesis	11
3	Method	12
4	Results and conclusions from previous work by IKEA constructors	13
4.1	User study	14
4.2	Mattress material experiments	15
4.3	FE-models	16
4.3.1	Mattresses	16
4.3.2	Human body	16
4.4	Full scale simulations	18
4.5	Takeaways from the IKEA constructors work	18
4.5.1	Results of IKEA constructors	18
4.6	Evaluating IKEA constructors results	19
4.6.1	Evaluating IKEA constructors material model accuracy	20
4.7	Results of my evaluation	23
4.7.1	Full body simulation run time	26

4.8	Discussion of IKEA constructors results	26
4.8.1	Individual mattress material models	26
4.8.2	Full mattress assembly	27
4.9	Conclusions	28
5	Improvements developed during this thesis	29
5.1	Accuracy	29
5.1.1	Mattress material models	29
5.2	Efficiency	31
5.2.1	Soft tissue material models	31
5.2.2	Decomposition	33
5.2.3	Reducing need for mass scaling	35
5.2.4	Reducing body bouncing	37
6	Results	39
6.1	Accuracy	39
6.1.1	Mattress material models	40
6.1.2	Soft tissue material models	45
6.2	Efficiency	46
6.2.1	Decomposition	46
6.2.2	Reducing the need for mass scaling	47
6.2.3	Reduced body bouncing	48
6.3	Summary of results	49
7	Discussion	50
7.1	Accuracy	50
7.2	Further improvements of accuracy	51
7.3	Efficiency	52
7.4	Further improvements in efficiency	52
8	Conclusion	54
	Appendices	56
A	Step-by-step method on replicating a directional compression test on a single specimen in LS-Dyna	56

B	More on dummy layers	65
C	Replicating previous results in LS-Dyna	67
C.1	Material parameter translation: Abaqus to LS-Dyna	67
C.2	Replication results	68
C.3	Settings from section C.2	73
C.4	Matlab script from section C.1	74
D	Editing decomposition	75
E	About the body tray	76
F	Tips and tricks using LS-Dyna and LS-Prepost	77

List of acronyms and abbreviations

BMI - Body Mass Index
CPU - Central Processing Unit
FEA - Finite Element Analysis
FE - Finite Element
FEM - Finite Element Method
IC or ICs - IKEA Constructor(s)
IKEA - Ingvar Kamprad Elmtaryd Agunnaryd
MPP - Massively parallel processing
RCB - Recursive Coordinate Bisection

Chapter 1

Introduction

The work in this thesis aims to improve the efficiency and accuracy of previous comfort simulations by IKEA constructors (IC) using finite element methods (FEM) in the program LS-Dyna. The comfort simulations consist of a computerized model of a human body being dropped onto a computerized model of a mattress, while measuring the resulting forces and deformations within both body and mattress. These measurements are to be used as a tool to evaluate mattress comfort in the product development process at IKEA.

In an effort to increase the efficiency of IC's simulations, which as the project came along also came to include increased accuracy, an initial understanding of FEM using LS-Dyna has to be established (section 1.1). Here the basic principles of FEM and its ins and outs in regards to efficiency are described. This is followed by an introduction to the subject of comfort as defined by IKEA (section 1.3), where the parameters of comfort measurable using FEM are presented.

In chapter 4, the methods of simulation, experimentation, and the results of previous work by IC are described and discussed. Since IC's work was done using another FEM-program, called Abaqus, the initial idea was to replicate their results using LS-Dyna while focusing on increasing efficiency. However, during this replication process, several significant inconsistencies between their

experimental data and their results were identified. Therefore, the project came to include an improvement in accuracy as well.

Based on the results of IC's work, the learnings from replicating them, and the study of FEM simulations in regards to comfort, a set of improvements in efficiency and accuracy are presented and described in chapter 5. The improvements are then applied to the simulations used to replicate IC's results and examined by comparing them to the provided real-life experimental data (chapter 6). In chapter 7 results are briefly discussed alongside a couple of suggestions for further improvements on accuracy and efficiency, that could be explored in future experiments. Finally, in chapter 8, some conclusions are drawn on the general process of simulating comfort using FEM.

1.1 Overview of the finite element method (FEM)

***Authors note:** The purpose of this section is not to provide the reader with a complete understanding of FEM, although it would be an exciting test of my writing skills, but rather provide the reader with a sufficient understanding of the subject to accurately evaluate the results and the general ideas of this thesis.*

FEM, or also known as finite element analysis (FEA), is a widely used computer numerical method used for solving large equation systems of partial differential equations. These large equation systems represent discrete versions of geometric bodies and materials to which certain conditions and forces are applied over a set period of time. The purpose of FEM is to determine the resulting forces and deformations to the body after this period. This is done by solving the large equation systems using Newton's second law $F = ma$ at set intervals, where each step relies on the previous, until a set point in time.

$$\text{FEM} = \text{Bodies} + \text{Forces} + \text{Materials} + \text{Boundary conditions} + \text{Time} \quad (1.1)$$

The three-dimensional bodies are made up of multiple ***elements*** (hence finite element) which in turn are made up of multiple ***nodes***. A node in three-dimensional space consists of an x, y, and z-coordinate relating to a known coordinate system, where an element consists of the volume encapsulated between these nodes. The simplest three-dimensional element consists of four nodes and is called a ***tetrahedral element*** (Figure 1.1).

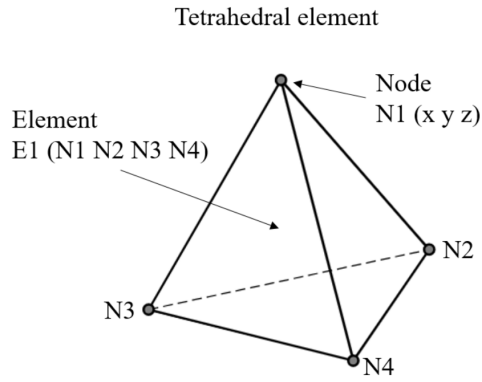


Figure 1.1: Tetrahedral element

The arrangement of multiple elements in the form of a body is called a *mesh*, and the size of the elements in this mesh is called the *mesh resolution*, where a higher resolution mesh requires more elements and subsequently more nodes, see Figure 1.2. Using nodes and elements, it is possible to describe any three-dimensional body numerically.

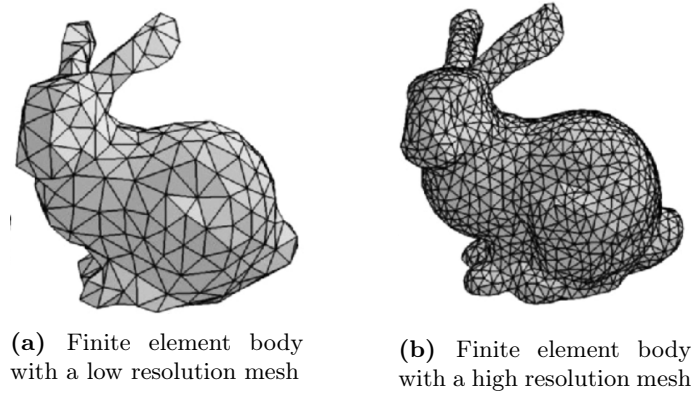


Figure 1.2: Variation in mesh resolution | Image from (Novaković et al., 2017)

The geometrical shape of a finite element (FE) body is described using elements. However, to properly model something, the FE-body also needs to

be assigned a material, like rubber, steel, or foam. The mathematical model describing the assigned material behavior under an applied load is called a **material model** (Thompson & Thompson, 2017). In Figure 1.3 the material behaviour under an applied load, or **stress vs. strain** characteristics, of three different materials are plotted.

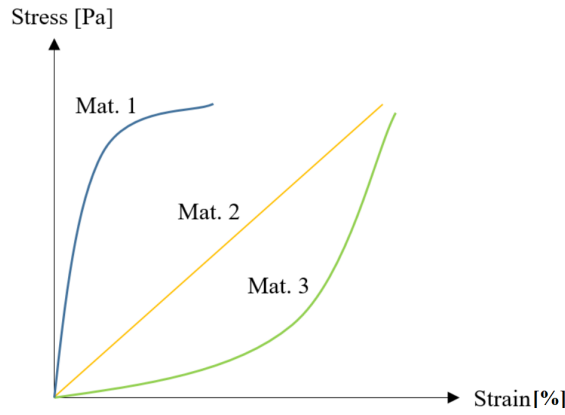


Figure 1.3: Stress vs. strain or material behaviour under an applied load

Figure 1.3 above depicts the uni-axial stress vs. strain characteristics of three materials with varying material properties. As shown in the Figure, materials can¹ demonstrate a strictly linear (Mat.2), a strictly nonlinear (Mat.3), or approximate initial linear and subsequent nonlinear behavior (Mat.1). This means that in FEM, the three materials would be defined by three separate material models. The characteristic stress vs. strain curve of a material can vary depending on xyz-direction. If this is the case, the material is characterized as an **anisotropic** material, if the stress vs. strain curves do not vary based on direction, it is characterized as an **isotropic** material.

Nodes define elements that define bodies, the material of the body is described by the material model, which can be linear, nonlinear, or both in combinations. However, FE-bodies do not deform without applying forces, and forces apply

¹A non-defined material can, of course, have any characteristic. However, the ones mentioned are common

to specific nodes or all nodes at the same time. Letting the forces acting on a body be described by vector $\bar{F}$, the material model describing the materials response to a force matrix K , and the resulting nodal displacement vector $\bar{U}$. An equation describing the relation between force and displacement to each element of a body caused by $\bar{F}$ can be established, (equation 1.2), known as *Hooke's law* ($F_x = kx$).

$$\bar{F} = K\bar{U} \quad (1.2)$$

K is often referred to as the stiffness matrix. Also, $\bar{F} = M\bar{a}$, where M is the mass matrix and $\bar{a}$ a vector of acceleration.

Lastly, to solve equation 1.2 some variables have to be known. Limiting the displacement vector $\bar{U}$ to certain known values of a couple of elements (which in turn attach to the bodies) a solution for the entire equation system crystallizes. This limitation in displacement is called a ***boundary condition***. By repeating this operation at each given ***timestep***, and recording the forces and displacements at each timestep, or ***cycle***, a simulation of motion is achieved.

1.2 Limitation of timestep in FEM

In this section, only explicit methods of FEA are discussed. However, implicit solutions are briefly discussed in chapter 7.

The run time required for a simulation to finish is the sum of the cycle time, i.e., the time required to solve equation 1.2 at each timestep and each node. For example, if it takes the computer 0.1s to solve the equation in one timestep, and the simulation consists of 10 timesteps, the simulation takes 1s to finish. Based on this example, it is evident that the size of the timesteps directly affects the run time of a simulation, and therefore increasing the size of these timesteps is an area of great interest.

A timestep cannot be longer than the time it takes for deformation to travel across the shortest side of the smallest element in a body, see equation 1.3 (Dynasupport, 2018), where deformations travel at the speed of sound in the respective material.

$$\Delta t \leq \frac{l_c}{c_m} \longrightarrow \Delta t_{max} = \frac{l_c}{c_m} \quad (1.3)$$

c_m being the speed of sound in a material, Δt the timestep, and l_c the shortest edge of the smallest element in a given body with a given material.

The speed of sound in a material is in turn governed by equation 1.4 (Dyna-support, 2018)

$$c_m = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} \longrightarrow c_m \propto \frac{E}{\rho} \quad (1.4)$$

where E = Young's modulus, ν = Poisson's ratio and ρ = density.

This means, given an FE-model with a specific mesh resolution and therefore a set (l_c), the limiting factor of simulation duration is the speed of which sound travels through the simulated material (c_m), which in turn is determined by how stiff (E) and how dense (ρ) the material is.

Knowing these limitations, adjustments can be made to a simulated material's parameters (E, ν, ρ), in order to increase the timestep further. One popular method of doing this is called **mass scaling** and it simply consists of artificially increasing the density (ρ) of a material to decrease the speed of sound (c_m) (see equation 1.4) and therefore increase the maximum timestep (Δt_{max}) (see equation 1.3). The increase in mass, due to the increased density, remains for the entire duration of the simulation.

1.2.1 Massively parallel processing (MPP) and decomposition

Using massively parallel processing (MPP) for all intents and purposes means "using a very fast and very large computer which divides the work between many processors". An MPP computer cluster is often used for FEM since it allows for faster simulations without any changes to existing models, simply because the computational power is greater. A computer cluster consists of multiple processor cores, often referred to as just **cores**, where each core has a certain computational power.

During MPP, a simulation is divided into chunks, which are distributed to each assigned processor core; this is called simulation *decomposition*, where the MPP solver intends to assign each processor the same amount of work. The default decomposition in LS-Dyna is called recursive coordinate bisection (RCB), an automatic decomposition method that LS-Dyna performs before the first step of the simulation. Put simply, RCB consists of "cutting" the model based on the longest xyz-direction of the model q times, as seen in the left-hand image of Figure 1.4, q being the number of cores assigned to the simulation. The decomposition leaves each core being assigned to calculate the deformations caused by the forces to the respective assigned chunk of meshed elements.

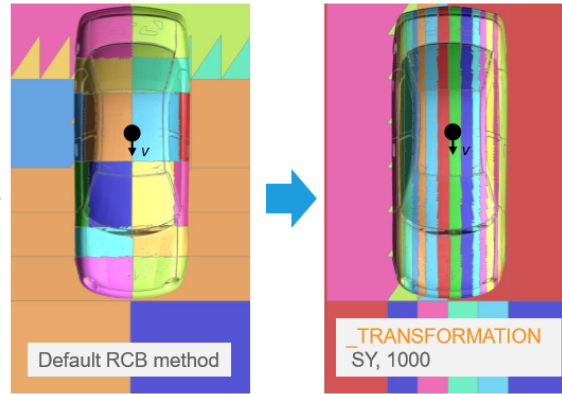


Figure 1.4: Left: Using LS-Dyna default RCB decomposition, Right: Using modified RCB decomposition | Image from (Oasys, 2018)

Comparing left and right-hand image in Figure 1.4, and assuming that deformation comes at a high computational cost, it is obvious that during large deformations to the front of the car, the processor load distribution of the right-hand image would be advantageous since the deformations are more evenly spread out on all processors.

1.3 (Dis)comfort according to IKEA

Defining and simulating comfort is an exercise in defining the subjective human experience, which, currently, is impossible using LS-Dyna. However, what has been defined rather precisely is *discomfort*. While comfort has proven highly subjective, discomfort can be relatively objective, as illustrated by the following two quotes:

“Comfort is associated with feelings of relaxation and well being. [...] The absence of these feelings will not lead to discomfort (emphasis added) because adverse biomechanical conditions are necessary for this.” (Zhang et al., 1996)

“Discomfort is associated with biomechanical factors (joint angles, muscle contractions, pressure distribution) that produce feelings of pain, soreness, numbness, stiffness [...] Eliminating physical constraints can reduce discomfort, but this does not necessarily produce comfort.” (Zhang et al., 1996)

In the case of mattress comfort, defined more correctly as lack of discomfort, IKEA has identified six critical biomechanical parameters (see section 1.3.1). These parameters can be simulated using an FE body model in combination with an FE mattress model.

1.3.1 Measuring comfort

The six parameters of comfort that have been identified by IKEA are the following (unsorted):

1. **Support** - Measured by looking at the pressure distribution on the top cover of the mattress while a person, or body model, is lying on top. Good support would consist of a spread out pressure and a relatively low mean pressure.
2. **Balance** - If heavier parts, such as hips, are sinking into the mattress too much, and lighter parts, such as the feet, are not sinking in at all – the user will feel imbalanced. A good balance would mean roughly equal deformation of mattress springs along the entire body.

