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Design of an instrument panel module for the passenger side of the functional generic rig used for cars collision tests

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ABSTRACT

One way to analyse the behaviour of a car safety features is performing a series of collision tests. One type of collision test is performed in a structure made with steel beams that is called functional generic rig. In this rig, the most important elements to evaluate in a certain crash test are set and some of those elements are simplified versions of the ones that should be placed in a real car. One of those elements is the instrument panel. The instrument panel is a key component because it restrains the occupant in a crash event and helps other safety features to work properly, but for many reasons in the generic rig collision test a simplified version of this panel is used.

Nevertheless, before performing the crash test using the generic rig, virtual models of this arrange are built and analysed using FEA, being a more inexpensive and faster way to accurately reproduce the response of the actual physical crash tests.

However, the response of the instrument panel module (IP module) currently used in the functional-generic rig on the passenger side does not reproduce the response of a real IP module from a full-scale vehicle collision test. For that reason, during this project the instrument panel of the passenger side of the functional generic rig was redesigned to obtain reliable results that can replicate the displacement and impact absorption of the passenger dummy during a collision test in a full-scale complete car.

The model design is basically made of a thin steel high deformable open-top box. The frontal panel of the box, is made of two panels, left and right, which have different thicknesses and that are covered by a layer of foam with adjustable thickness. Also, the lateral left and right inclination angles measured from the vertical are different, to mimic the frontal shape of a car IP.

The model designed is able to replicate the instrument panel behaviour of 6 different car target models, only by changing the thickness of the left and right side of the frontal panel, and the results can be adjusted only by changing the foam layer thickness.

Key words: Instrument panel, FEA, collision test, functional generic rig, glove box, dynamic analysis

CONTENTS

PREFACE

This Master's Thesis has been carried out at the Department of Mechanical Engineering in collaboration with the Section of Restraints at Volvo Cars.

The project was possible thanks to the help and supervision of David Ramos from the Restraints department at Volvo Cars. We appreciate the trust that he put on us when he decided to choose us to work in this project, he has also been present any time we needed him and willing to answer all our questions. He taught us how to behave and carry out a job in a big company like Volvo Cars, he was our mentor and introduced us to the software that we have used for this project, which was completely new and unknown for us.

Secondly, we would also like to thank Zlate Dimkovski from Halmstad University, who supervised us but yet gave us enough space for developing this thesis in our own ways. We would also like to acknowledge Sigge Svenson, Stefan Pauli and Chetan Kotur from Volvo Cars for always finding a time for helping us in the development of this project.

Finally, we want to thank to all those people that have supported us during this period, friends, roommates, classmates, professors and family. We are extremely thankful for your love and companionship.

NOTATIONS

Abbreviations listed alphabetically.

CAD, Computer Aided Design
CAE, Computer Aided Engineering
CAM, Computer Aided Manufacturing
C*X*, the options are CA, CB, CC, CD which means: Concept A, Concept B, Concept C and Concept D
C*X_Y_Z W*cm Foam, Concept X with a frontal panel with Y mm thickness on the left side, Z mm thickness on the right side and a W cm layer of foam.
FE, Finite Element
FEA, Finite Element Analysis
IP, Instrument Panel
QFD, Quality Functions Deployment
VM*X*, Volvo Model *X*, with *X* being 1, 2, 3, 4, 5 and 6

1. INTRODUCTION

1.1. Background

Nowadays, Volvo Car Corporation is regarded as the role model for traffic safety based on their products and commitment to safety. Many safety features are present in today´s Volvo Cars that are designed to avoid or decrease the severity of the injuries caused by an accident. Some of these features are completely designed as safety components and can be easily identified, e.g. airbags or seatbelts.

Nevertheless, there is one key component which even if not being perceived as a safety feature, plays a very important role in both restraining the occupant in a crash event but also assisting other safety features to work properly, this is the instrument panel. Instrument panels vary widely from project to project and are difficult to characterize, they need to be good at absorbing the impact of the occupants' legs but at the same time need to provide a stable surface for the airbags to deploy correctly (Ramos, 2017).

One way to analyse the behaviour of a car´s safety features is performing a series of full-scale vehicle crash tests to reproduce the dynamic conditions of the real-world accidents. However, the complex and destructive nature of these crash tests makes them very expensive and for this reason, before a complete full-scale car is submitted to a collision test, there are two previous instances of simplified tests which can be implemented (Figure 1.1):

- A cockpit-like structure crash test, which is implemented with the exact same cockpit pieces of a full-scale complete car and at the same time in the production process.
- A functional-generic rig crash test, which is implemented with cockpit pieces that are similar to the ones that are going to be used in the complete car crash test or are simplified versions of those pieces. One of the advantages of the rig crash test is the possibility of performing it at early stages of the production process, when the complete production of the car is still far in time.

During these tests, the structure is subjected to controlled accelerations representative of a particular crash environment. This acceleration is modelled after accelerometer data collected from actual full-scale complete car crash testing (or is estimated if it is needed at early stages of the production process) and is commonly referred to as a sled pulse (Smyth, 2007).

These two previous steps are intended to help predicting and understanding the car´s behaviour at a fraction of the cost but also identify any changes or improvements needed during the development process of the project. But before even performing the sled tests, virtual models of this arrange, the cockpit-like

structure and the complete full-scale car, are built and analysed using FEA. Those FE models are intended be a less expensive and faster way to accurately reproduce the response of the actual physical crash tests. During the whole testing process these models are compared with the physical tests and improved or refined if needed.
Nowadays, the response of the IP module of the functional-generic rig is not sufficiently accurate especially on the passenger side, in which influence in the dummy kinematics and airbag performance is much higher. For this reason, is necessary to redesign it to obtain precise and reliable results that can replicate the displacement and impact absorption of the passenger dummy.

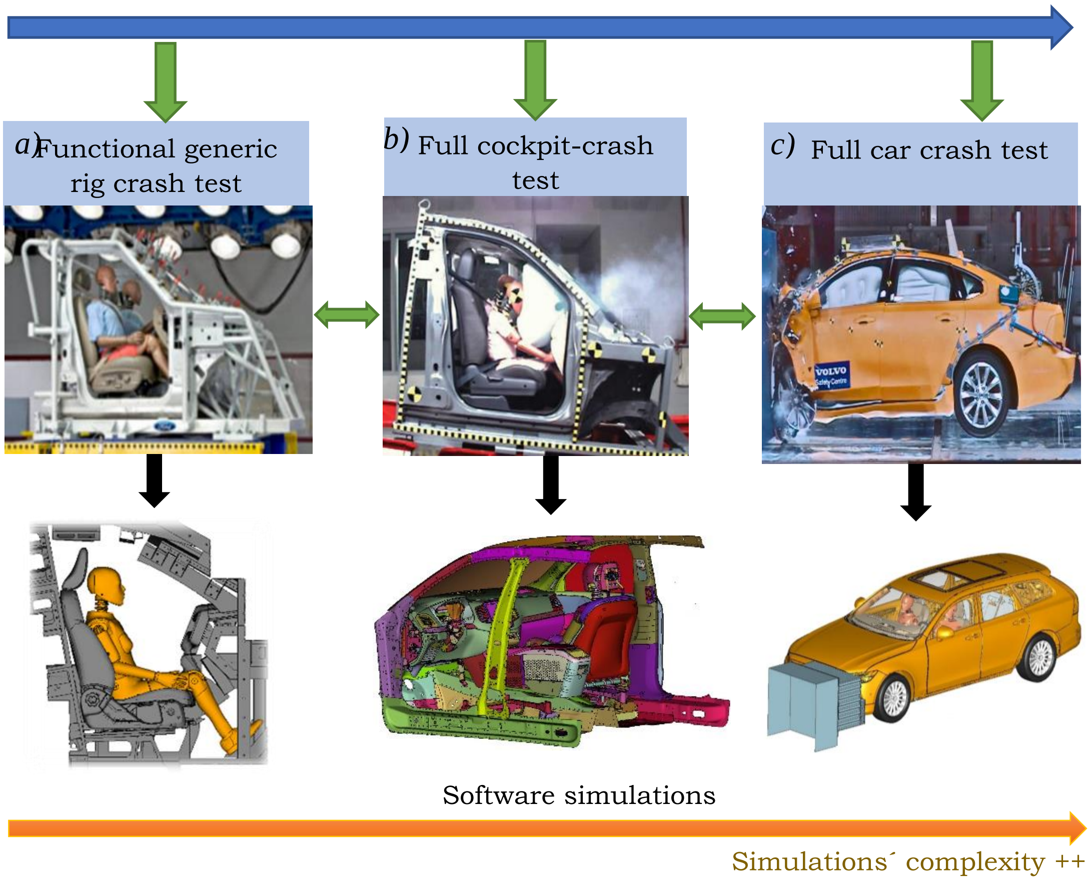


Figure 1.1, car testing process: a) functional generic rig test (Auto, 2017), *b) cockpit test* (Arens, 2017), *c) complete car test (YOUCARS, 2016;* Jergeus, 2016). *Every collision test performed has a corresponding simulation analysis*.