-
3. ***Tension*** - Internal soft tissue (fat, muscle) stress, and torsion. The lower the stress and torsion, the better.
 4. ***Sinking-in*** - Similar to balance, but referring to the more immediate deformations of the top of a mattress, how “evenly” top materials are deforming.
 5. ***Spinal position*** - Lateral² straightness of the spine. The straighter the better.
 6. ***Imprint*** - Deformations on the top portion of the mattress, very similar to sinking-in but concerning the specific angle at which soft tissue wraps around the pelvis due to deformations of the top layers of the mattress.

Since these parameters have been identified as objective factors on the experience of comfort, it is desirable to measure them with the highest possible degree of accuracy.

²right to left

Chapter 2

Purpose of master thesis

The overall purpose of simulating interactions between the human body and a product is to increase efficiency in the product development cycle by reducing the need for user studies. By creating functional FE-models of products and the human body, the interaction between them can be simulated and evaluated in a reliable, and efficient manner. Studying the parameters of comfort using FE-models also allows for the future development of a tool for the customer to be utilized when trying to decide what specific mattress/product to choose.

The purpose of this thesis is to study and improve IKEA's current method of simulating the human body in interaction with a mattress, which was developed by IC in a previous project. My main focus is on general improvements that increase simulation efficiency of the interaction between all human body types and all models of mattresses. An improvement would constitute an increase in efficiency at the cost of accuracy, however, the reversal is not true, since the simulations provided by IC already run too slow. An increase in accuracy is always desired.

Chapter 3

Method

Provided with a report of a previous study by IC using the FEM-program Abaqus, the results (images of pressure distribution and deformations), raw real-life experimental data (stress vs. strain data of individual materials in the Lambda¹ mattress), a human body model (mesh of male with normal body mass index (BMI), 80kg), and material data for all component materials in the IKEA mattress Lambda, I was given the task of replicating IC's results using the FEM-program LS-Dyna with a higher efficiency.

In addition, I performed a real-life experiment where a body model with similar bio mechanical features to the one used by IC, was placed on the Lambda mattress. The resulting vertical displacements of the top layer of the mattress were measured using indentation sensors as well as the pressure distribution on the top layer.

By comparing IC's results from Abaqus, with my results of replicating IC's results using LS-Dyna, the given and produced experimental data, and by reading up the many intricacies of FEM, suggestions on improvements to the efficiency and accuracy of simulating mattress comfort are presented and tested in LS-Dyna.

¹The actual name of the mattress has been omitted

Chapter 4

Results and conclusions from previous work by IKEA constructors

***Authors note:** The previous report Biomechanical comfort - Final report 20180212 conducted by IC is heavily referenced in the following sections, hence reference to the report will be made as "Previous report p.xyz". The report is an internal IKEA document and will therefore not be made publicly available. However, access to this report is not required for understanding this thesis.*

Some groundwork for this master thesis has already been done by IC and was provided to me in a report by IKEA. The following is a list of topics collected from IC's report that are relevant to my continued work.

- A user study (30 subjects) aiming to establish what mattress users finds comfortable and why (section 4.1)
- Performed tensile and compressive experiments on the mattress materials of mattress Lambda, firm and mid firm (section 4.2)

-
- Built FE-models of mattresses Lambda , firm and mid firm¹ (section 4.3.1)
 - Built high-resolution FE-models of human bodies of varying BMI (section 4.3.2)
 - Initial full-scale simulations (section 4.4)
 - The relative importance of IKEA’s key factors of comfort (section 4.5.1)

4.1 User study

The user study performed by IC included thirty subjects, fifteen men and fifteen women, with variation of height, BMI, and mobility. The tests consisted of letting each subject lay down on different mattresses², where pressure data was collected using a pressure sensor mat. After and during testing, each subject was also interviewed and asked to describe precisely why a particular mattress was comfortable or not.



Figure 4.1: The three most common sleeping positions identified by IC | Images from *freepik.com*

Three common sleeping positions, supine, prone, and side were identified (see Figure 4.1). By correlating these sleeping positions with experimental pressure

¹Firm and mid firm are sub-models of the mattress

²Lambda firm & mid firm

data and the interview data, a rating on IKEA's comfort parameters³ was established. These parameters are presented in Table 4.2 in section 4.5.1.

4.2 Mattress material experiments

Mattress material experiments consisted of individual compression tests on all foams, polyester, and springs of the Lambda mattress. It also included compression tests on the entire Lambda assembly (right image in Figure 4.2). All compression tests were conducted according to the ASTM 3574 testing standard. By applying a known load [N] in a specific direction and then measuring the resulting displacement [m] in a given direction, a material-specific characteristic force vs. displacement curve [N/m] and stress vs. strain curve [$\text{Pa}/\frac{\Delta m}{m}$] could be collected, exemplified by the experimental curve of the Lambda firm polyester (Figure 4.11, section 4.7). The experiments were performed on 3-5 specimens of each material, and the resulting average curves are plotted as "experimental" in section 4.7.

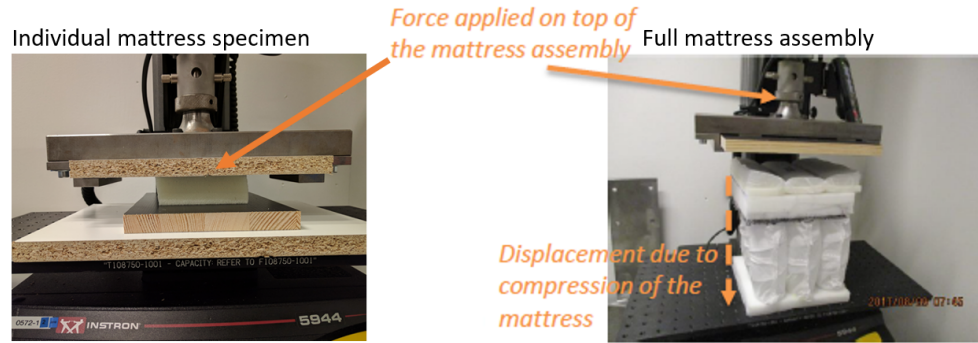


Figure 4.2: Compressive experiments on mattress material and assembly conducted by IC | Lambda firm

By analyzing the stress vs. strain behavior during compression, collected during the experiments described, mechanical parameters of each mattress

³Several other parameters of comfort have been identified, however since these parameters could not be simulated (i.e., subjective) they are not within the scope of this thesis

material could be synthesized. However, the details on this synthesis have unfortunately not been disclosed. Discussed further in section 5.1.1.

4.3 FE-models

4.3.1 Mattresses

Authors note: *Since my simulations focus on general improvements, and not specific, all simulations have been done using the same mattress, Lambda firm.*

IC's provided FE-model of Lambda firm (Figure 4.3) is a composite assembly of springs, foams, fabric, and polyester.

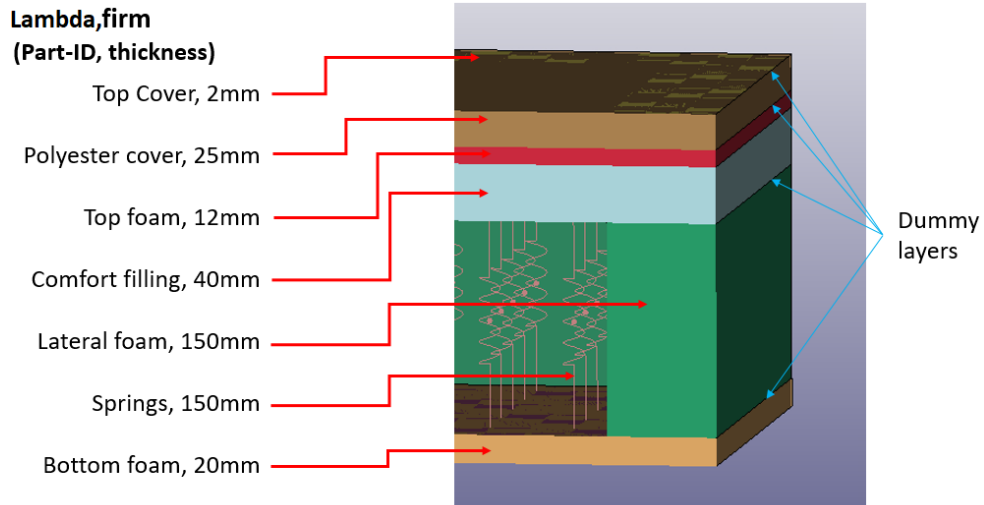


Figure 4.3: Lambda firm, layer and part-ID schematic of the FE-model | The dummy layers are part of a FEA trick to prevent elements from collapsing during high strain. More on dummy layers in Appendix B

4.3.2 Human body

The FE-models of the human bodies have been created by performing high-resolution MRI-scans of four different subjects of varying BMI lying in two

different sleeping positions, side and supine. The models have then post-processed and meshed. Based on the user study, areas considered to be of high impact on comfort were modeled using higher mesh resolution, while areas considered to be of low importance to comfort, such as fingers and toes, had their mesh resolution reduced.

In Figure 4.4, the FE-model of a man, normal BMI, 80 kg can be seen. I have used this model in all full-body simulations.

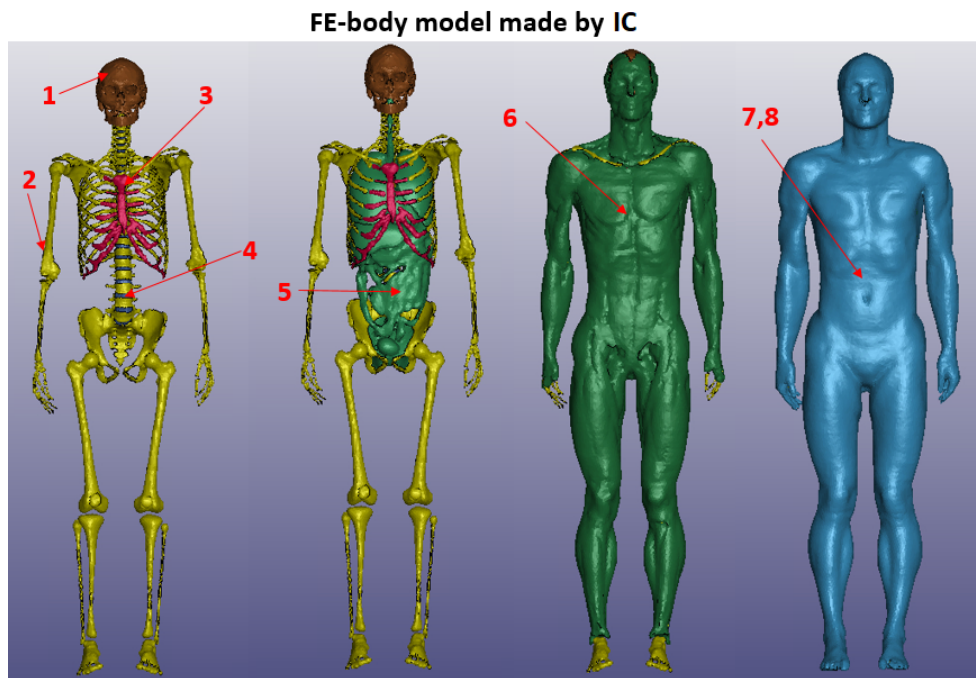


Figure 4.4: The FE-model of the body consists of 8 separate parts, which each are assigned their own specific material properties | Skull (1) Skeleton (2) Cartilage (3) Inter vertebrae (4) Organs (5) Muscle tissue (6) Fat tissue (7) Skin (8) | Male, normal BMI, 80kg

4.4 Full scale simulations

The simulation is run by dropping the body model into a "free fall" landing on the mattress and waiting until a steady-state is achieved (see Figure 4.5), the steady-state being the interesting part of the simulation since lying still constitutes the primary use of a mattress.

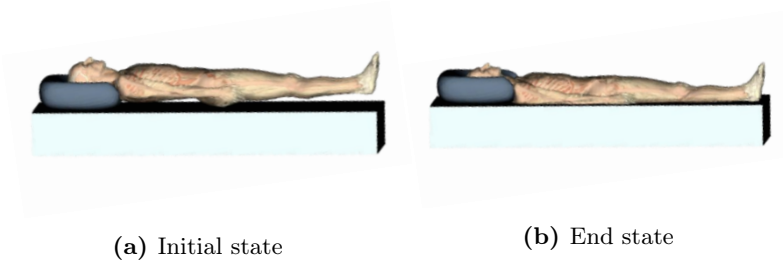


Figure 4.5: Left: Body position at $t=0s$ | Right: Body position at $t=6s$ | Male, normal BMI, 80kg

Table 4.1: Key numbers of ICs (LS-Dyna replicated) simulations, more on these numbers in section 1.1

Previous key simulation data	
Run time (on 20 cores)	10h 19min
Simulation duration until steady-state	6 s

4.5 Takeaways from the IKEA constructors work

4.5.1 Results of IKEA constructors

Based on the user study and the simulations, a weighted list of IKEA's six parameters of comfort (section 1.3.1) was developed, as demonstrated in Table 4.2. These parameters were sorted in order of importance based on their respective influence on the user's experience of comfort. They were also later used in a customer study⁴ by IC, where the parameters proved reliable.

⁴Previous report p.159

Table 4.2: IC’s suggested parameters of simulatable comfort and their relative importance | Previous report p.159 | **Note:** Since the weighted table is considered an internal IKEA document, their relative importance has been omitted in the public report. However, the actual rating is not needed to understand the contents of this thesis.

Parameter of comfort	Importance
Support	-
Balance	-
Tension	-
Sinking in	-
Spinal position	-
Imprint	-

Along with the parameters of comfort, ICs report also included the previously mentioned (section 4.2) synthesized mechanical parameters of the materials in Lambda. The material parameters were provided according to Table 4.3. The material parameters for human soft tissue were also provided, in a similar form as the mattress materials. However, since the development of the soft tissue parameters were part of an internal process, the methods of validation are left undisclosed.

Table 4.3: Material parameters as provided by IC of each mattress material | E_i =Young’s modulus [Pa] in direction i, G_{ij} = Shear modulus [Pa] in direction ij, ν_{ij} =Poisson’s ratio in direction ij, (1 2 3) = (i j k) = perpendicular directions | Previous report pp. 54-63

E_1	E_2	E_3
G_{12}	G_{13}	G_{23}
ν_{12}	ν_{13}	ν_{23}

4.6 Evaluating IKEA constructors results

Authors note: *To fully understand the previous work, a great effort was made by me in replicating the results of IC’s full-body simulations. The replication was needed in any case since IC’s work was done using the program Abaqus,*

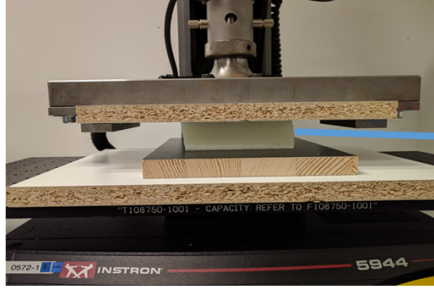
while IKEA now wants to use LS-Dyna. Detailed results and methods of this replication are found in Appendix C. The purpose of replicating IC's results, is to thoroughly establish that the large difference between their results and mine, presented later on in this report, is not due to an error in the method I have used, but an increase in accuracy.

4.6.1 Evaluating IKEA constructors material model accuracy

Using the material parameters provided by IC as described above (section 4.5.1) the full-body simulations could be replicated using LS-Dyna with a satisfactory level of accuracy, accuracy in this case being defined as: The deformations of the mattress, the contact pressure, and the internal stresses of the body model, comparing ICs results and the replicated results in LS-Dyna, are visually similar enough (see Appendix C) to where the difference between them can be attributed to using different programs.

Now, IC's results and the results of my replication match each other, but in order to validate that the material models provided by IC were behaving as expected, I performed individual mattress material simulations. With the purpose of replicating the experimental data they collected, as described in section 4.2, see Figure 4.6. These individual material model verification simulations (Figure 4.7), consisted of applying a known z-displacement to a rigid plane and measuring the resulting force required to perform this displacement, which in combination with a known area and thickness, provides a stress vs. strain curve comparable to IC's provided experimental data. Details on the individual material simulations are found in Appendix A.