1.2. Aim of study

This project has many objectives to be accomplished, which are listed below according to their importance:

1- Redesign an IP module to be used in a functional-generic rig which is able to replicate the behavior of a production IP regarding leg kinematics of the passenger dummy during a frontal collision test with the passenger dummy unbelted.
2- The design of the instrument panel is aimed to be generic and able to be adapted to any car model just by adjusting certain parameters in the FE model and in the physical functional-generic rig also.

1.3. Limitations

The scope of this project compels only the design of an IP module to be used in a generic sled to be used during sled crash tests for certain cars models. We will not focus on the response of the other components of the cockpit or in the way they interact with the IP, for that reason, the instrument panel will be considered as isolated in the situation with not possible intrusions on the cockpit during a collision.
This research is focus only on the kinematics of the dummies legs and in its force-displacements knees ratio under a few load cases. In addition, even though there is friction between the dummies knees and the IP module, it will not be precisely estimated for our particular case and instead, a generic friction definition will be used.
Moreover, the upper part of the instrument panel will be discarded from analysis because it is covered by the passenger airbag during a frontal crash.

1.4. Individual responsibility and efforts during this project

This project has been made by two authors, who have shared the efforts during the thesis project and, therefore, share responsibility and credit about it.

1.5. Study environment

This project was made in the restraints group at Volvo cars facilities under the supervision of David Ramos, CAE engineer in the restraints group. Volvo Car Corporation is an automotive company that acts in the premium sector. Everything done at Volvo Cars starts with people and that is what make them different from other car companies and it is at the heart of everything they create. This master project finds its root on the need of improving the results obtained during the functional generic rig collision test in order to advance in the field of interior safety.

2. Methodology

2.1. Alternative methods

For product development, many methodologies are actively used around the world. Some examples are the Stage-Gate, Fredy Olsson´s, and the Ullman´s product development process.

The Stage-Gate Product Development Process is methodology that states that the product innovation starts with ideas and ends as soon as the product is launched onto the market. This model uses a complex process of decision-making and developing an idea from beginning to end of the process itself. In general, Stage-Gate includes Product Development (business justification and preliminary capabilities), Development activities (technical, marketing and operational development) and Commercialization (market launch and training after launch) into one complete, reliable process (Cooper, 2006)

Fredy Olsson's product design method divides the work into five parts: Product Option Study, Principle Design, Primary Design, Manufacturing design and Final construction

The first part of Freddy Olsson´s method is Preliminary Design where the author describes how to produce a product type according the customer needs. In the second part, the Principle Design, there is a goal is to develop a principle solution in the sketch or simpler model form. It is done through five different moments, product definition, product survey and criteria set-up, production of product suggestions, evaluation of product proposals and presentation of chosen product proposal (Olsson, Principkonstruktion, 1995a). Then, the primary structure follows each component and detail chosen or constructed based on the principle solution. In that case, material selection is also made it is up to date (Olsson, Primärkonstruktion, 1995b). The fourth part is manufacturing design in which all parts are analyzed. It is done one error analysis, a life cycle analysis and a cost estimate and then, if so conveniently, a function prototype is being tested. The last part refers to work that occurs after the product has been tested and possibly deficiencies in the construction emerged (Olsson, Principkonstruktion, 1995a).

Ullman states that regardless of the design problem, 5 basic actions need to be taken during the designing process: Plan how to solve the problem, understand the problem, generating alternative solutions, evaluate the alternatives and selecting the final solution

These actions are not necessarily taken in 1-2-3 order. In fact, they are often interrupted and re-thought due to solution generation and evaluation that improves the understanding of the problem (Ullman, The mechanical design process, 2010).

2.2. Chosen methodology for this project

The design process developed in this document will be considered as an original design due to the lack of experience of the authors in this field. After carefully considering the different available options, the methodology that will be applied

in this report is the one suggested by David Ullman in the Book "The mechanical design", this chosen was made because of previous personal experience working with Ullman´s theory.
In Appendix I, can be observed a Gant chart showing the schedule followed to develop this project. In Appendix II, can be found information about the history of de design process and case studies illustrating the application of Ullman´s methodology and in chapter 3 of this thesis can be found more detail about Ullman´s theory.

2.3. Preparations and data Collection

The preparation and data collection for this report was performed using the software listed below:

- CAD Software: CATIA, an acronym of computer aided three-dimensional interactive application and Solidworks are two softwares suites for computer-aided design (CAD), manufacturing (CAM), engineering (CAE), PLM and 3D, developed by Dassault Systèmes. These two platforms were used for the CAD modelling of the different models created during this thesis.
- ANSA Pre-processor: ANSA is an advanced multidisciplinary CAE pre-processing tool with the necessary functionality for full-model build up, from CAD data to ready-to-run solver input file. This program was used for setting and preparing the CAD models into a simulation environment. This software has been proved to be highly efficient to store, retrieve and monitor model components from CAD models (BETA C. s., 2007) and the highly-specialized ANSA tools can greatly reduce the time of pre-processing by automating various difficult operations (Rorris, 2009).
- META Post-processor: META is a multi-disciplinary CAE post-processor, that has capabilities of interaction between animations, plots, videos, reports and diverse objects *(BETA, 2017)*. In this project, it was used to observe and analyse the results of the simulations performed in LS-DYNA because META allows the extraction of responses and histories, from data that can derive from various solvers *(Korbetis, 2007)*and is more efficient and easy to understand that the LS-DYNA post-processor.
- LS-DYNA: LS-DYNA is a general-purpose finite element software based mainly on explicit time integration. It is used for analysing large deformation static and dynamic response of different structures (Hallquist, 2006) and is one of the preferred softwares find in the literature for analysing collisions and some examples are: the college of automotive engineering that used LD-DYNA to analyse a frontal car collision (Chunke Liu, 2014), the Godavari Institute of Engineering and Technology that implemented this software for simulating frontal vehicular crashes (Tejasagar, 2012) and the NASA Langley Research Center that with LS-DYNA analysed the collision of a full-scale helicopter (Annett, 2017), .

During this thesis, LS-DYNA was used to perform the simulations previously prepared with ANSA pre-processor.

3. THEORY

3.1. Summary of the literature study and state of art

3.1.1. Ullman´s product design theory

Following a concrete and logical design process technique to design a product helps to reach satisfying and successful results regardless the nature of the product. Customers and management always want the products to be as cheap and as good as possible and in the shortest time.
The decisions made when implementing a design process have a great effect on the cost of a product but cost very little; the design process can determine up to the 75% of the manufacturing cost (Karl Ulrich, 1993). Also, the decisions made during the design process determine product's quality and the time it takes to produce a new product.
Moreover, Ullman states that 85% of the problems with new products (low quality, long time or high cost) are the result of a poor designprocess. The different part of the Ullman´s design process are listed below:

1. Product discovery: Product discovery is the first stage on product design and is used to establish the need and objectives of the design project, the design "problem" is established.
2. Project planning: During the second phase, it is planned how to solve the problem and is considered how to allocate the resources (money, people, equipment) during the project; this phase is usually characterized by speculating about the unknow, forming design teams, establishing a schedule, and estimating the costs. Gantt charts, critical path method diagram or design structure matrix[1] are commonly used in this phase.
3. Product definition: During this part of the development process takes place the problem understanding. The first task to do in this stage is to identify the customers for the products, using focus groups, surveys and interviews for gathering customers´ requirements and later generate engineering specifications. During the product definition, is determined by benchmarking[2] techniques how well the competition meets the goals and how must be the target and threshold values of the engineering specifications. One of the most popular techniques to

[1] Modelling technique that can be used for designing, and managing complex systems. Is used primarily on the area of engineering management (Eppinger, 2012).
[2] Technique used to identify and apply the best demonstrated practices to product development or business operations (Bain&Company, 2015).

organize customers´ requirements and engineering specifications is the QFD[3] method, furtherly explained in Appendix 3.
4. Conceptual design: Using the results from the previous phases, different alternative solutions (concepts) are generated and evaluated. Brainstorming[4], TRIZ[5], consulting from experts or patents and morphological matrices[6] are some of the strategies used to generate different concepts. All concept proposals must be described in the same level of abstraction in order to be later compared, sketches, CAD models, detail drawings or analytical models can be used.
When many concepts are generated, the goal is to evaluate them considering their performance and compare them with the requirements already developed, expending the least amount of resources on deciding which concepts have the highest potential. For this purpose, are used several tools like computer simulations, prototypes, technology readiness assessment[7], decision matrices. After evaluating the product design relative to performance, cost, ease of assembly, reliability, environmental friendliness, and maintainability are evaluated.
5. Product development and product support: In this last stage, after a concept (or several) is selected, it is refined into an actual product (or products) and prepared to be released into the market. After a product is released, there is still a continuous need of assembly and manufacturing support, introducing the product to the customers and providing support also to vendors. (Ullman, The mechanical design process, 2010)

3.1.2. The instrument panel

The instrument panel is the module inside the car´s cockpit, located behind the steering wheel and extended from the driver´s window to the passenger window as shown.
Originally, the instrument panel was a barrier of wood fixed at the front of a horse-drawn carriage with the purpose of protecting the driver from debris thrown up by the horses´ hooves (MiriamWebster, 2017).
When carriages evolved into horseless carriages powered by an engine located in front of the driver, the instrument panel main function was to protected vehicle occupants from the heat and oil of the engine and carry some basic instruments like speedometer and a compartment to put the gloves (Miller, 2016). Nowadays however, it serves many other purposes like holding instrumentation to show car´s control parameters, airbags housing, vents for heating and air conditioning,

[3] Quality Function Deployment: Structured approach to define customer requirements and translate them into specific plans to meet those needs (DRM, 2016)
[4] Process for generating creative ideas and solutions through intensive and freewheeling group discussion (BusinessDictionary, 2017).
[5] TRIZ (Russian abbreviation for "Theory of Inventive Problem Solving") is a scientifically based inventive problem solving process. Is based on the study of global patent literature and the identification of the most creative patents (Jack Hupple, 2016).
[6] Form of random stimulation that consist on building a matrix with one column with functions to accomplish and several adjacent columns with different concepts proposals (InnovationTools, 2013).
[7] Techniques used for analysing if the technologies that are about to be used in the project are developed or will be soon developed (A. Olechowski, 2015).

speakers for audio systems, glove compartment, anti-start module and wiring of the electric installation, etc.

3.1.3. Materials and manufacturing

At the beginning, the instrument panel module was built from separate components that needed to be painted and then all held together by a supporting beam made of steel that lay behind the panel (cross car beam). After the development of high performance plastics technology, instrument panels could be manufactured from all-urethane and all-polypropylene resins. This results in a seamless instrument panel with high design freedom for allocating all the items held by the IP module, a moulded-in colour, minimal corrosion rate, minimum levels of noise, vibration and hardness, significant cost savings for the manufacturer and the possibility of an in-plant recycling process (Gerard, 2014). After overcoming IP modules built from separate pieces, most vehicle manufacturers adopted one-piece rigid IP modules.

They were built using the injection technique with only one type of material, generally thermoplastic plastics such as ABS (acrylonitrile butadiene styrene), PP (polypropylene), PPE (Modified polyether), etc. They had a certain hardness and were not deformable.

However, to increase passive safety inside the passenger compartment, flexible IP modules have been developed. They have displaced the rigid ones, because they can reduce the injuries in case of collision. These modules have a sandwich-type structure, formed by the combination of three components: base support, intermediate padding and outer coating.

The base support provides the necessary rigidity to the part, serving as a support and fixation element. The materials commonly used are:

- Metal: steels or aluminium alloys.
- Plastics: thermoplastics such as ABS, PP, PPE, etc.
- Various agglomerates: mixtures of resins, paperboard, and fibres.

The padding is the component that intervenes in greater amount in the increase of the passive safety, since it dampens the possible impacts of the occupants against the panel. This intermediate layer is formed by polyurethane foam, which contributes at the same time the necessary volume to the piece. The outer coating, on the other hand, protects the padding, provides the aesthetic appearance to the on-board dashboard and it is usually formed by a PVC sheet (Angelfire, 2017). The globe box, on the contrary, is not made of a three-materials sandwich arrangement. This compartment is manufactures with an inner structure that provides support and an outside panel that provides the aesthetic appearance and both are entirely made with ABS thermoplastic.

3.1.4. Product design process

The design process of an instrument panel, generally speaking, follows a very similar designing procedure that any other piece of the car. This procedure is approximately within a range of years long and is compelled by several defined steps.
At the beginning, the designers have several different IP proposals to choose from, each of them can embrace different themes and styles. During a period that can take a few of months, designers get threshold values to modify and adapt the original IP proposals: general dimensions, screen characteristics, positioning of diverse objects. These threshold values cannot be changed and are determined by guidelines.
Designers try to follow a design "DNA" of the brand which means that the design should be representative of a brand product and the customer should see it and recognise it like part of the brand portfolio. They also need to constantly benchmark with other car companies, organize focus groups with current car owners and research about new technologies inside and outside the vehicle industry. The research of new technologies is crucial because in this stage, designers came up with ideas that will reach the customers several years after, so they must think ahead about what customers want to have in their cars in the future.
During several months takes place an interaction process between the designers and the engineers. In this instance, the designers receive feedback of their proposal from several engineering groups: restraints, ergonomics, human-machine interface, package team, ventilation, material, IP engineers. Within these phase a single design is chosen and work is focused only on its development. Based on this design and after certain maturity of the engineering work, starts the appearance approval with the objective of refining the last small appearance details.
In the end, takes place the freezing of the design phase which is a non-movable date that indicates the end of the design modifications and the beginning of the production process (Kotur, 2017).

3.2. Chosen topic

3.2.1. The functional generic rig test

A functional generic rig is a rigid structure made generally of steel used to perform a car crash test under controlled acceleration conditions (Cidaut, 2017). The rig test offers a method of simulating crash conditions at an early stage of the design process of a new car, to obtain crash data a much lower cost than when crashing a whole vehicle.
The rig is mounted on the top of a rail system equipped with hydraulic cylinders that are used to apply the crash-pulse to the sled. The force applied to the rig is car dependent (body shape and structure, weight, powertrain) and variates within

projects. On the top and bottom of the rig structure, accelerometers are placed to measure the car response to the applied pulse the crash is recorded using high speed cameras. Temperature is a variable that is tested when analysing some components isolated like airbags or seatbelts, but in this type of tests (collision tests with a large number of pieces involved) there is no reason to control external variables like pressure or temperature.
The weight of the rig is limited by the maximum acceleration the rail is intended to apply and the interior is usually compelled by the seat belts, the carpet, the IP module, seats, steering wheel, airbags, and windshield. Those interior elements are fastened to the rig´s steel structure using adapters precisely designed for every car model; the doors (or the place where doors should be) are built to ensure visual and physical reach during mounting.
The rig structure is built with beams that are specially designed to hold the different interior elements. This structure is carefully reinforced to be able to cope with several crashes without being deformed or without presenting fatigue problems. However, for a generic rig to be convenient it must also be inexpensive and its building process should be simple and no time consuming (Ramos, 2017).