Individual mattress material experiment



Individual mattress material simulation

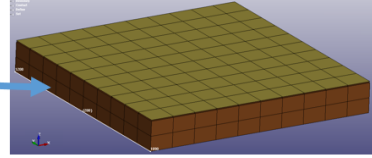


Figure 4.6: Real-life experiment and replication simulation of individual mattress material specimens modelled in LS-Dyna | Lambda firm

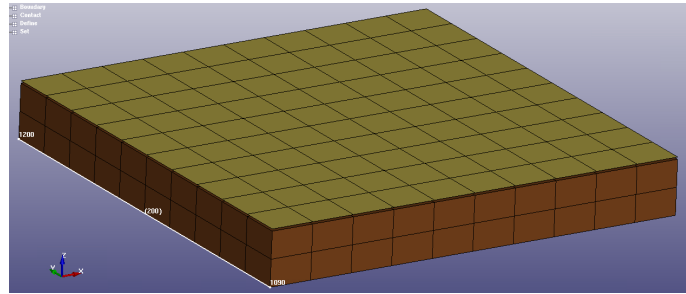


Figure 4.7: The setup of a mattress material specimen (brown) and the compression plane (yellow) used when replicating ICs individual specimen compressive experiments in LS-Dyna. The compressive force is applied on top of the yellow plane.

Following the compressive simulations of individual mattress material specimens, the individual materials were assembled into a full mattress assembly (Figure 4.9), in which the compressive stress vs. strain behavior of all mattress materials in combination was examined by similarly applying a known z-displacement, see Figure 4.8.

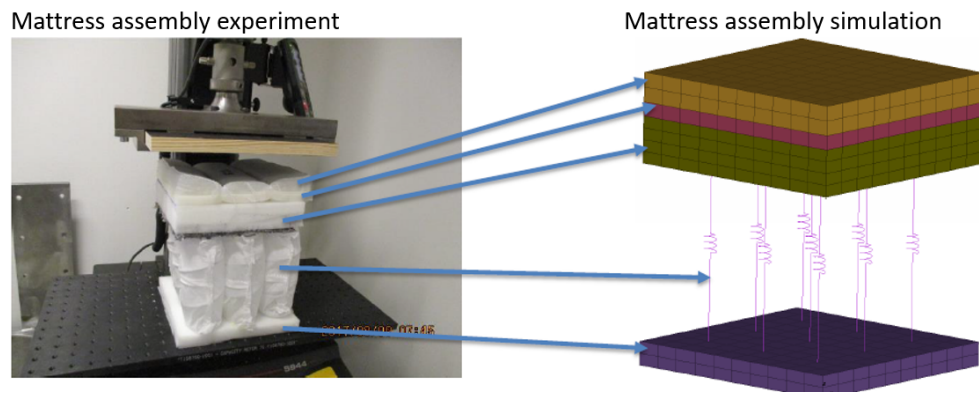


Figure 4.8: Experiment and experiment replication simulation of the full mattress assembly modelled in LS-Dyna | Lambda firm

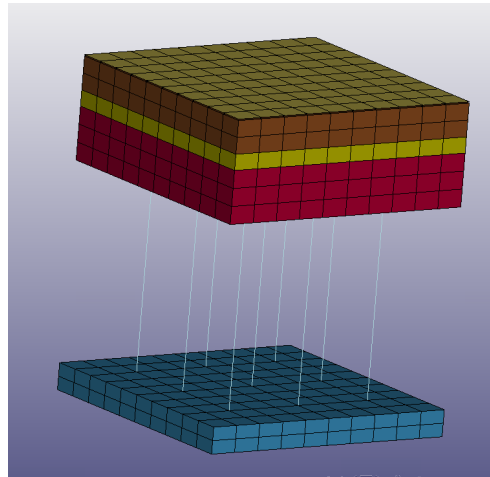


Figure 4.9: Replicating previous full mattress assembly compressive experiments in LS-Dyna

The springs were also validated using similar methods as described above; see Figure 4.10.

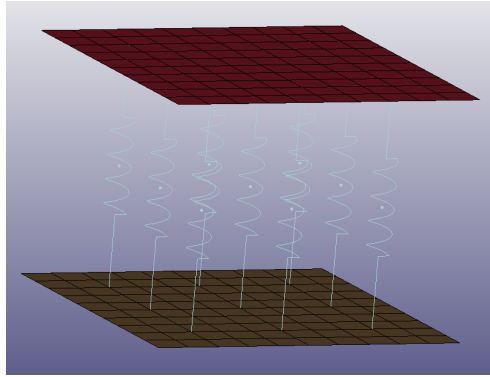


Figure 4.10: Spring compression simulation, using 9 identical 150 mm springs

4.7 Results of my evaluation

Results of the above described replication experiments revealed a discrepancy between the experimental results by IC and my simulated results when using the material parameters provided by IC. When replicating ICs experiments in LS-Dyna neither the individual mattress materials nor the mattress assembly behaved as expected, as shown in Figure 4.11, 4.12, 4.13 and 4.14. These figures show stress vs. strain behaviour of the mattress materials, demonstrating a large deviation between the real-life experimental results of IC, and my simulations made using their parameters. The springs, however, did match my results, as seen in Figure 4.15. Results will be discussed in section 4.8.

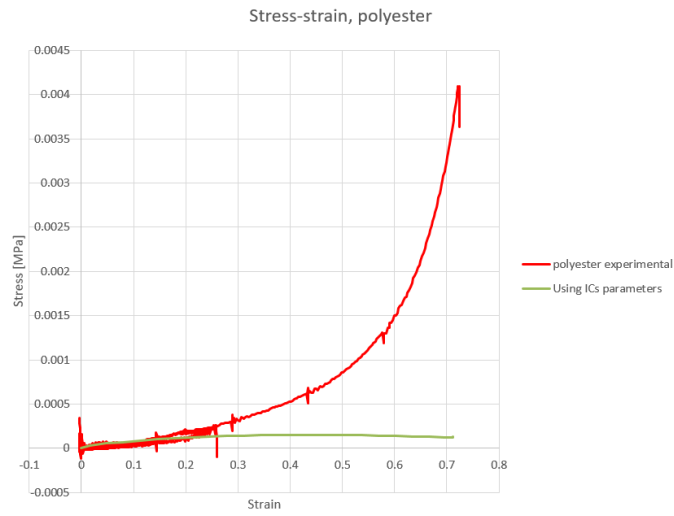


Figure 4.11: Polyester | Real-life experimental stress vs. strain (red), stress vs. strain using IC's provided material parameters (green) | Lambda firm | Polyester cover in Figure 4.3

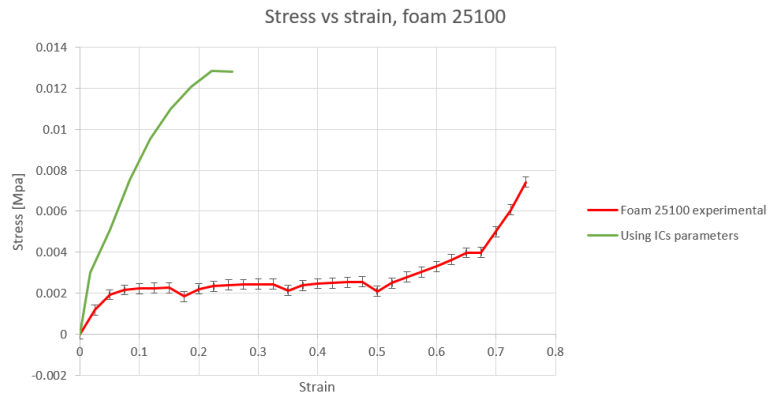


Figure 4.12: Foam 25100 | Real-life experimental stress vs. strain (red), stress vs. strain using IC's provided material parameters (green) | Due to convergence issues the full displacement did not fully succeed | Lambda firm | Comfort filling in Figure 4.3

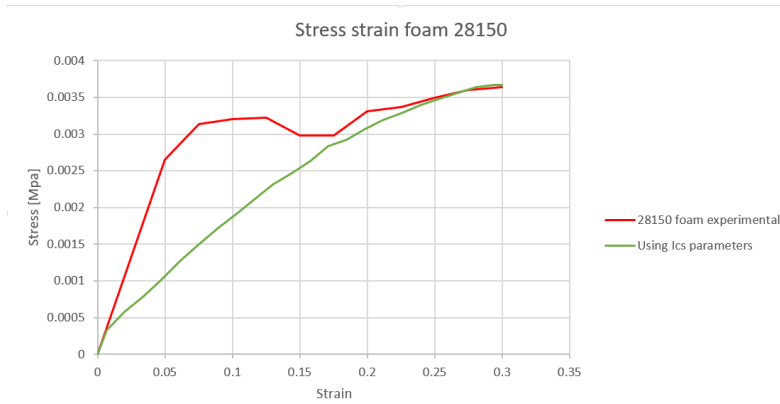


Figure 4.13: Foam 28150 | Real-life experimental stress vs. strain (red), stress vs. strain using IC's provided material parameters (green) | Lambda firm | Top foam, Bottom foam and Lateral foam in Figure 4.3

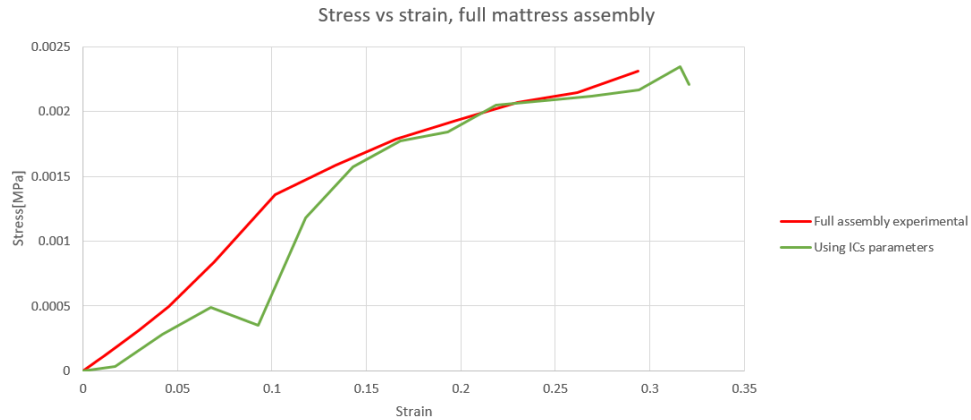


Figure 4.14: Full mattress assembly | Real-life experimental stress vs. strain (red), stress vs. strain using IC's provided material parameters (green) | Lambda firm

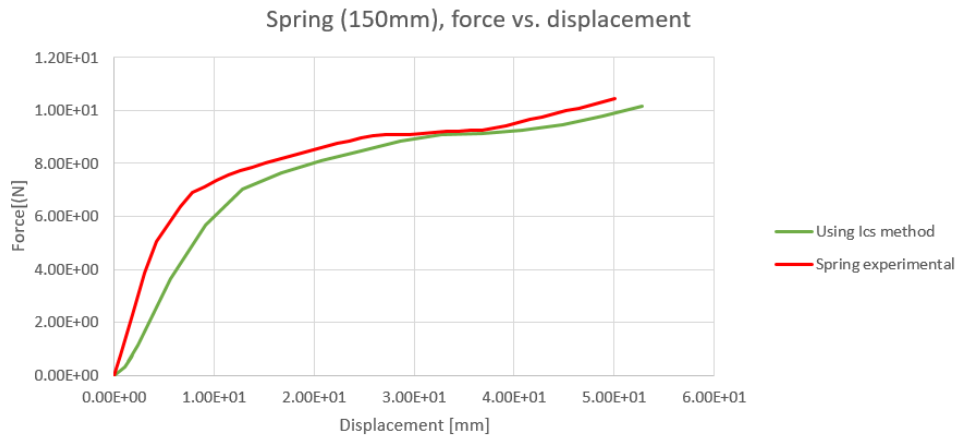


Figure 4.15: Force vs. displacement behaviour of a single LS-Dyna simulated spring using IC's methods (green) compared to the real-life experimental data of a similar specimen (red) | Lambda firm, 150mm spring

4.7.1 Full body simulation run time

At a required run time of 10h 19min for a 6s simulation, the current setup is too slow to be useful in the product development cycle according to IKEA.

4.8 Discussion of IKEA constructors results

4.8.1 Individual mattress material models

What explains the discrepancy between experimental and simulated data?

Comparing the experimental data to my simulated data using IC's material parameters in LS-Dyna (section 4.7), the difference in how real-life mattress materials and simulated materials behave is very noticeable. In the simulations the mattress materials behave more akin to simple linear elastic materials, where the real life experimental curves of these materials strongly suggest non-linearity. Below I present three hypotheses in which possible reasons for this discrepancy are discussed. However, since no data of previous individual

material model validation is provided, where individual material models are compared to experimental data, these remain hypotheses.

1. A material model issue - The material parameters of the foams and the polyester were provided in such a way (see Table 4.3 section 4.5.1) as to where the logical material model to use in LS-Dyna would be MAT_02, an orthotropic material model that uses all three-directional Young's moduli, shear moduli, and Poisson's ratios (E_i, G_{ij}, ν_{ij}) provided. The previous report mentions using the Abaqus material model called "Elastic anisotropic Engineering constant"⁵, a linear elastic anisotropic material model (ABAQUS, 2009) very similar to MAT_02 in LS-Dyna, with good results. But since no data of these results are presented, and the results in LS-Dyna are not good, the material model may not be applicable.

2. A solver issue - Abaqus and LS-Dyna are two very different programs, perhaps some crucial material information is lost in the transition between the two. It could be further examined by running the programs in parallel and comparing the results.

3. Incorrect method of validation - Looking at, for example, the polyester stress vs. strain curves in Figure 4.11, the curves are relatively similar up to strains of about 0.15 where they start to diverge. If the validation process did not inquire about stress vs. strain behavior above this strain, the material model mistakenly could be considered accurate.

4.8.2 Full mattress assembly

While the individual material models are not accurate, the full mattress assembly remains quite accurate, indicating that the main contributor to the characteristics of the full mattress assembly stress vs. strain curve, Figure 4.14, are the springs, which, as seen in Figure 4.15, are behaving as expected.

⁵.p 49 in previous report

4.9 Conclusions

The previous full-body simulations were able to be replicated using inaccurate material models. However, since the behavior of the full mattress assembly only partially relies on the foam material models being accurate, and instead relies more on the springs being accurate, the results of the full-body simulations are not *that* inaccurate, but they can not be considered valid.

The previous work done by IC, the user study on comfort, and the resulting parameters of simulatable comfort, Table 4.2, can still be considered accurate, since they are not affected by the relative accuracy of the material models.

The full-body simulations run slow, and as mentioned in section 4.3.2, some simple measures of mesh rationalization have already been taken. There are no direct improvements to be made based on previous results regarding efficiency. Since little to no mention of the actual simulation settings in Abaqus was made, it is hard, based on previous work, to draw any conclusions about decreasing the required simulation duration. Lowering the simulation duration, will depend on new ideas.

Chapter 5

Improvements developed during this thesis

In this chapter, ideas of improvements to the full body simulations are presented, these were developed during the study of IC's work as described in chapter 4, literature on the subject, and reading about FEM in general. The results of implementing these improvements are presented in chapter 6.

5.1 Accuracy

5.1.1 Mattress material models

A material model is as accurate as its stress vs. strain curve is similar to the stress vs. strain curve of the corresponding real-life experiments. Using ICs provided material parameters, as discussed in section 4.8, the mattress material models are not very accurate; however, what is accurate is the material model of the springs, Figure 4.15 (section 4.7). The springs use a material model that derives its stiffness directly from an experimental force vs. displacement curve, while the foams and the polyester models are not, as indicated by the schematic flowchart below (Figure 5.1) of the previous material model creation.