3.2.2. Current status

Only when the car is almost fully designed the interior components of the sled can be defined and it can be built. Sled tests are actually performed at the same time period than the complete car crashes; when a complete car crash test present some anomaly or a feature that should be furtherly explored, sled tests are performed to explore the anomaly. This way, sled tests are an inexpensive and easier to implement way to analyse the real car behaviour. However, it would be more convenient to perform these sled tests early on the design process before the car is fully designed and for this to be possible, every component of the generic rig should have a comparable response that they would have in a real car.
Nowadays, the response of the IP module on the passenger side of the functional-generic rig is not sufficiently accurate. The model currently used in the IP module on the passenger side in the rig, is compelled by some heavy components that can move back and forward due to a sliding mechanism.
This mobile mechanism weights approximately 85kg, costs around 25000 kr and has damping elements on the back of the plate that allow the plate to perform small rotation in front of different load cases with the knees intercepting the IP in many different angles (Svensson, 2017).
Like stated before, the response of the IP module of the functional-generic rig is not sufficiently accurate on the passenger side, this means that the force imprinted on the dummies knees is not the same force that a dummy suffers during a complete-car collision test. Figure 3.2 shows the differences between the female dummy femur responses with the actual IP model of the functional-generic rig during the crash test, compared with the femur response of a female dummy in a complete-car crash test. In Figure 3.2 can be noticed that, contrary to what happens on a complete-car crash test, in the case of IP model set in the generic rig

the force curve is irregular and the knees seem to intercept the IP module more than once.

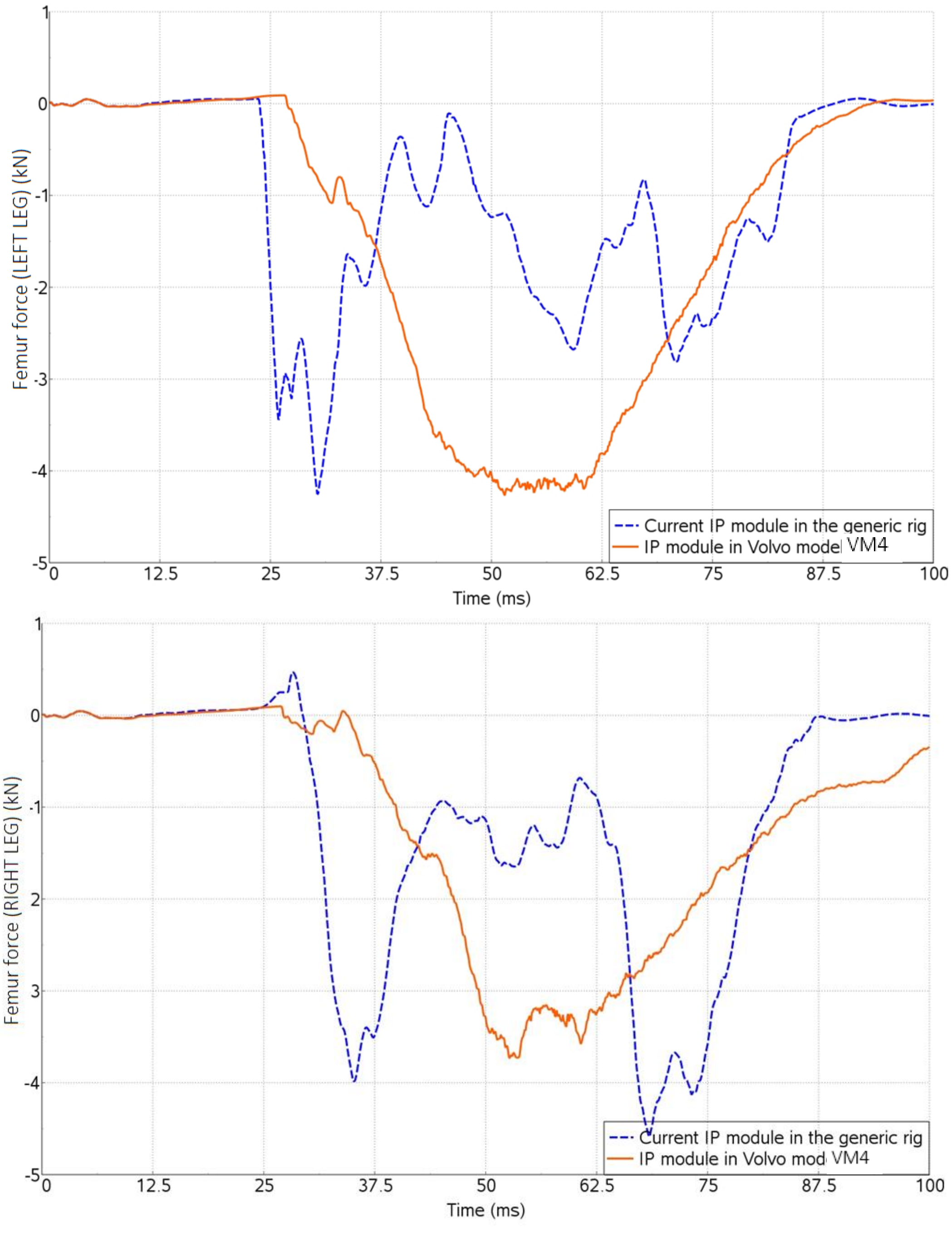


Figure 3.2, Femur force(kN) vs. time (ms) of the model VM4. Female dummy femur´s response in the functional-generic sled using the actual IP model compared with the female dummy femur´s response during an unbelted complete-car crash test.

4. Results

4.1 Product development

The modality chosen for the design process is a design for manufacturing and assembly, this means that the focus was set on fulfilling the main objectives with a design orientated to be manufacturing and assembly friendly.
First, for achieving a complete product definition, the QFD tool was implemented to help to understand the IP module that needed to be designed.
A complete explanation of the QFD tool and the procedure followed to implement it in this thesis can be found in Appendix III.

4.2. Conceptual design

With the QFD complete, after research, brainstorming sessions and consulting with experts, 12 concepts were developed as shown in Figure 4.3 below (A short description of all of them can be found in Appendix IV).
As the figure shows, the concepts can be divided in two "families": dynamic concepts and static concepts.
Dynamic concepts are complex models designed to accompany the movement of the knees when they collide with the IP module. These designs are not supposed to break or deform, and hence, can be re used several times before being disposed.
The static concepts, however, have less pieces and are simpler than the dynamic models. They are designed to severely deform and even break after the knees impact on them and for this reason, after used they should be disposed and replaced.

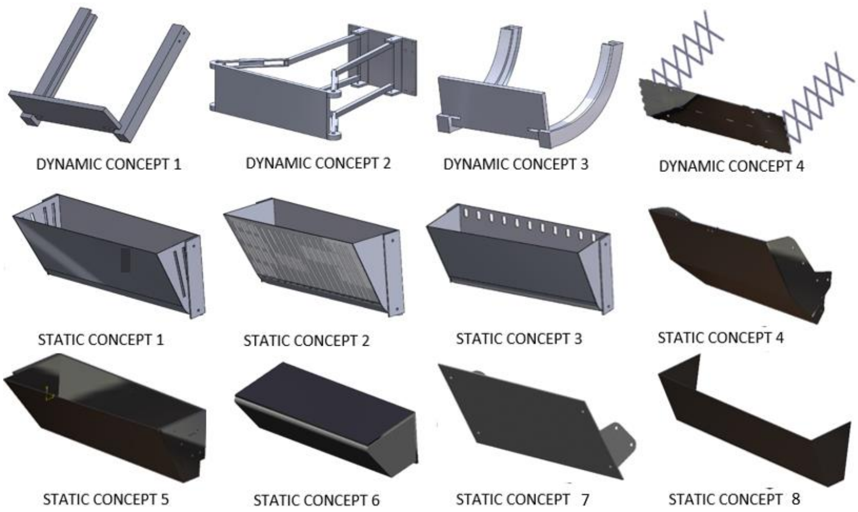


Figure 4.3, concepts developed for further testing. On the top: Dynamic models; on the bottom: Static models

4.3. Concepts evaluation

4.3.1. Decision matrix

For pre-selecting between the 12 created concepts, it was first implemented the decision matrix shown in Figure 4.4.
The comparison criteria chosen for implementing the matrix were a mixture of customers´ requirements and engineering specifications. The weight of the criteria was assigned after consulting with experts.
All the concepts were evaluated, and were assigned points from 1 to 5 depending on how well they met the criteria. After this procedure, all the mobile non-deformable concepts were discarded because in the overall ranking they were the models that got fewest points.

		Concepts											
Criteria	Weight	1	2	3	4	5	6	7	8	9	10	11	12
Robust design	30												
Adaptable to different models and load cases	25												
Little time consumed to manufacture it	20												
Little time consumed to install it	15												
Inexpensive	10												

Figure 4.4, decision matrix implemented for discarding concepts.