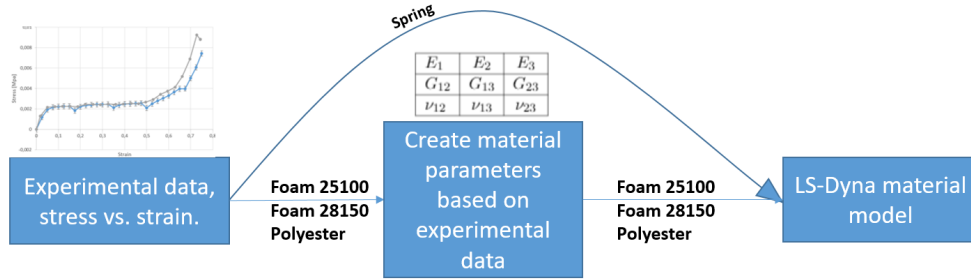


Figure 5.1: Flowchart of ICs material model creation

The advantage of using material parameters to define the behaviour of the polyester and the foams, which IC suggests, instead of directly referencing an experimental curve like the springs do, is that there is no need to perform experiments. Using parameters is also an option if, for example, the real-life experimental data of a material only partially cover the strains that the material is subject to during simulations. Wanting to simulate a linear elastic material with strains up to 0.5 but only having access to experimental data of strains up to 0.3, a parameterization of the Young's modulus could be done, and used to simulate any strain, the key being that the material model and the parameters are verifiably performing as expected.

As discussed in section 4.8, the material model previously used by IC for the mattress materials, and the models used when replicating their results, is linearly anisotropic. This means that the material model accounts for varying material parameters in three different directions. However, the material model is *linearly* anisotropic, which by looking at the experimental curves in section 4.7, the mattress materials are not. The accuracy of the mattress material models could improve by using material models that can be directly fed experimental data, as is done for springs which are behaving very accurately.

Ideally, a nonlinear anisotropic material model such as MAT_040¹ would be used, assuming that the foams and the polyester actually are anisotropic. Currently, the real-life experimental data of the mattress materials only account

¹keyword *MAT_NONLINEAR_ORTHOTROPIC in LS-Dyna

for the stress vs. strain characteristics in one direction, where, since it is anisotropic, MAT_040 requires all three. However, there is an alternative material model called MAT_057², which could be described as a nonlinear isotropic material model. This material model can be directly fed experimental data of stress vs. strain behavior, which it applies in all directions, hence the material model is isotropic.

Given that the mattress materials are anisotropic, using an isotropic material model would not suffice in describing the deformation and strains from a full spectrum of movement. However, since the load on a mattress is entirely due to gravity it is entirely uni-axial, under which it can be argued that anisotropy and isotropy is of minor importance.

Therefore, using MAT_057 in combination with the experimental data for each material could provide more accurate mattress material models.

5.2 Efficiency

5.2.1 Soft tissue material models

Improving the accuracy of the human soft tissue material model is hard, mainly since there is no available experimental data to compare to when examining whether a change to an existing material model, has made the simulations more or less accurate. As previously mentioned, ICs provided material parameters of human soft tissue were collected and verified as part of an internal and classified process. Therefore, all I got was a set of already validated material parameters that I am unable to either verify or refute. Hence, an improvement to the human soft tissue material models can only consist of an increase in efficiency, as accuracy is unable to be evaluated without access to proper experimental data.

In a master thesis about simulating WAT (white adipose tissue, aka fat) using LS-Dyna, it was concluded that the most cost-effective material model to

²keyword *MAT_LOW_DENSITY_FOAM in LS-Dyna

use during low strain rates (0.002-0.2 [1/s]) is MAT_77_O³(Engelbrektsson, 2011), a hyperelastic rubber material model. Engelbrektsson used a similar modeling approach as I suggest for the mattress material models in section 5.1.1. In this approach stress vs. strain characteristics are directly fed into the material model, where stiffness is continuously adjusted to fit the experimental data. Furthermore, the characteristic stress vs. strain curve of WAT is highly dependent on strain rate, as seen in Figure 5.2.

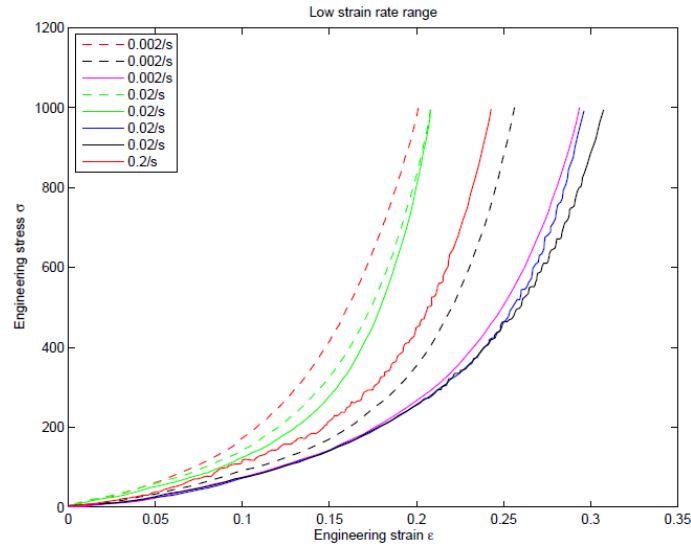


Figure 5.2: Stress vs. strain characteristics of white adipose tissue under strain rates of 0.002-0.2[1/s] | Image from (Engelbrektsson, 2011)

Since there is no way to verify material model accuracy without experimental data, I will not attempt to improve its accuracy. However, improving the efficiency of the soft tissue material models would still be of interest. By implementing a placeholder stress vs. strain curve based on Engelbrektsson's graph (Figure 5.2), an examination of whether material model MAT_77_O has any significant potential gains in terms of efficiency can be done.

³keyword *MAT_OGDEN_RUBBER

5.2.2 Decomposition

In an article about improving LS-Dyna efficiency during large-scale simulations and large deformations (Yamada, 2017), specifically car crash simulations, the issue of processor load imbalance is brought up. This happens when the massively parallel processing (MPP) decomposition, or, the initial and automatic dividing of computational tasks between allocated processors, is done in a way that results in differences between the computational load of each processor.

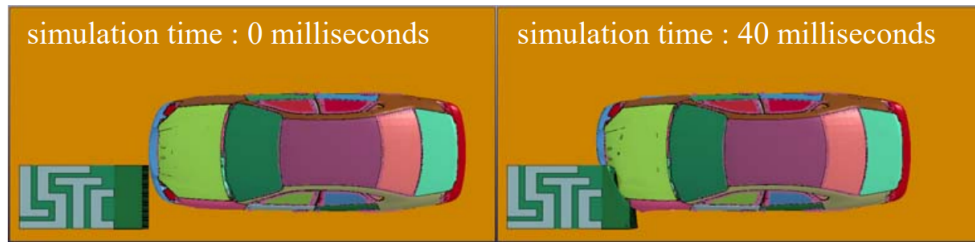


Figure 5.3: Problematic decomposition | *Figure 1* in article (Yamada, 2017)

In Figure 5.3 the issue of load imbalance is exemplified. In the image, each color corresponds to a specific processor being tasked to calculate the deformations of that part. Initially, this decomposition is perfectly fine since all parts experience about the same loads. This is also why LS-Dyna has divided the load in this way. However, at 40ms when the crash has occurred, and the deformations are ongoing, the computational load of the processor assigned the hood (light green) is higher than the load of the processor assigned to the trunk (turquoise), causing a load imbalance. During the load imbalance, the simulation only moves forward as fast as the processor with the highest load, which potentially implies a large time loss.

Similar to a low speed car crash, the deformations of a mattress caused by a falling body are quite significant. Currently, the simulations run using the default RCB decomposition scheme, resulting in a decomposition according to the image in Figure 5.4 and a core load balance according to Figure 5.5. The purpose of altering the decomposition is basically to flatten this curve.

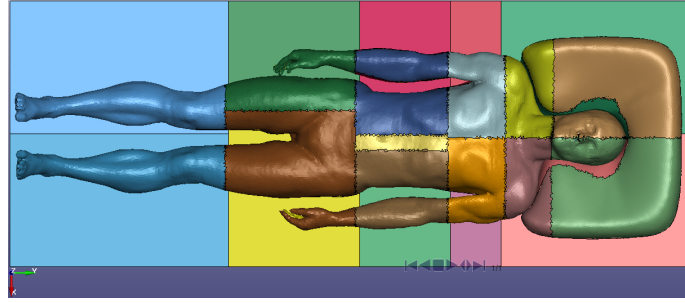


Figure 5.4: Default and current RCB decomposition using 20 cores in LS-Dyna | Lambda firm, normal BMI, 80kg

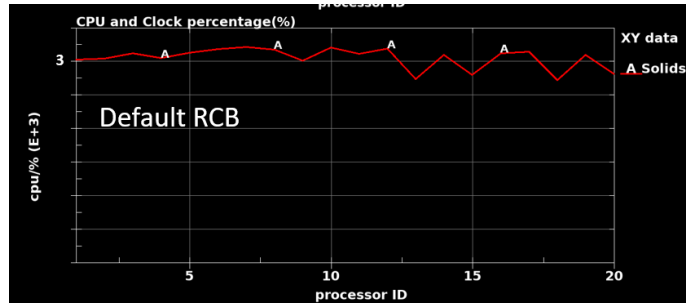


Figure 5.5: Relative percentage load on each core while using the default RCB decomposition scheme in LS-Dyna | Lambda firm, normal BMI, 80kg, 20 cores

By altering the decomposition scheme of the full body simulation similar to the right hand image in Figure 1.4 (section 1.2.1) the following decomposition is achieved (Figure 5.4). The method is described in Appendix D.

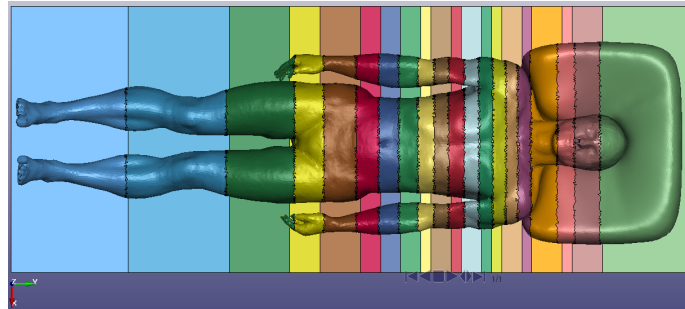


Figure 5.6: Suggested alternative decomposition in LS-Dyna | Lambda firm, normal BMI, 80kg, 20 cores

5.2.3 Reducing need for mass scaling

In the result files ⁴ of the full-body simulations used to replicate ICs results, that run in 10 hours using 20 cores, a list of the 100 elements requiring the smallest timestep is shown. According to this list, the skeleton, skull and cartilage (part 1, 2, 3 in Figure 4.4, section 4.3.2) are the parts that are being mass scaled (artificially increasing the density of a material to increase the timestep) the most, as also visible in the graph in Figure 5.7.

⁴ctrl+f "smallest timestep" in d3hsp file

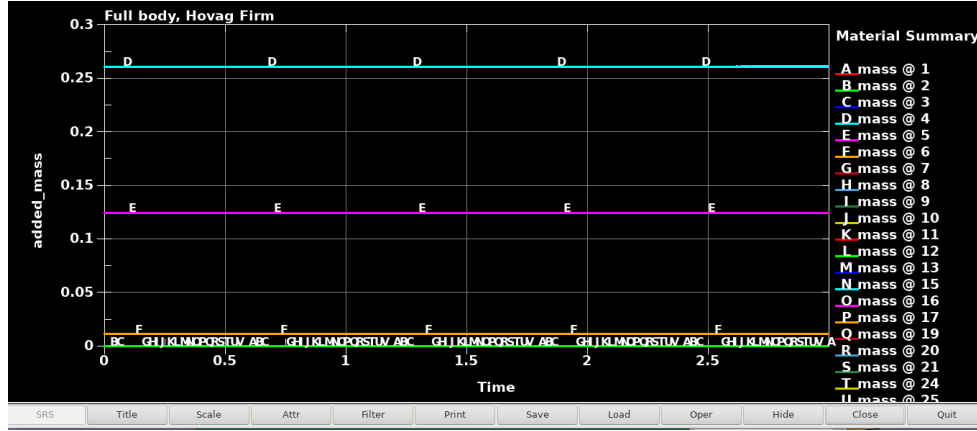


Figure 5.7: Added mass due to mass scaling over a 3s simulation, the skeleton (D), skull (E) and cartilage (F) being mass scaled the most | Lambda firm, normal BMI, 80kg, 20 cores

The reason why these specific parts are being mass scaled is that they are the stiffest in relation to density and therefore require the smallest timestep. By looking at the equation of sound speed through a material, where sound speed $c_m \propto \frac{E}{\rho}$ (equation 1.4 in section 1.2) it is evident that a material such as human bone, which has evolved to be very stiff in relation to its density, is an exceptionally ill-suited material for explicit FE simulations.

To reduce bottlenecking of the timestep, mainly caused by the skeleton being mass scaled, a mathematically rigid material model like MAT_020⁵ could be implemented on the elements of the skeleton, the cartilage and the skull. MAT_020 is a material model that cannot deform and therefore has certain mathematically advantageous properties that allow LS-Dyna to use any timestep. This would altogether remove the need for mass scaling of the skeleton etc. and potentially reduce the needed simulation run time. Using a rigid material will cause the skeleton to be non-deformable, but no large deformation of the skeleton is expected. Therefore, the rigid material model should not affect the accuracy of the simulations, if implemented correctly.

⁵keyword *MAT_RIGID in LS-Dyna

5.2.4 Reducing body bouncing

As described in section 4.4 the simulations are initialized by letting the body fall onto the mattress and waiting until a satisfactory steady-state occurs. Figure 5.8 shows a plot of vertical displacement (z-direction) on a specific pelvic node, indicating that the model has a quite significant tendency to oscillate, as expected of an assembly like a mattress when a large object is dropped onto it. However, since the steady-state, where the curve is flat, is the interesting part of the simulation, the time spent going from initial impact to steady-state is wasted, since the simulation, during oscillation, is not of interest.

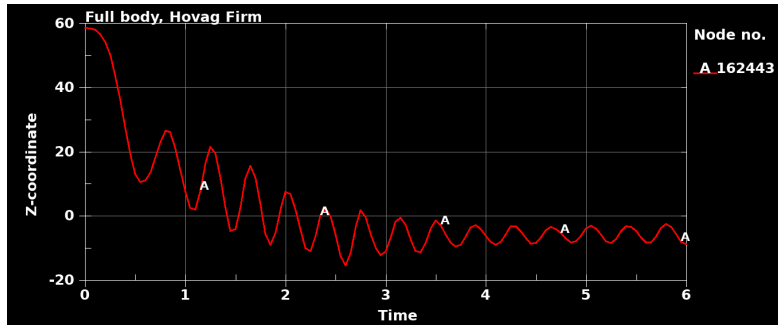


Figure 5.8: Plot showing the body’s tendency to oscillate when dropped onto the mattress | Lambda firm, normal BMI, 80kg | **Note:** The curve is a simulation running without dampers, which were used in ICs simulations. IC achieved a steady-state at 6s. Dampening is discussed further in section 7.4.

To reduce oscillations and achieve a steady-state faster, a tray could be used to lower the body onto the mattress (see Figure 5.9). The tray would be lowered at an acceleration of slightly less than the gravitational acceleration so that the body and tray keep in contact. A tray would increase control over the initial contact between the body and the mattress and could reduce bouncing, therefore decrease the time until a steady-state is reached. Further technical details on the body tray can be found in Appendix E.