4.3.2. Impact simulations

All the concepts were built in CAD software (CATIA and SolidWorks) using the functional generic sled structure CAD model as a reference. Then, the models were pre-processed in ANSA, following the procedure of cleaning the geometry[8], extracting the mid-surface of every shell element and then, meshing.
To be able to use those geometries to perform a simulation to test the different concepts, LS-DYNA file format was used. On the LS-DYNA file, the hole simulation model was built; all the information regarding the general structure of the model was set in a master file (. key) and the specific information was added in using includes (.k), as explained in Appendix V.

[8] Meshing software must deal with problems or imperfections in the model geometry and a geometry cleaning procedure can be needed. Exporting files out of CAD software and into a neutral file format accepted by the meshing software (for example. igs) can introduce misrepresentations in the geometry that need to be corrected. Also, another problem are modelling errors caused by the user in the CAD software (the user may not create ta perfect geometry, causing some parts to overlap, or introduce small gaps between parts that should touch) (Michael L. Brewer, 2008).

For continuing the selection process, the first simulations performed were made with a pair of knees intercepting the IP module designed, with a velocity provided by Volvo which similar to the velocity acquired by the knees during a whole-car collision test. The designs were tested within the IP supports of the functional-generic rig for the passenger side (not the entire rig structure), fastened on the same places where they were supposed to be attached during a rig collision test. Using these simulations many features of the different models were analysed:

- Force imprinted on the dummy´s left and right legs.
- Displacements of the knees
- General deformation of the IP model.

Testing the models using the rig support for the passenger side instead of the entire rig, allows to perform many useful simulations in a short period of time. These types of simulations take approximately 45 minutes whereas the ones using the complete rig can take up to 8 hours.
In this instance, all the models selected after implementing the decision matrix were tested, analysed, improved and then tested again, until the results were useful. Nearly 140 successful simulations were performed and a concept based on the static concept number 5 (from Figure 3) was selected for further development. The model selected and the functional-generic rig support for the passenger side are, in Figure 4.5.
The selected concept has three main parts, shown in Figure 4.6:

1. Frontal panel: The model has a frontal panel made of two different thin steel plates, left and right (a), welded together in the middle. This feature allows the model to have different thicknesses in the left and right sides. On the outside, the frontal panel has a thick layer of foam[9] (b).
2. Supportive structure: This also thin steel structure is welded to the frontal panel, creating with it, a box structure with an open top (c).
3. Back support: The back support is a thick steel structure (d), fastened to the rig in the laterals. This structure connects the supportive structure with the rig. The supportive structure is fastened to the back support with two screws located in the centre of the back support (e).

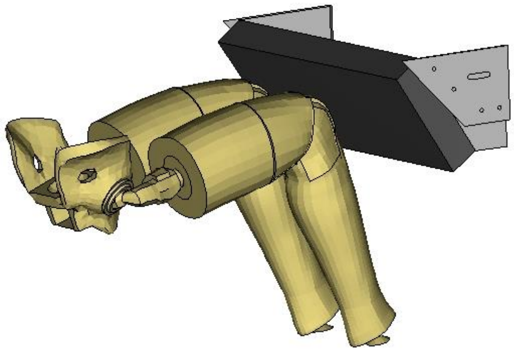


Figure 4.5, concept selected for further development.

[9] Foam: epp foam 30g/l.

The frontal panel weights approximately 20kg and has two different inclination angles on the right and in the left side. These angles differences are intended to mimic the real inclination measured on-cars´ IPs.

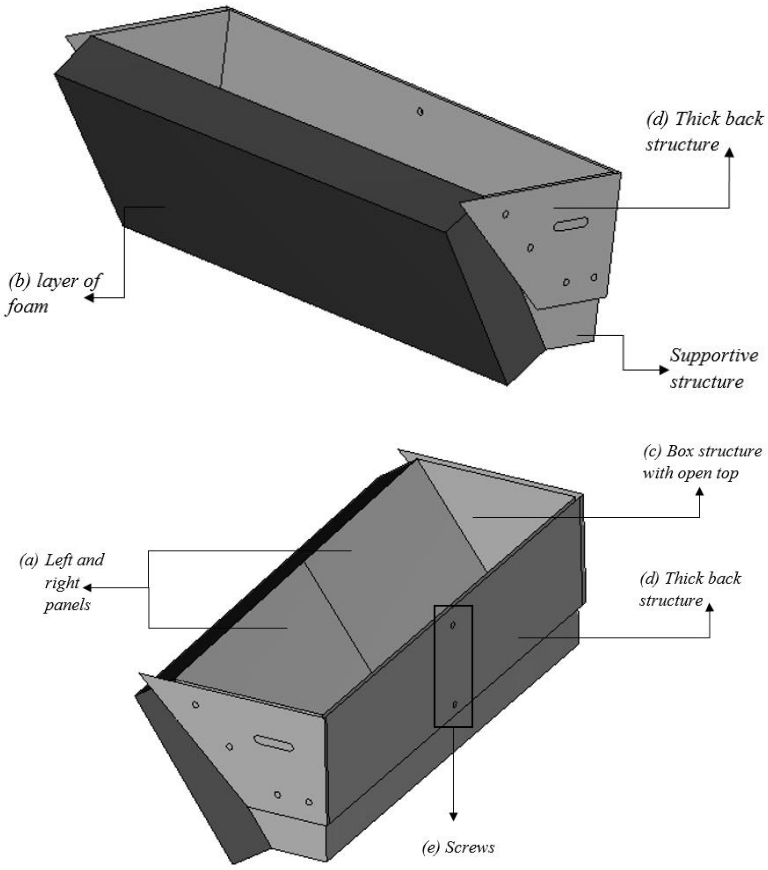


*Figure 4.6, Front and back view showing the different parts of the concept selected for further development***.**

4.4. Product Development

Finally, a parametric analysis was performed to analyse the behaviour of the model after modifying selected parameters with the objective to adapt the design to replicate the behaviour of 6 different car models: VM1, VM2, VM3, VM4, VM5 and VM6, whose main differences and characteristics can be found in Appendix VI.

For a design to be able to replicate the response of a real IP module during a collision test, it should show the same femur force and knees displacement that are in a comparable range.
The parameters chosen to be changed in the selected model to adapt it to the different cars were:

- Thickness of the frontal left plate.
- Thickness of the frontal right plate.
- Thickness of the frontal foam layer.
- Left lateral inclination angle.
- Right lateral inclination angle.

The first three parameters are intended to control the force imprinted on the knees, to try to decrease or increase it according to what is needed. The last two parameters have the purpose of aiming to a certain force spectrum related with the specific shape that a real IP has; as the QFD analysis shown, this parameter is of great importance.
For starting the parametric analysis, four models were then created based on static concept 5 with the objective of analysing the behaviour of the concept when the left and right inclination angles are changed:

- CA (35^o left, 33^o right)
- CB (43^o left, 40^o right)
- CC (49^o left, 40^o right)
- CD (57^o left, 54^o right).

The angles of models CA, CB and CD were selected to match the angles of 3 of the 6 target car models, VM4, VM6 and VM3 respectively. In the targeted models, the difference between the left and right angle is small, between 2^o and 3^o.
Nevertheless, the angles of concept CC were chosen to be between 30^o and 60^o, with a difference between the left and right angle of 9^o. Figure 4.7 shows a physical comparison among CA, CB, CC and CD.
Every one of the newly created models were tested with different thickness in the left and right frontal panel (1, 2, 3, 4 and 5 mm) and with different thickness of foam (6cm, 8cm and 10cm).

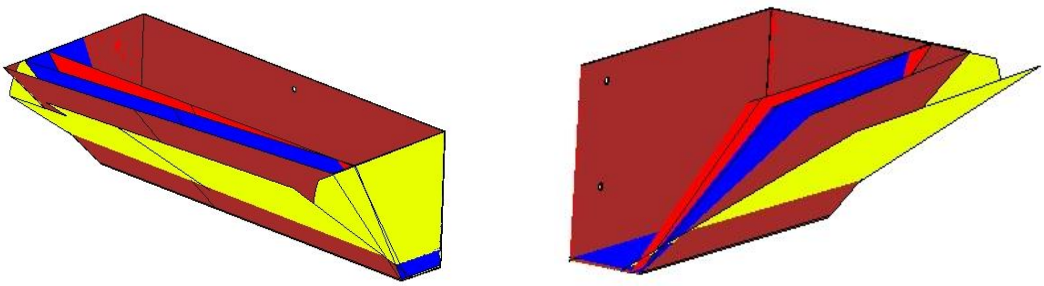


Figure 4.7, physical comparison among models CA (red), CB (blue), CC (brown) and CD (yellow).