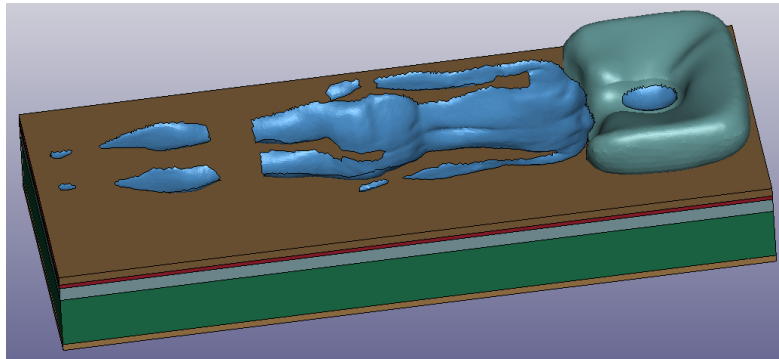


Figure 5.9: Suggested body tray (blue) used to lower the body onto the mattress in order to reduce oscillations in LS-Dyna | Lambda firm

Chapter 6

Results

The results presented in this chapter constitute the results of implementing the suggested improvements presented in chapter 5. A discussion is held in chapter 7.

6.1 Accuracy

Figure 6.1, 6.2, and 6.3 show the plots of the stress vs. strain behaviour of individual mattress materials in simulations vs. real-life experiments, as described in section 4.6.1. The plots display each material's real life experimental behaviour (red), the simulated behaviour using ICs material parameters (green), and the new and improved behaviour using MAT_57 (blue).

6.1.1 Mattress material models

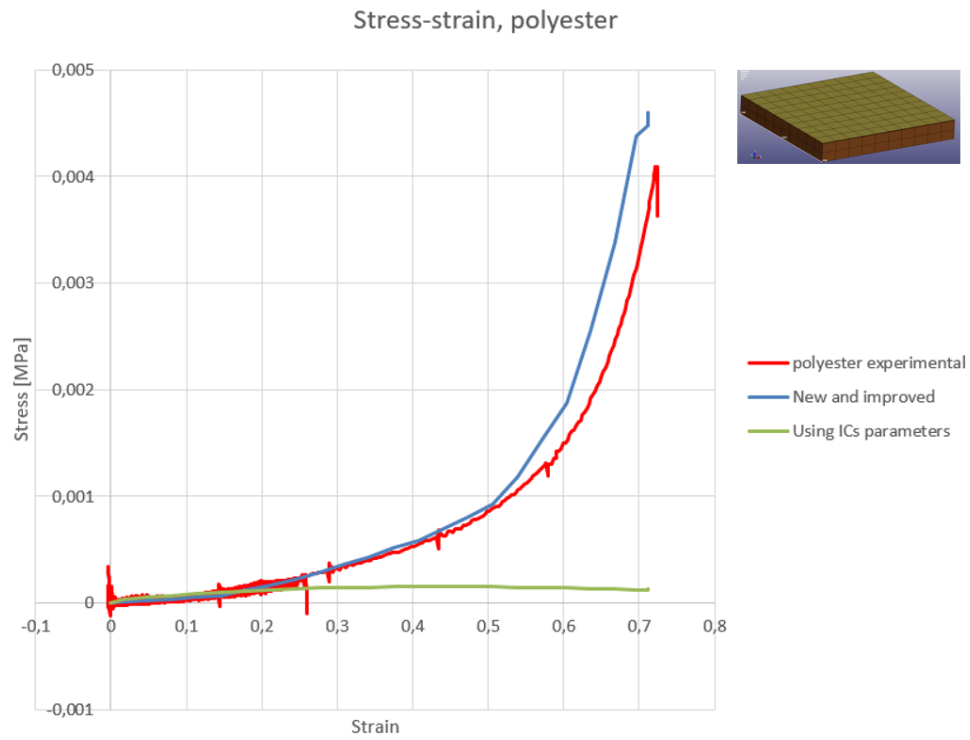


Figure 6.1: Stress vs. strain behaviour of polyester, real-life experimental (red), simulation using ICs parameters (green), and the new and improved simulations using MAT 57 (blue) | Lambda firm | Polyester cover in Figure 4.3

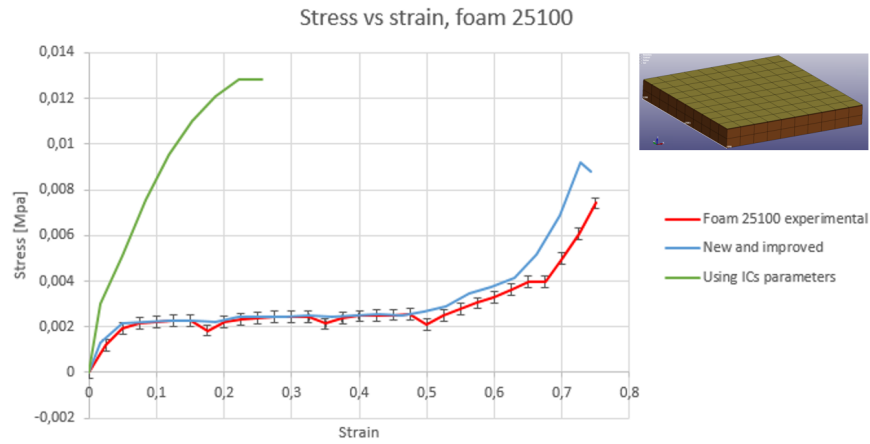


Figure 6.2: Stress vs. strain behaviour of foam 25100, real-life experimental (red), simulation using ICs parameters (green), and the new and improved simulations using MAT 57 (blue) | Lambda firm | Comfort filling in Figure 4.3

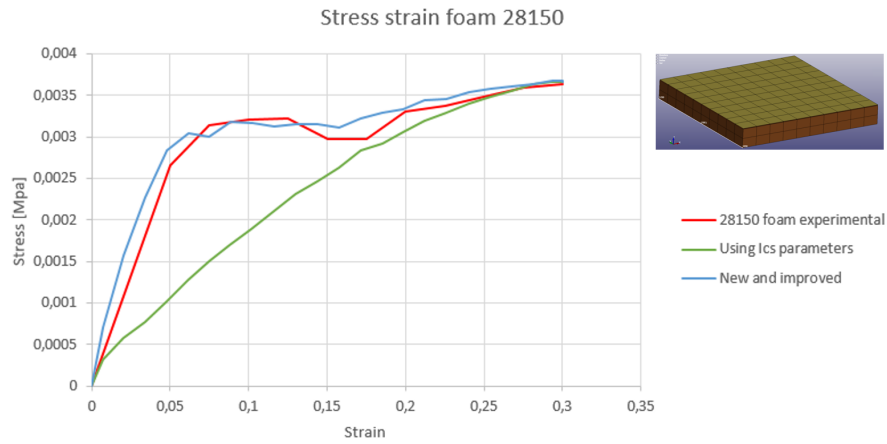


Figure 6.3: Stress vs. strain behaviour of foam 28150, real-life experimental (red), simulations using ICs parameters (green), and the new and improved simulations using MAT 57 (blue) | Lambda firm | Top foam, Bottom foam and Lateral foam in Figure 4.3

Figure 6.4 shows the plots of the stress vs. strain behaviour of the full mattress assembly of simulations vs. real-life experiments, as described in section 4.6.1. The experimental behaviour of the assembly (red), the behaviour using ICs material parameters for all component materials (green), and the behaviour using the new and improved component materials (blue).

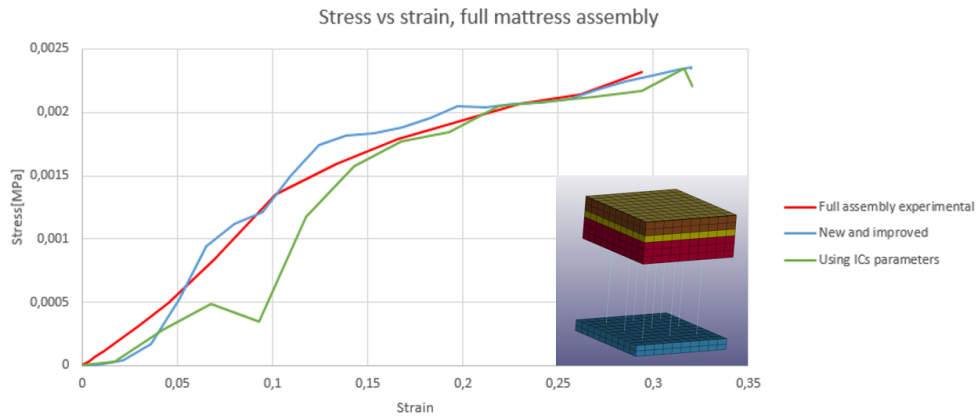


Figure 6.4: Stress vs. strain behaviour of the full mattress assembly, real-life experimental (red), simulations using ICs parameters for all mattress components (green), and the new and improved mattress components using MAT 57 (blue) | Lambda firm

Figure 6.5, 6.6, and 6.7 contain plots of the vertical displacement of the top layer of the mattress along section cut planes. There are three figures, each plotting displacements of the same experiment/simulations but along different axes and sections of the body, as indicated by the supporting images. The red curve plots real-life experimental values, green the simulated displacements using ICs material models, and blue, plotting the simulated displacement using the new and improved mattress material models. The results show that using the new and improved material models, the displacement is more similar to the real-life experimental data.

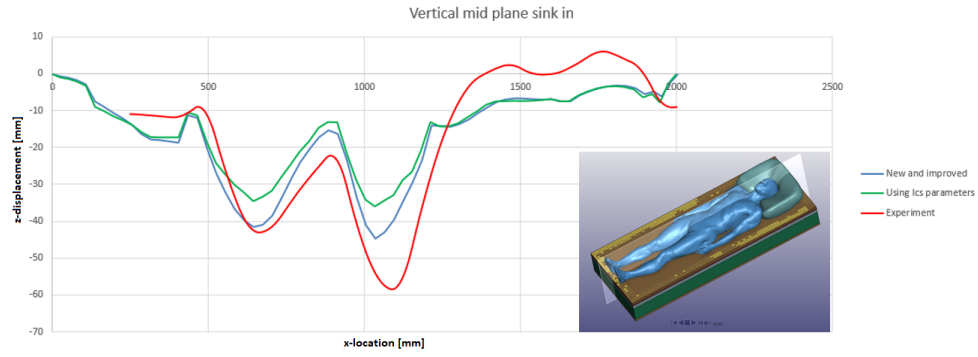


Figure 6.5: Comparing full body simulation(s) and experimental values of sink-in of the mattress top cover in the mid zy-direction | Displacement using new and improved material models (blue), displacement real-life experiments (red), and displacements using IC's provided material parameters (green) | Lambda firm

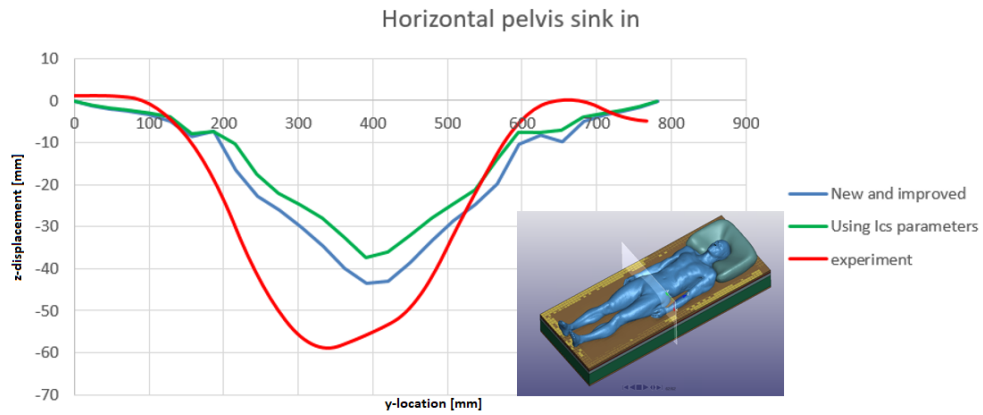


Figure 6.6: Comparing full body simulation(s) and experimental values of sink-in of the mattress top cover in the zx-direction along the pelvis | Displacement using new and improved material models (blue), displacement real-life experiments (red), and displacements using IC's provided material parameters (green) | Lambda firm

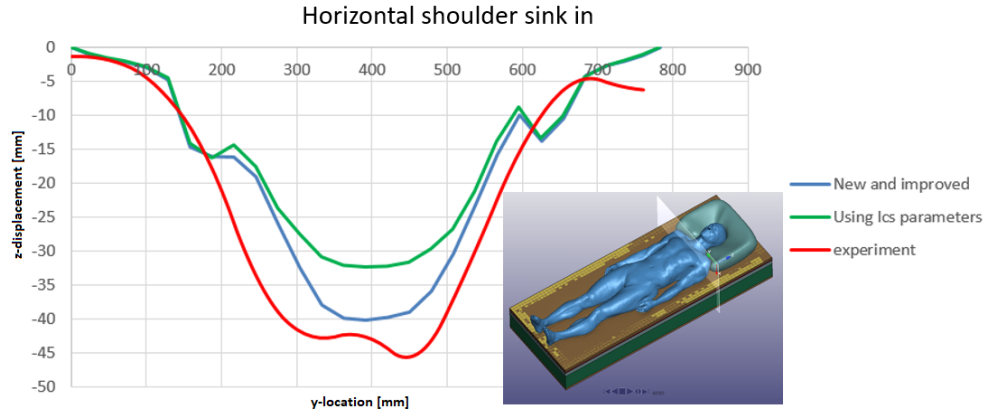


Figure 6.7: Comparing full body simulation(s) and experimental values of sink-in of the mattress top cover in the zx-direction along the shoulders | Displacement using new and improved material models (blue), displacement real-life experiments (red), and displacements using IC's provided material parameters (green) | Lambda firm

Figure 6.8 shows the vertical pressure distribution on the top layer of the mattress when a body is laying on it. To the left (a) is the simulated pressure distribution using ICs parameters, in the middle (b) is the experimental pressure distribution, and to the right (c) is the pressure distribution using the new and improved material parameters. Comparing the three, it is visible that that using the new and improved material models results in a pressure distribution more in line with the real-life experimental pressure distribution.

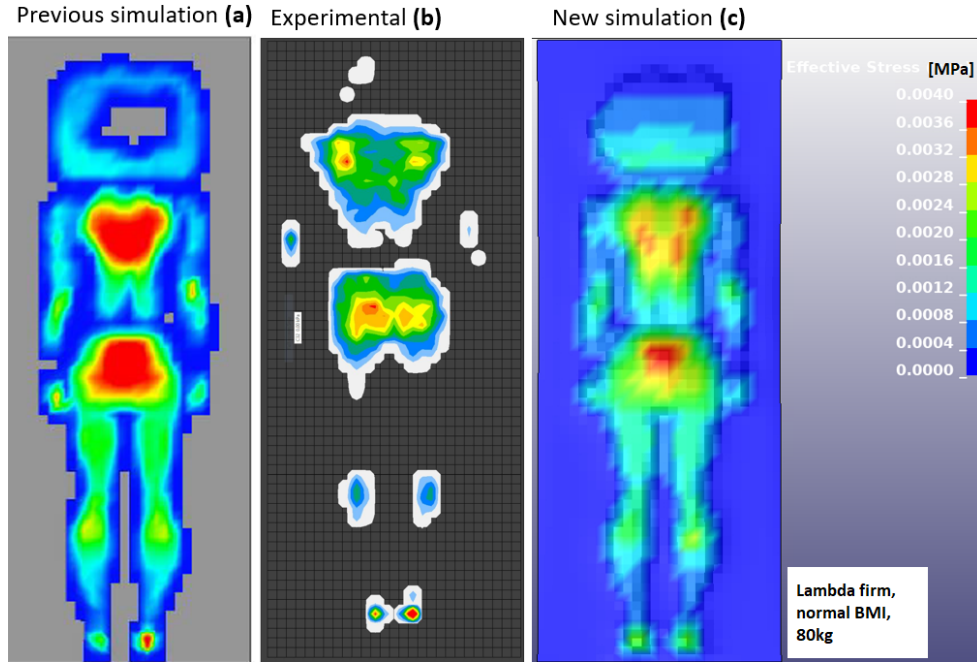


Figure 6.8: Pressure distribution on the top cover | Pressure distribution from simulation using IC's parameters (a), real-life experimental pressure distribution (b), and pressure distribution using the new and improved material models (c) | Lambda firm

6.1.2 Soft tissue material models

As mentioned in section 5.2.1, it is hard to evaluate a material model for fat and muscle, since the real-life experimental data is scarce. A material model using MAT_077_O based on a principle stress vs. strain curve was implemented for the WAT (fat), without any noticeable improvement (i.e., reduction) in simulation run time.

6.2 Efficiency

The efficiency is measured by comparing the run time of the new simulations vs. the run time of the simulations used to replicate ICs results.

6.2.1 Decomposition

Results in Table 6.1 and Figure 6.9 are achieved using the methods described in section 5.2.2. The results show an increased load balance between the cores which results in a slight reduction in simulation run time.

Table 6.1: Change in simulation run time by altering the decomposition scheme | Lambda firm, normal BMI, 80kg, 20 cores

Default RCB	Altered RCB	% change
10h 19min	9h 49min	-4.7%

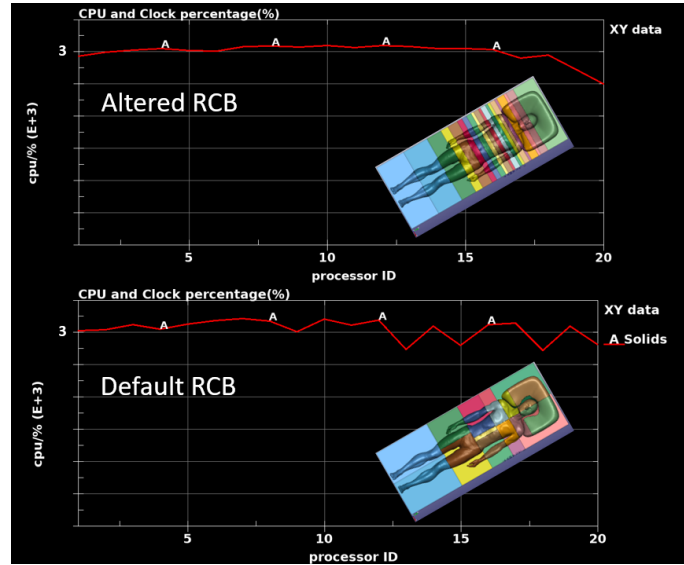


Figure 6.9: Percentage CPU usage per simulation assigned core | Lambda firm, normal BMI, 80kg, 20 cores

6.2.2 Reducing the need for mass scaling

The results in Table 6.2 were achieved using the methods described in section 5.2.3. The results show a significant reduction in simulation run time as the solver is allowed to use a larger timestep. Figure 6.10 also show that no accentuation of the skeleton is lost in the process.

Table 6.2: Simulation duration before and after reducing mass scaling | Lambda firm, normal BMI, 80kg, 20 cores, 6s duration

Before	After	% change
10h 19min	2h 9min	-79%

Figure 6.10 shows an overlay of two simulations at the end state (at 6s), the only difference being the material model used for the skeleton. (The mattress and the rest of the body is there, but hidden).

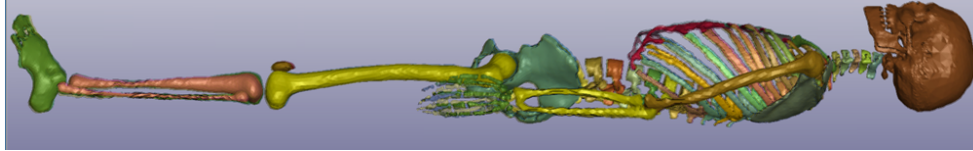


Figure 6.10: Overlay of two skeletal resting positions using different material models | Lambda firm, normal BMI, 80kg, 20 cores

6.2.3 Reduced body bouncing

The results show a decrease in the human body models tendency to oscillate after initial contact with the mattress, see Figure 6.11. Using the body tray a sufficient steady-state is achieved at 3s, effectively cutting the run time in half.

Table 6.3: Simulation duration required for steady-state | Lambda firm, normal BMI, 80kg, 20 cores, 6s duration

Before	After	% change
10h 19min	5h 9min	-50%

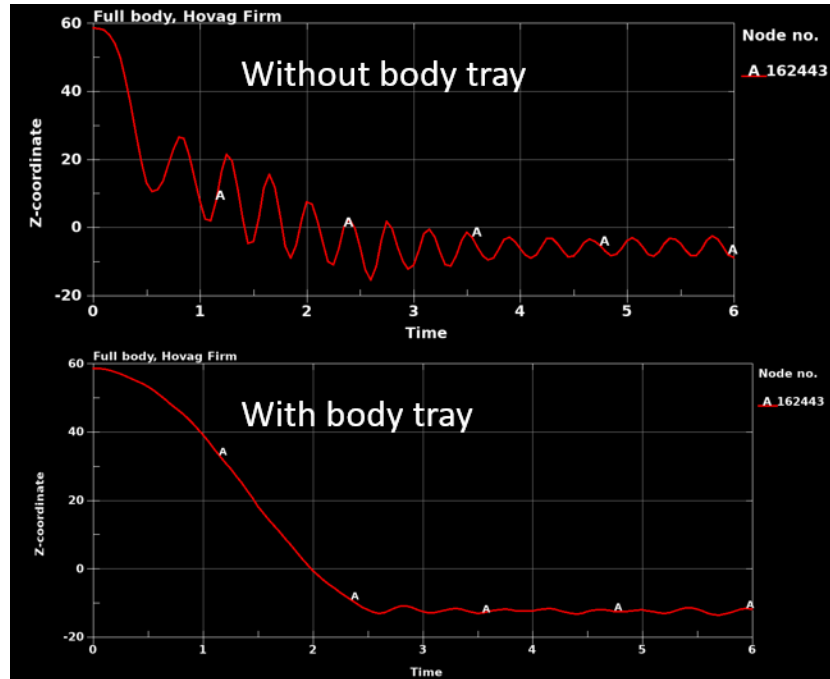


Figure 6.11: Oscillations of the body model with and without the body tray, a sufficient steady state now occurs at 3s | Lambda firm, normal BMI, 80kg, 20 cores

6.3 Summary of results

The accuracy of the individual mattress material models, and the full mattress assembly has been improved, as shown in section 6.1.1, by using mattress material models based on experimental data rather than parameters provided by IC.

The total efficiency of the simulation has also improved, as shown in section 6.2.1 by altering decomposition, in section 6.2.2 by reducing the need for mass scaling, and in section 6.2.3 by reducing bouncing, leading to a total decrease in simulation-time by 90%, see Table 6.4.

Table 6.4: Total reduction in simulation run time while maintaining accurate results
| Lambda firm, normal BMI, 80kg, 20 cores, 3s duration

Before	After	% change
10h 19min	1h 4min	-90%

Chapter 7

Discussion

7.1 Accuracy

The accuracy of the simulations must be considered to have improved. The new and improved individual material models for the Lambda mattress assembly resulted in simulations which behaved more in line with experimental data. However, it is relevant to mention that the experimental data presented in Figure 6.5, 6.6, and 6.7 (section 6.1.1) were collected using a slightly different body model than the simulated data, since the person whose body was modeled was not available. It is not ideal to compare data using different bodies. However, as figures 6.1, 6.2, 6.3 and 6.4 (section 6.1.1) show, the entire mattress assembly and all its component materials are accurate, which would lead to more accurate full-body simulations. An overall increase in accuracy is also what the pressure distribution (Figure 6.8, section 6.1.1) suggests.

While on the whole, the simulations are more accurate than those of IC, the soft tissue materials are neither better nor worse. Evaluating the behaviors of soft-tissue materials is impossible since relevant experimental data is not available, as mentioned in section 5.2.1.

Also, in previous simulations by IC dampers were used to reduce the oscillations of the body model post-impact with the mattress (mentioned in Figure

5.8, section 5.2.4). New simulations should use dampers, to avoid continued oscillations seen in the lower curve of Figure 6.11 (chapter 6). However, using dampers for some reason caused major instability issues in the simulations, and they would not run properly, hence they were removed. The oscillations that remain (lower curve of Figure 6.11, chapter 6) are minimal, and should not affect the accuracy of the results in any significant way.

7.2 Further improvements of accuracy

As of now, the primary point of uncertainty are the soft tissue material models. Merely accepting the material parameters "as is" based on ICs experiments, whose data is not available is a point of contention. Ideally, validation of each material part of the full-body simulation, body and mattress, should be done individually to correspond with real-life experimental data. Hereafter, the validated materials should be assembled into a full-body simulation and validated once again vs. a set of full-body experimental data. This was done for the mattress materials, but not for the soft tissue materials in the human body model. Tensile and compressive testing of each component material in the human body model (or similar) should be performed, which in turn, could then be used in a similar process of validation as the mattress materials, described in section 4.6.1. Using the validated material models of human soft tissue, in combination with validated mattress material models, new full-scale simulations should be run and verified vs. full-scale experimental data. By doing this, the simulations would become even better. A proper set of validated material models for the human body would, of course, not only be useful in this specific case, but in all future simulations involving the human body.

Another important factor for the experience of comfort is the pillow, as discussed in IC's report. The pillow used for all simulations in this thesis have been placeholders, and they have had only minor effects on the simulation outcome. This is mainly due to the fact that there is no model available for IKEA pillows. In order to obtain simulations corresponding to real life experience of comfort, it would require building proper material models and meshes of the pillows and then re-run the full body simulations.

7.3 Efficiency

The efficiency of the simulation increased dramatically due to the reduced need for mass scaling and the addition of a body tray to reduce bouncing. While the body tray is a pure improvement, i.e., there are no simplifications or assumptions made to accommodate the improvement, whereas the reduction in mass scaling is not entirely as pure, but almost. The reduction in mass scaling is achieved by assuming that the skeleton does not suffer any significant stresses while lying on the mattress, and therefore no significant deformations occur. This assumption proved to be correct, looking at Figure 6.10 (section 6.2.2), where the resting positions of two identical simulations (using the verified material models for the mattress) are superimposed on top of each other, the only difference being the skeleton's material models.

7.4 Further improvements in efficiency

The remaining point of low efficiency would be the time it takes until the simulation achieves a steady-state, currently about 3s. The limiting factor being the speed at which the body moves towards the mattress, which would be the speed of the body tray. The tray moves just a bit slower than the gravitational acceleration, in order to reduce the bouncing described in section 5.2.4. Ideally, the body would fall and come into contact with the mattress as fast as possible, and all energy from this fall would then dissipate using a finely tuned damper. A perfectly tuned damper could reduce the required run time to 1.5s or even less. However, since a perfect damper would be dependent on some preliminary tuning, the time saved using it would have to be balanced vs. the time required to set it up. A simple, non-tuned damper would probably suffice and should be added.

While the decomposition did not provide any significant time saved in this case, the concept of altering the decomposition to distribute the processor load on the allocated processor cores more evenly remains compelling. It is a factor to keep in mind for all future large scale simulations involving any but minimal deformations.

This thesis revolves around using what is called explicit FEM. This means

that the results of each cycle in the simulation is dependent on the results of the previous cycle, where the first cycle is dependent on the boundary conditions. Explicit FEM can be compared to walking up a set of stairs, where each new step is reached from the previous one. While explicit FEM is the most common method, there is another method available called implicit FEM. In practice, implicit FEM can be described as letting the computer guess the future state of a system and then check the accuracy of this guess using Newton's $F = ma$ equation. Based on the difference between results and the true equilibrium value (δ), the computer makes a new guess, until a solution of sufficient accuracy is reached. Implicit FEM solutions can be described as "oscillating" towards a steady-state where the solution lies. Hence the implicit method of simulation is more suitable for small deformations. An implicit solution eliminates the need for a timestep and provided a good enough guess could finish the simulation almost instantly. But, how do you make a good enough guess?

Chapter 8

Conclusion

The results of my simulations show that the accuracy of all parameters of comfort, except tension, which remained the same, has been increased. The simulations also run more efficiently, and the previous results by IC are achieved ten times faster than before. Both accuracy and efficiency have been improved using methods and assumptions that are applicable to all future similar simulations of comfort; they are general, which was the purpose of this thesis. Since the improvements are general, future changes to the mattress material models, the human soft tissue material models, or the addition of a pillow will not increase the simulation time dramatically.

The simulations run faster and more accurately, but one question remains: *How accurate are the simulations in their efforts of predicting comfort?* My results show that they are quite accurate. The experience of comfort is subjective. While the new material models for the mattress are accurate and they run efficiently, the true accuracy of the simulations can only be tested with a large customer study, where all material models of the mattress and the human body are validated separately. However, the purpose of these simulations is currently not to mimic both the objective and subjective reality perfectly, but to act as a reliable tool in the early stages of product development. In doing that, the principles and methods presented in this thesis will make future work on the subject faster and more accurate.

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Appendix A

Step-by-step method on replicating a directional compression test on a single specimen in LS-Dyna

The reason this long and very detailed description of how the real-life compressive experiments were replicated is because it was specifically requested by IKEA.

The purpose of the methods described in this chapter of the appendix is to replicate an experiment similar to the one in Figure A.1 using LS-Prepost and LS-Dyna

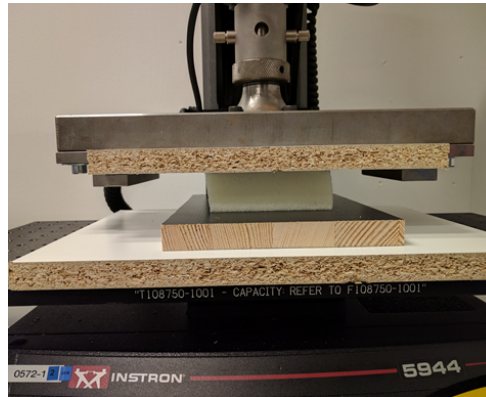


Figure A.1: Compressive experiment of a soft material specimen

If you DO NOT want to use an experimental stress vs. strain curve in the LS-Dyna material model, you can skip step 1 and step 3, don't skip step 2 though.

Detailed process step-by-step

1. Export experimental stress vs. strain curve from excel using the .csv format. In excel: **[file → export → change file type → CSV]** Make sure the decimal-separator in the .csv is set to dot (0.1), not comma (0,1). In excel: **[file → options → advanced → decimal separator]** Also make sure no text or other data is exported in the .csv. It is to look as Figure A.2.

	A	B
1	0	0
2	6.02E-06	0.01
3	1.04E-05	0.02
4	1.35E-05	0.03
5	1.58E-05	0.04
6	1.75E-05	0.05
7	1.9E-05	0.06
8	2.06E-05	0.07
9	2.24E-05	0.08

Figure A.2: Example of .csv stress vs. strain export

2. In LS-Prepost: Define a coordinate system in keyword *DEFINE COORDINATE SYSTEM. Any coordinate system will do. But in these instructions the compression is occurring in z-direction.
3. Import the .csv into LS-Prepost. In DEFINE_CURVE: [**Load XY-Data** → *select the .csv* → **Open** → **Accept**] Make sure variable DATTYPE is set to 0 and that the axes of the imported curve is correct, inspect by clicking [**Plot**], the vertical axis in LS-Dyna is stress and horizontal is strain. If the axes are mixed up click [**ChangeXY** → **Accept**], and inspect again using plot.
4. Construct a mesh of the material specimen in question in LS-Prepost, see Figure A.3. Make sure to construct the mesh using similar measurements as the real- life experimental specimen. Regarding mesh resolution, there is no set specification. However, if the material is to be used in an assembly with other similar materials, make sure to use about the same mesh resolution for all of them. Also, it is good practice to use the same mesh resolution as is to be used in the final model. The elements are set as solid in keyword [SECTION SOLID.]