4.4.1. Functional generic rig test

After selecting only one concept for development and performing the parametric study, one of the resultant parameters combinations was analysed in a simulation with the entire generic rig, to show if the results were still favourable and similar to those obtained with the simulations using only the rig support for the passenger side. The model chosen for this test was CA with a panel thickness 3mm on the left, 1mm on the right and a foam layer of 6cm (CA_3_1 6 cm Foam). Figure 4.8 shows the IP model in the complete functional generic rig simulation.
In this instance, the knees are not thrown at the IP module with a certain speed but is the entire rig structure who suffers an imprinted acceleration pulse that makes the entire structure move and the knees collide, consequently, in the IP.

a) b)

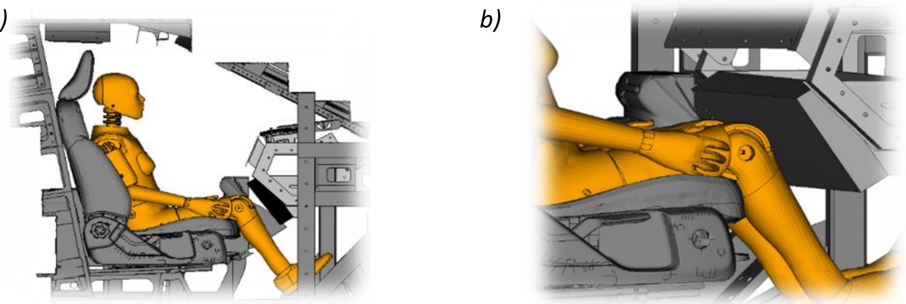


Figure 4.8, a) lateral view of the generic rig structure with the selected IP model installed, b) close view to the designed IP module for the passenger side.

4.5. Results summary

After the knee drop test simulation round, the chosen model to be placed in the functional generic rig and to perform the parametric analysis was the model CA. Model CA is essentially an open-top thin steel box and weights approximately 20 kg. This box has different inclination angles on the left and right side and different thickness on the left and right side of the frontal plate, which is covered with a foam layer (Figures 4.5 and 4.6).
The knee drop test simulations suggested that the selected model is able to adapt to the 6 cars target models. Later, a simulation test using the complete structure of the rig was perform and its outcome shows that the results obtained with the knee drop test are trust worthy.
The selected model fulfilled all the features required in the QFD analysis and is not only able to reproduce the real cars response but is also faster to manufacture and cheaper than the s IP module currently used in the rig. Manufacturing this model for the first time has an approximate cost of 10500 kr, but after the first model is built (and because the thick back support is going to be reused), every

new manufactured model costs about 5500 kr and consumes less than 24 hs of labour.

Thickness (mm)		Max. Force	
Left panel	Right panel	Left knee	Right knee
1	3	4,2	5,4
1	4	4,2	5,9
1	5	4,2	6,6
2	1	5,2	4,2
2	2	5,0	4,8
2	3	5,0	4,7
2	4	5,0	5,9
3	1	5,5	3,9
3	2	5,4	4,6
3	3	5,5	5,4
3	4	5,5	5,8
4	1	6,0	3,9
4	2	6,0	4,6
4	3	6,0	5,2
4	4	6,1	5,9
5	5	7,0	6,6

Table 4.1, forces on the knees obtained after variating the thickness of both sides of the frontal panel in the model CA.

Table 4.1 shows the maximum forces obtained for the left and right legs, for every variation of the thickness in the frontal panel of concept CA, using a 6cm foam layer. The tendency of those results indicates that increasing the thickness of the left panel increases the force on the left knee and increasing the thickness on the right panel increases the force on the right knee.
Results with thickness 1_1 and 1_2 were excluded from the table because it seems to be a minimum threshold thickness after which the knees response doesn´t follow the tendency explained above. The results shown in the table can be slightly adjusted adding 2 more centimetres of foam, this can decrease the force magnitude in about a quarter of kN. In Appendix VI can be seen the force results obtained with different variations of concept CA compared with each of the 6 cars targets. There, can be also observed that he knees displacements obtained using the concept CA have similar values to the ones obtained in the 6 cars target models.

4.6 Discussion

The first selection process, the decision matrix, showed that dynamic models are expensive and complicated. The have more pieces which can make them less robust, more time consuming and more expensive than the static models. Moreover, their behaviour is more difficult to predict and control due to the interaction of a large number of pieces.
Having the dynamic models discarded, the focus of the drop knees simulations was first, to find a model (or models) that show knee forces in the interval of forces obtained with a complete car with a real IP module; and second, find a model where the knees intercept the IP module only once.
Nevertheless, before selecting a definitive model, some important conclusions were elicited from the knee drop simulations analysis:

- The most "problematic" knee is the left one. The left knee impacts first and absorbs the first impact which is more drastic than the one absorbed by the right leg, it is convenient to use a frontal panel with a different thickness for the left and right side.
- The model should be as deformable as possible. Rigidity is a feature that should be avoided in the model itself but also in the attachment to the generic rig. The generic rig is a stiff structure and if the model is overly attached to it, the forces on the knees will increase. For exploring the effects of rigidity on the design of a new IP module, static concept 4 was analysed with a frontal panel of 2 mm.
  First, the model was built and tested with the knee drop simulation, using the features stated in Appendix IV, which is a frontal panel allowed to rotate, like a glove box door, and attached on the top to a supportive back beam (Figure 4.9, a). Second, the model was modified removing the back beam and adding a supportive back structure like shown in Figure 4.9, b. This second version of the model was also tested and the results of both versions were compared.
  The knee force vs. time can be found in Figure 4.10. This figure suggests that increasing the model rigidity by adding a supportive back structure leads to an augment on the force imprinted on the knees without modifying the frontal panel thickness and this resultant force is approximately 4 kN higher than the higher force obtained in any of the car target models.

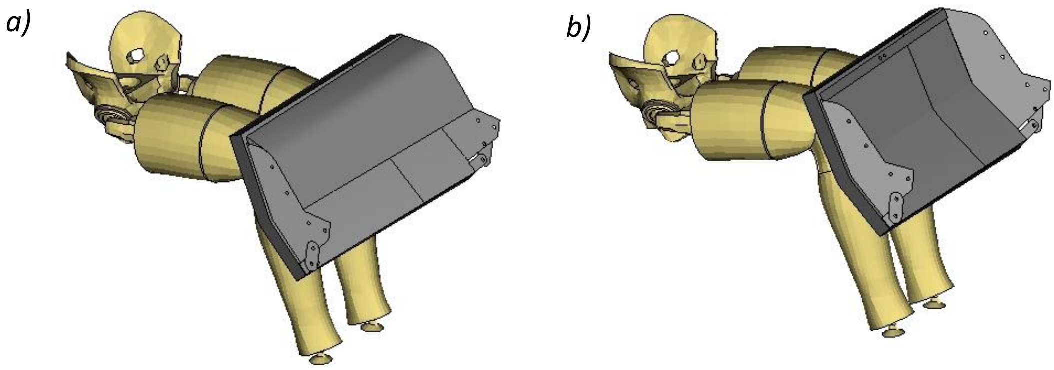


Figure 4.9, static model 4 tested to acknowledge the effects of rigidity. a) Original model, b) Modified model to be more rigid.