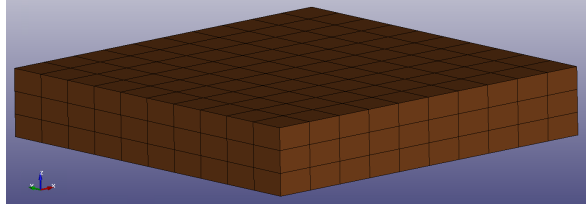


Figure A.3: If the real-life specimen is a rectangular block, build the mesh as a rectangular block

5. Construct a compression plane and place it on top of the material specimen, see Figure A.4. Make sure the compression plane, which should be defined using shell elements in keyword [SECTION SHELL], is placed so not to cause initial penetration with the solid elements of the specimen. For example, if the shell elements of the compression plane are defined as being 1mm thick, the compression plane should be placed 0.5mm above the specimen top surface.

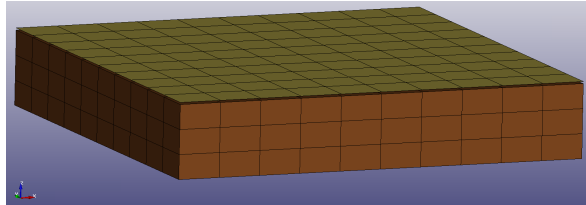


Figure A.4: Mesh of specimen (brown) and compression plane (yellow)

6. Define contact between specimen and compression plane using keyword *CONTACT AUTOMATIC SURFACE TO SURFACE. Set SSID to the part-ID of the specimen, and MSID to the part-ID of the compression plane. Set variables SSTYP and MSTYP to 3.
7. Define translation of the compression plane. Use keyword *BOUNDARY PRESCRIBED MOTION RIGID, see Figure A.5. The displacement over time is defined as the function LCID, or $f(t)$ multiplied by SF, i.e. the total translation at time $t=\mu$ is $SF*f(\mu)$. In this exemplary case, the

desired displacement is -25mm over 0.1s. Therefore, $f(t)$ is defined as a straight line with a positive slope, see Figure A.6, and SF is set to -25.

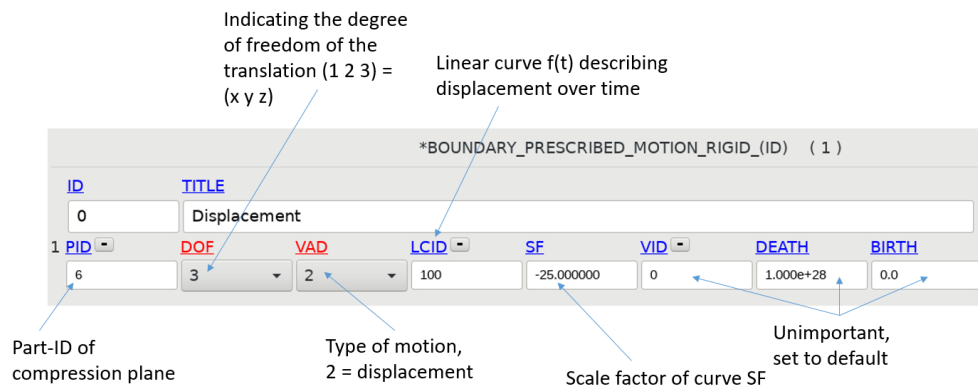


Figure A.5: Example keyword defining boundary translation

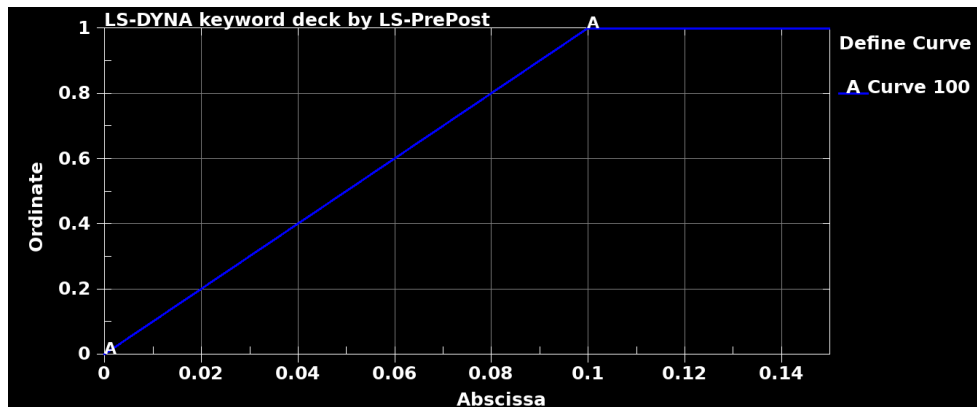


Figure A.6: Example curve of displacement rate over time $f(t)$ of the displacement plane. The displacement equals the value of $f(t) \cdot SF$

8. Set boundary conditions. Create a node set, in LS-Prepost [Model → Create entity → Set Data → *Set Node → Cre → Plan 3 Nodes → *click three nodes on the bottom of the specimen* → select at

this point all nodes of the plane should be selected → **Apply** → **Done**] of the bottom nodes of the specimen, see Figure A.7. Use the defined node set in keyword `*BOUNDARY SPC SET` according to Figure A.8 to create the boundary condition.

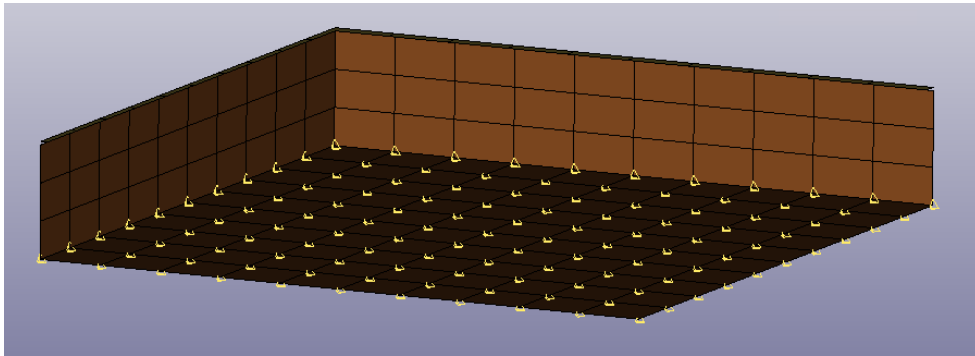


Figure A.7: Bottom nodes of specimen used in a boundary condition

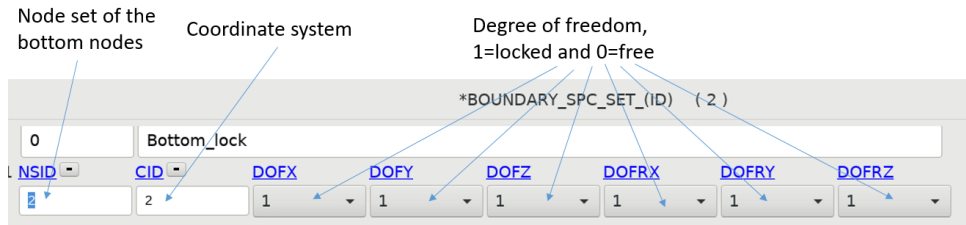


Figure A.8: Keyword defining the boundary condition, since we want the bottom of the specimen not to move all degrees of freedom are locked

9. Set materials. Choose a fitting material model in `*MAT` for the specimen. Set the material of the compression plane to `*MAT RIGID` (Mat 020), set to material parameters to that of steel. $E=206$ [GPa], $RHO=8000$ [$\frac{kg}{m^3}$], $PR=0.3$. Make sure the units in LS-Prepost are input correct.
10. Inspect material directions are defined correctly. If the material you are modelling is isotropic, you can skip this step. If it is anisotropic,

make sure the material directions are applied as desired, in LS-Prepost click [**Element tool** → **Identify** → **Element** → **Mat Dir** *click a specimen element and inspect*]. Adjust until satisfactory inside the material keyword.

11. Tell LS-Dyna to output the correct files. Add keyword *DATABASE BINARY D3PLOT. Set variable DT to 0.005, or other if desired.
12. Run the simulations. It could be needed to lower TSSFAC in *CONTROL TIMESTEP if there are instability issues. In prepost there is a very useful tool called **Model checking**  if issues persist.
13. Export the results. Open the d3plot-file in LS-Prepost and plot the force over time on the compression plane [**Binout** → **Load** *select binout0000* → **spcforc** → **All** → **Total** → **z_force** → **Plot** →. **Important note:** There is a strange bug in where the scroll list, where you select z_force, is not visible and you have to drag and enlarge the window to see it. → *now the plot should be visible* → **Set option as shown in Figure A.9** → **Save**]

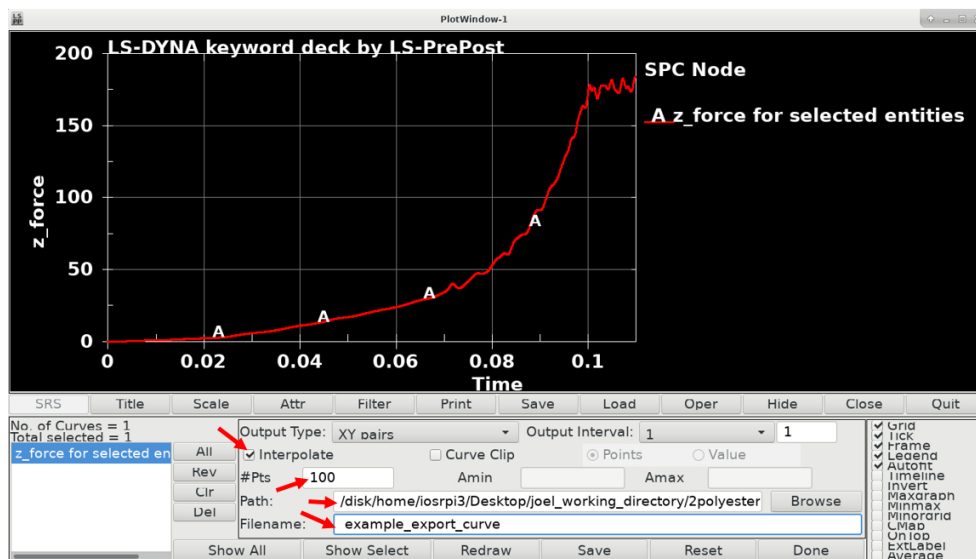


Figure A.9: Example of exporting a force over time curve from LS-Dyna. All changes from default are indicated by red arrows

14. Export the displacement of the compression plane. In the d3hsp in LS-Prepost click [**Post** → **History** → **Part** → **Z-Rigid body displacement** → *click the compression plane* → **Plot**]. Export the curve using the same settings as the previous curve. It is important that the number of interpolation points (#Pts in Figure A.9) are the same for both curves.
15. Import both curves into excel. In an excel document [**Data** → **From text** → *select to show All files (*.*)* → *select file* → **Import**] this should open *Text import Wizard - Step 1 of 3*. In the text import wizard [**Next** → *delimiter Space*] → **Advanced...** → **change decimal separator id need be** → **OK** → **Finish** → *click any cell* → **OK**]
16. Now what remains is simply to divide the force applied with the top area of the specimen to get the stress, and the vertical displacement with the thickness of the specimen to get the strain. Compare simulated stress vs. strain to the real-life experimental data of the specimen material by

plotting them in the same graph. **Done.**

Appendix B

More on dummy layers

When simulating nonlinear elastic materials that are subject to extensive deformations, simulations often have issues with elements collapsing, i.e., they compress too much, and the simulations terminate. There are many workarounds to this issue, and using dummy layers is one of them.

The dummy layers are placed on both sides of the material in compression, tied to the material's top and bottom planes by sharing elemental nodes. By defining the planar dummy layers as shell membranes and giving them a slight thickness, say 1mm, and then defining the contacts to where the dummy layers **only** interact with each other the elements in compression are prevented from collapsing since the 1mm thick dummy layers come in contact before. See Figure B.1 below.

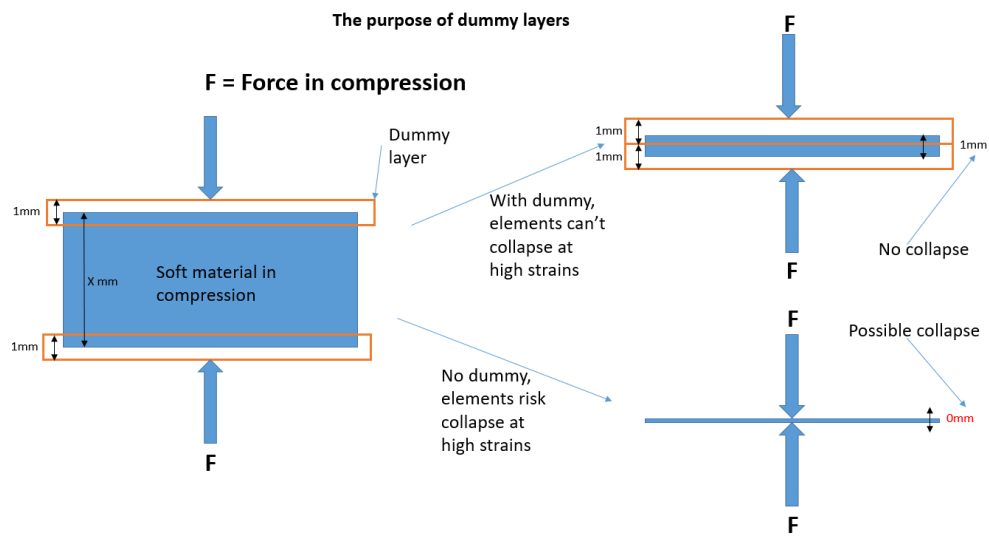


Figure B.1: Dummy planes

Appendix C

Replicating previous results in LS-Dyna

C.1 Material parameter translation: Abaqus to LS-Dyna

See Appendix C.4 for referenced matlab script

Initially, when working with MAT_02¹ and the previous material parameters, there were many issues with instability or instant crashes of the simulations. This turned out to be caused by an issue in translating the material parameters into LS-Dyna, which is required since Abaqus uses another variation of material coordinate-system when applying the mechanical parameters. For instance, in Abaqus, when modeling an orthotropic material, Poisson's ratio in the 1,2-direction (ν_{12}) is used, whereas the LS-Dyna orthotropic material model would use Poisson's in the 2,1 direction (ν_{21}). These ratios would be interchangeable were the material isotropic. However, they were not as indicated by varying directional Young's moduli.

¹An orthotropic elastic material model, which seemed logical to use since it made use of all provided previous material parameters

Parameter translation between the programs was performed using equation C.1 (Jones, 1975) and a matlab script.

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j} \quad (C.1)$$

where i,j=material direction, E_i is Young's modulus in i-direction and ν_{ij} is the Poisson's ratio on the i,j-direction.