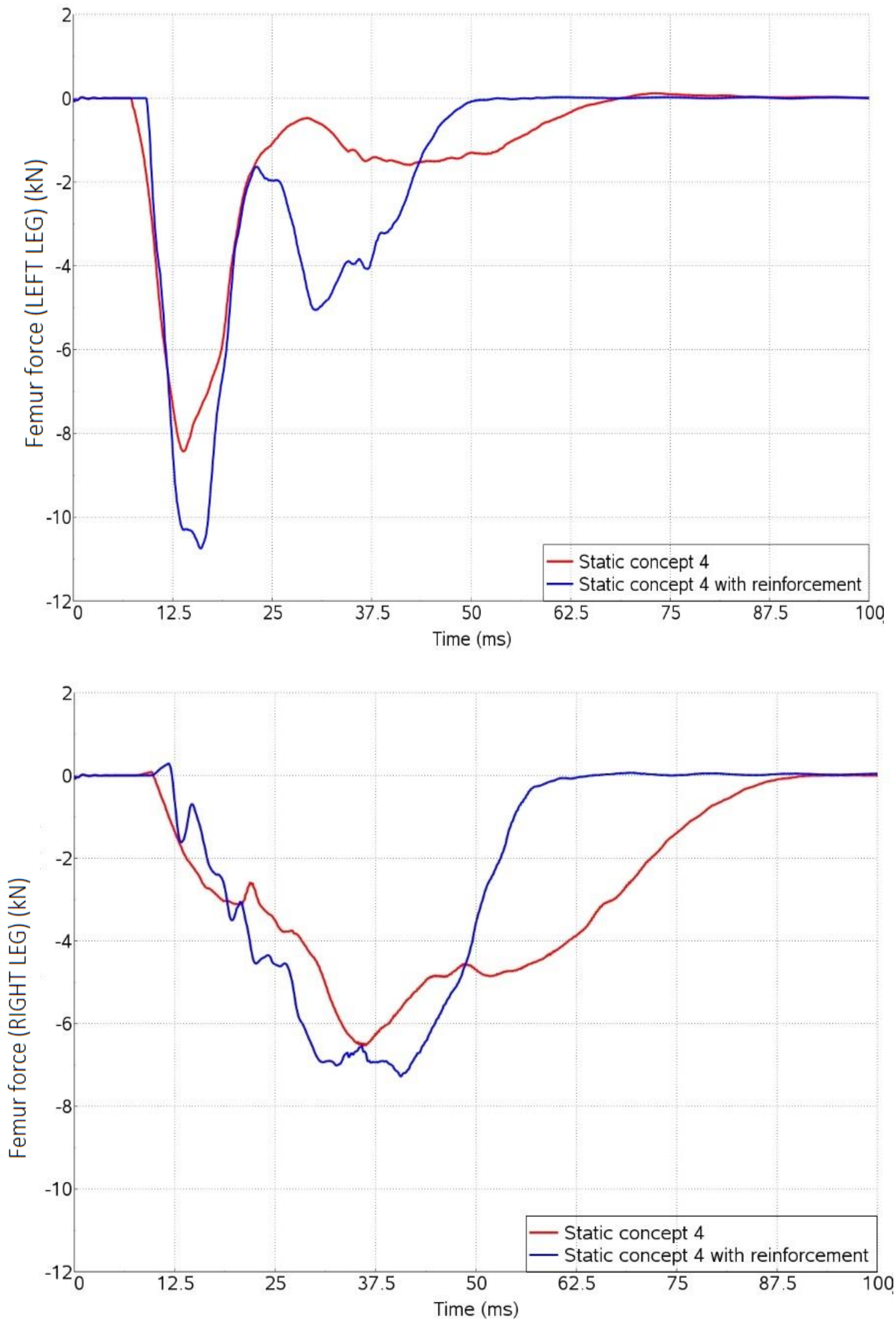


Figure 4.10, knee forces vs. time obtained for the static concept 4 and the modified, more rigid, version of that same model.

- The models that shown the best results were those that have a structure similar to a real globe box; this means a box-like structure with the frontal panel inclined with different angles in the left and right side.

From the parametric analysis performed on the static concept 5 (Figures 4.5 and 4.6), the most important conclusions are:

- Analysing CA, CB, CC and CD it was not observed any force tendency regarding the angle variation. The results among those concepts are different but it would be necessary to make more models with different angles to be able to come to a conclusion on this matter. The graphs for femur force vs. time for comparing models CA, CB, CC and CD with different frontal panel thickness can be found in Appendix VII.
- If steel is going to be used for building the model, is necessary to set an energy absorbent material on top of it, for example, foam. The simulations results suggest a minimum of 6cm foam to decrease the force on the knees. Using thinner foam the forces on the knees are not only too high but the force vs. time curves are irregular with many different peaks (Figure 4.11). Nevertheless, using foam that is too thick (10cm or more) has been proven to be sometimes counterproductive and actually increase the impact on the knees. The optimal foam thickness seems to be between 6cmm and 8cm, as Figure 4.12 and Figure 4.13 suggest.
- Even if the optimal foam thickness is between 6cm and 8cm, the difference measured in the knee force is only around a quarter of kN. From these results can be inferred that the election between 6 or 8cm of foam is not critical but it can be used to refine the results and adjust them more to the target models.
- Variating the thickness of the left and right panels a wide spectrum of forces can be reached with concept CA, approximately from 4 to 7 kN for each leg. In Figure 4.14 is shown the femur force vs. time for different thicknesses of model CA, there, the curves follow a tendency and when the overall thickness is decreased, the femur force decrease as well. Nevertheless, Figure 4.14 also suggest that results are more or less unpredictable under what seems to be a minimum threshold panel thickness around CA_1_1 6cm Foam and CA_1_2 6cm Foam.

The results from the functional generic rig simulation test shown that:

- The knees intercept the IP module only once, differentiating these results from the ones obtained with currently used IP model.
- The force imprinted on the knees using the model CA_3_1 6 cm Foam, is similar in magnitude to the force observed in a frontal collision test with the car model VM4. These results are shown in Figure 4.15.
- The results obtained in the simulation with the complete generic rig are comparable with the ones obtained with the knee drop test that used only the passenger side IP module rig support.

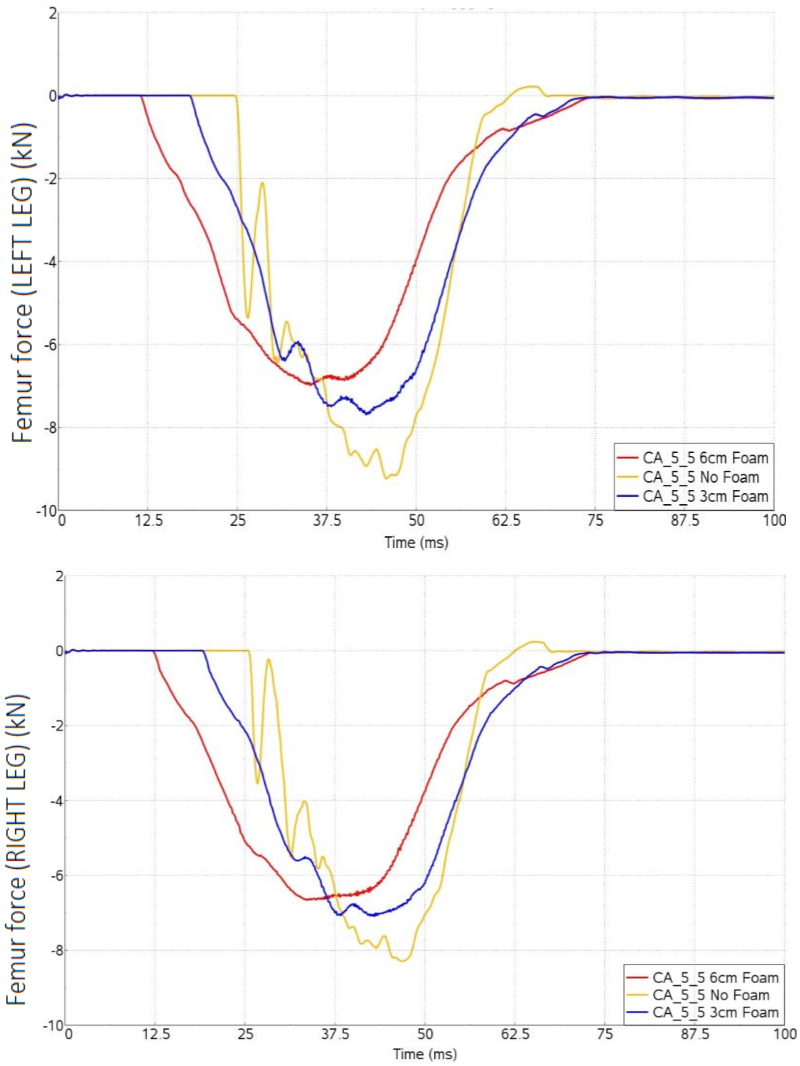


Figure 4.11, concept CA with a frontal panel of 5mm in both sides with 6cm foam, 3cm foam and no foam. It can be appreciated how the curves become smother when increasing the foam thickness.