C.2 Replication results

See Appendix C.3 for specifics on how the LS-Dyna images in Figure C.2, C.3 and C.4 were created using LS-PrePost

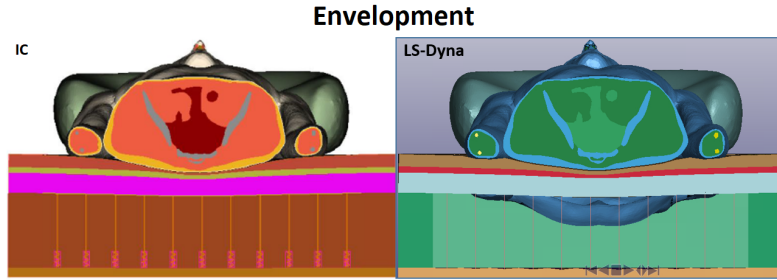


Figure C.1: Body to mattress envelopment simulations from IC's report (Previous report p.112) (left) , LS-Dyna replication simulation (right)| Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male

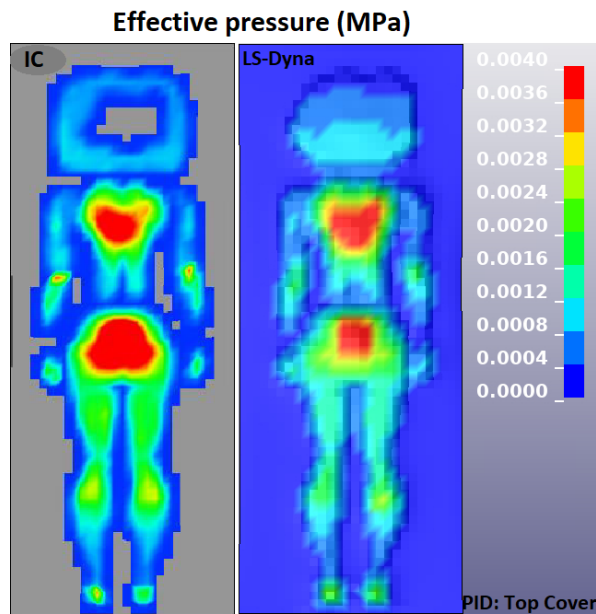


Figure C.2: Effective contact pressure in top cover | Pressure distribution from IC's simulations (Previous report p.197) (left), LS-Dyna replication simulation (right) | Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male | **Note:** The top cover in the above Figure is modeled as a *membrane element*, hence the above plot is of von Mises stress and not pressure per se, however, in a membrane element von Mises stress = pressure.

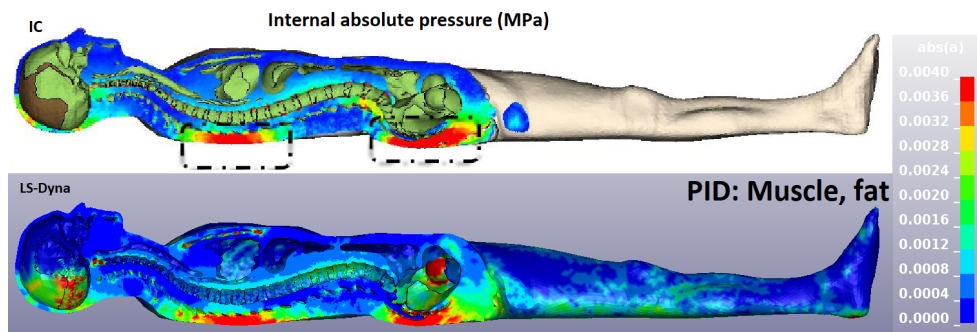


Figure C.3: Internal effective pressure in fat and muscle from IC's simulations (Previous report p.198) (top) | LS-Dyna replication simulation (bottom) | Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male

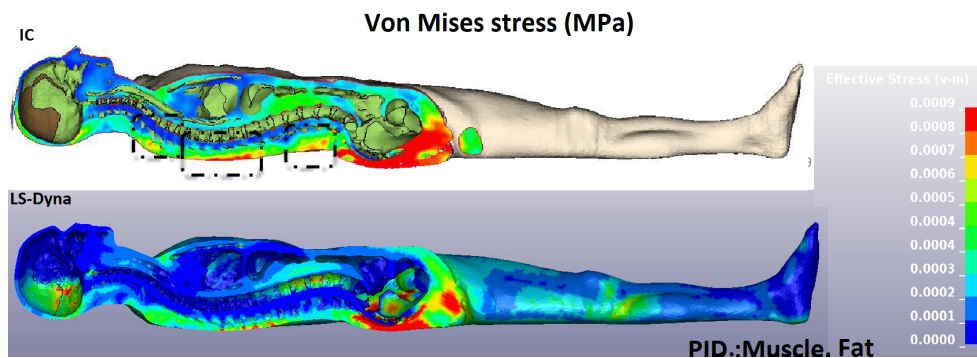


Figure C.4: Internal Von Mises stress in fat and muscle from IC's simulations (Previous report p.199) (top), LS-Dyna replication simulation (bottom) | Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male

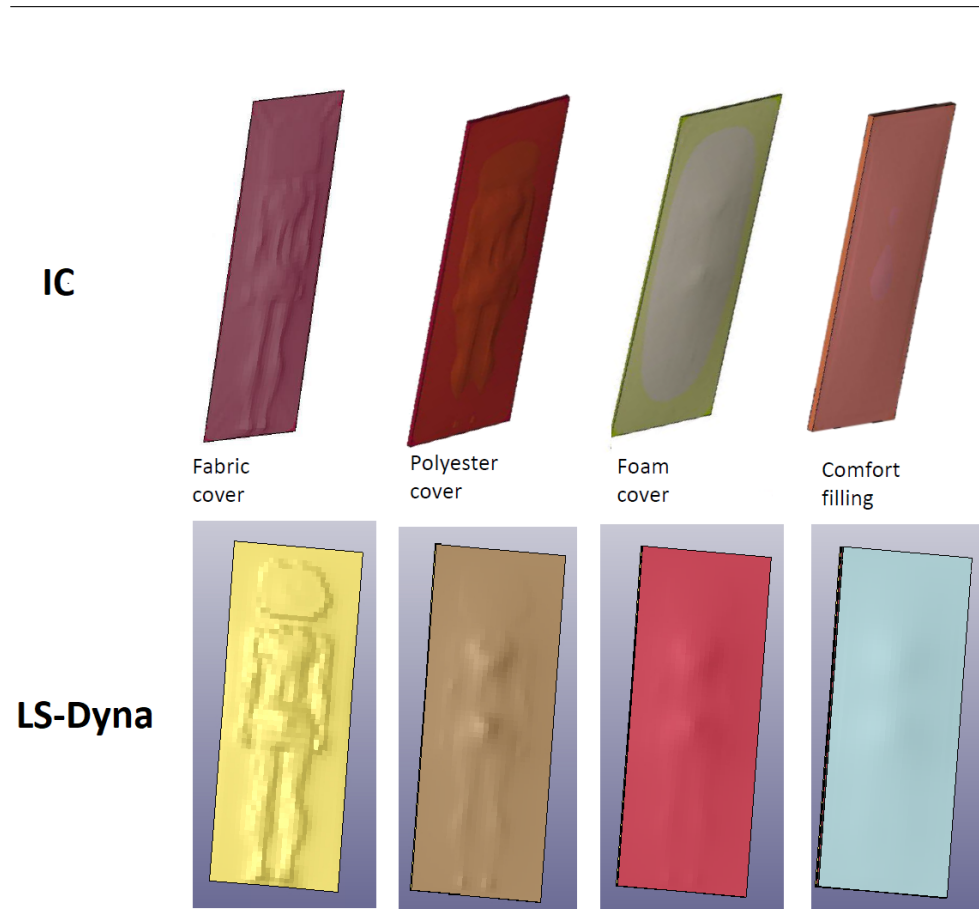


Figure C.5: Deformation of each mattress layer mattress top cover, polyester cover, top foam/foam cover, comfort filling from IC's simulations (Previous report p.77) (top row), LS-Dyna replication simulation (bottom row) | Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male

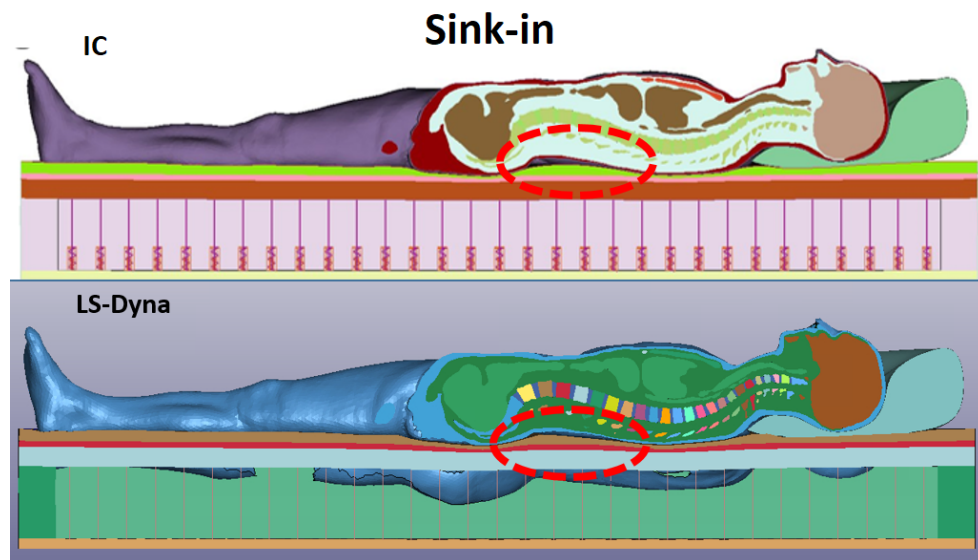


Figure C.6: Body sink in and mattress assembly deformation from IC's simulations (IKEA Biomechanical comfort Part A 20190906. p.82) (top), LS-Dyna replication simulation (bottom) | Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male | The red marking is indicating that neither of the bodies are similarly not supported in the lower back, which IC put a large emphasis on pointing out, hence I show it as well.

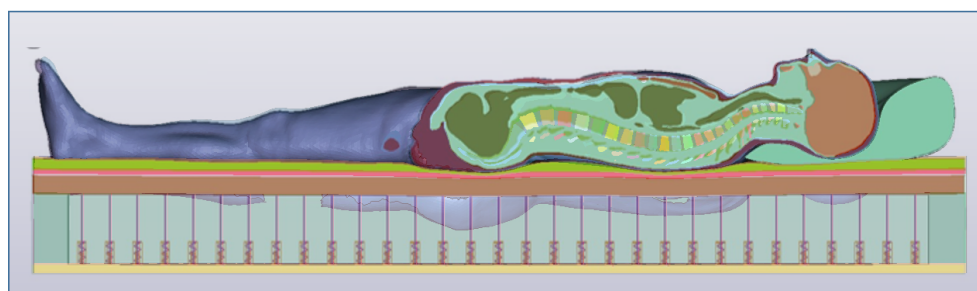


Figure C.7: Overlay of the images in Figure C.6, the "shadow" under the body is just the body tray | Mattress: Lambda firm | Body: Normal BMI (26), 80kg, male

C.3 Settings from section C.2

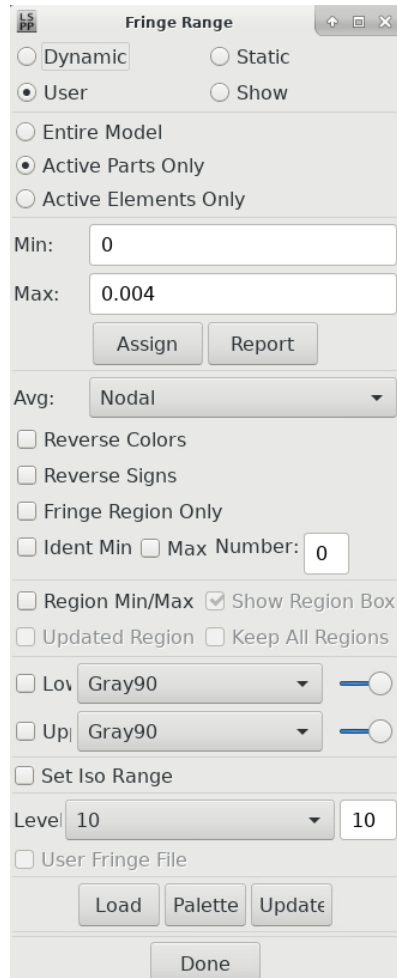


Figure C.8: Fringe settings used when plotting the vms of the (R) images in Figure C.2 and C.3 using LS-Prepost. Since the top cover consists of membrane elements the vms can be approximated as pressure

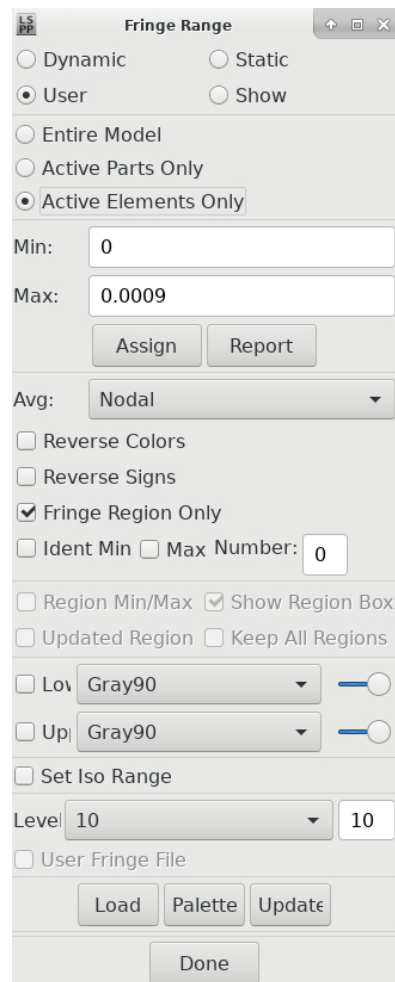


Figure C.9: Fringe settings used when plotting the vms of the (R) image in Figure C.4

C.4 Matlab script from section C.1

This script was used when translating IC's provided previous material parameters of the polyester material. By simply inputting the other values for variables (PRAB, PRAC, PRBC, GAB, GAC, GBC, EA, EB, EC) the same translation was done to foam 25100 and 28150.

```
1 %Joel Elinder , 2020-03-31
2 %Script used for converting given Orthotropic material
  parameters from abaqus to LS-Dyna
3 clc
4 clear all
5 format long
6 %This script is for the by IC's given polyester
  parameters
7 %Abaqus given Poissons ratio
8 PRAB = 0.4; %V12 in abaqus
9 PRAC = 0.4; %V13 in abaqus
10 PRBC = 0.3; %V23 in abaqus
11 %Shear moduli [MPa]
12 GAB=0.11; %G12 in abaqus
13 GAC=0.08; %G13 in abaqus
14 GBC=0.04; %G23 in abaqus
15 %Young's moduli [MPa]
16 EA=0.11; %E1 in abaqus
17 EB=0.05; %E2 in abaqus
18 EC=0.0007; %E3 in abaqus
19 %Calculate corresponenting ls-dyna input
20 PRBA = PRAB*(EB/EA) ;
21 PRCA = PRAC*(EC/EA) ;
22 PRCB = PRBC*(EC/EB) ;
23 GCA= GAC*(PRCA/PRAC) ;
24 PR= [PRBA PRCA PRCB]
25 G = [GAB GBC GCA]
26 E = [EA EB EC]
```

Appendix D

Editing decomposition

By introducing the LS-Dyna keyword `*CONTROL MPP DECOMPOSITION TRANSFORMATION` and changing the keyword parameters `SX`, `SY` or `SZ` to a different value than 0 (default), say 1000, the RCB-algorithm will consider the axis 1000 times longer.

Using `*CONTROL MPP DECOMPOSITION SHOW`, the current decomposition can be visualized which is quite useful during altering of the `SX`, `SY` and `SZ` parameters.

Appendix E

About the body tray

The body tray was constructed by duplicating elements on the underside of the skin in the body model. These elements were then translated (-)1mm (away from the body) in the z-direction to avoid initial element penetration. There is no contact defined between the body tray and the mattress, only between the body tray and the skin of the body model. Hence the body tray glides through the mattress as the skin of the body model and the mattress come into contact.

Appendix F

Tips and tricks using LS-Dyna and LS-Prepost

Troubleshooting using the grep-command - When building simulations, you always get a lot of errors and premature terminations. However, it is not always made clear by LS-Dyna why the simulation crashed. If run using Linux, it is possible by opening the terminal in the result folder of the crashed simulation [**right click → open terminal here**] and type [**grep Error mes***] (case sensitive) to get a very handy list of exactly where in the result files there is an error.

Creating a simple macro in LS-Prepost - If doing repetitive tasks, like taking screenshots from a specific angle on many different models, it is possible to create macros in LS-Prepost by copying the command-history from the message box (double click the white line in the bottom right of LS-Prepost) and pasting it in the command line, (bottom left).

Thank you!