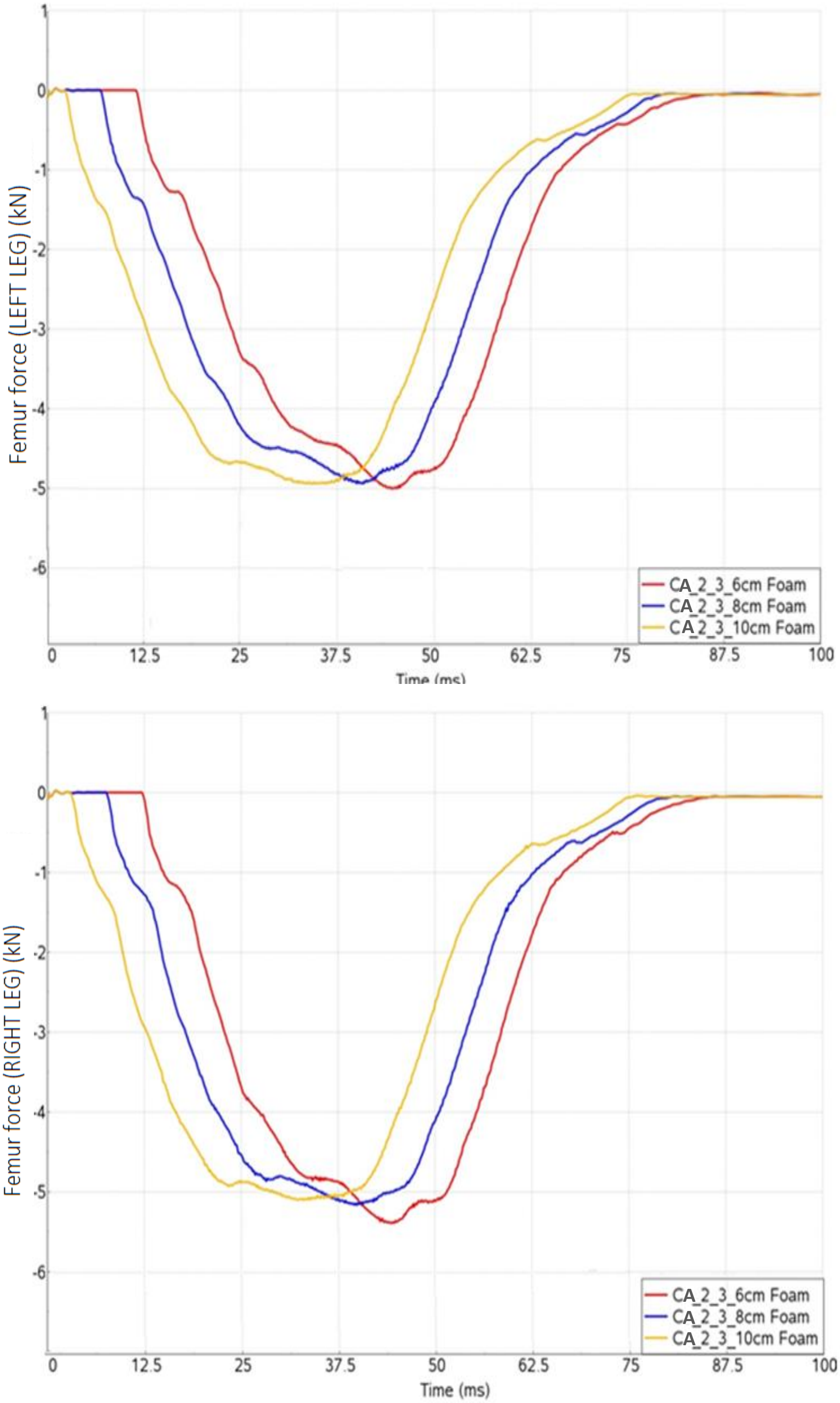


Figure 4.12, example illustrating how the force on the dummy´s knees changes when adding a 8cm foam layer instead of a 6cm layer. Nevertheless, there is almost no change observed between 8cm and 10 cm of foam.

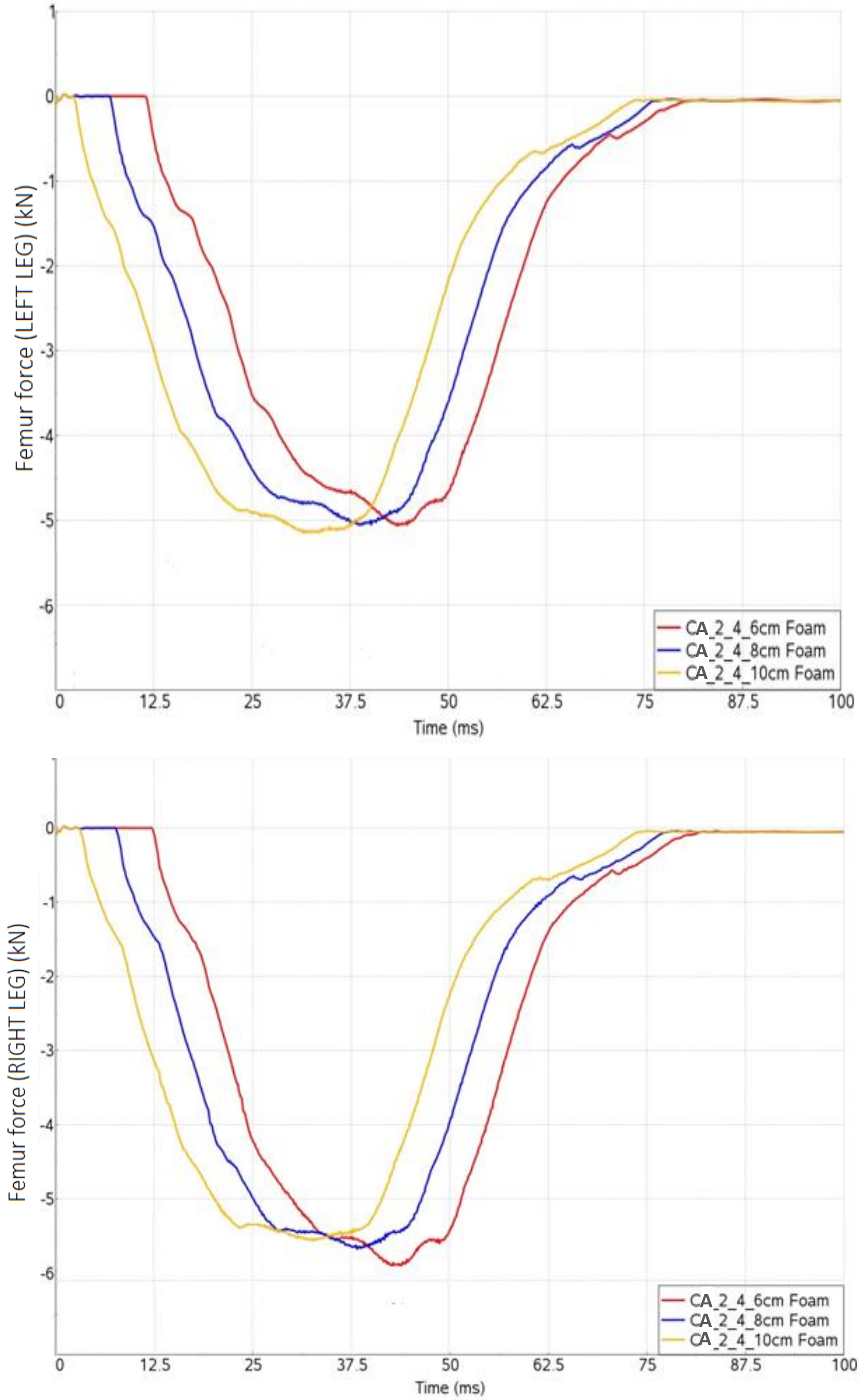


Figure 4.13, example of how sometimes can be counterproductive the utilization of a foam layer thicker than 8cm to diminish the force on the dummy´s knees.

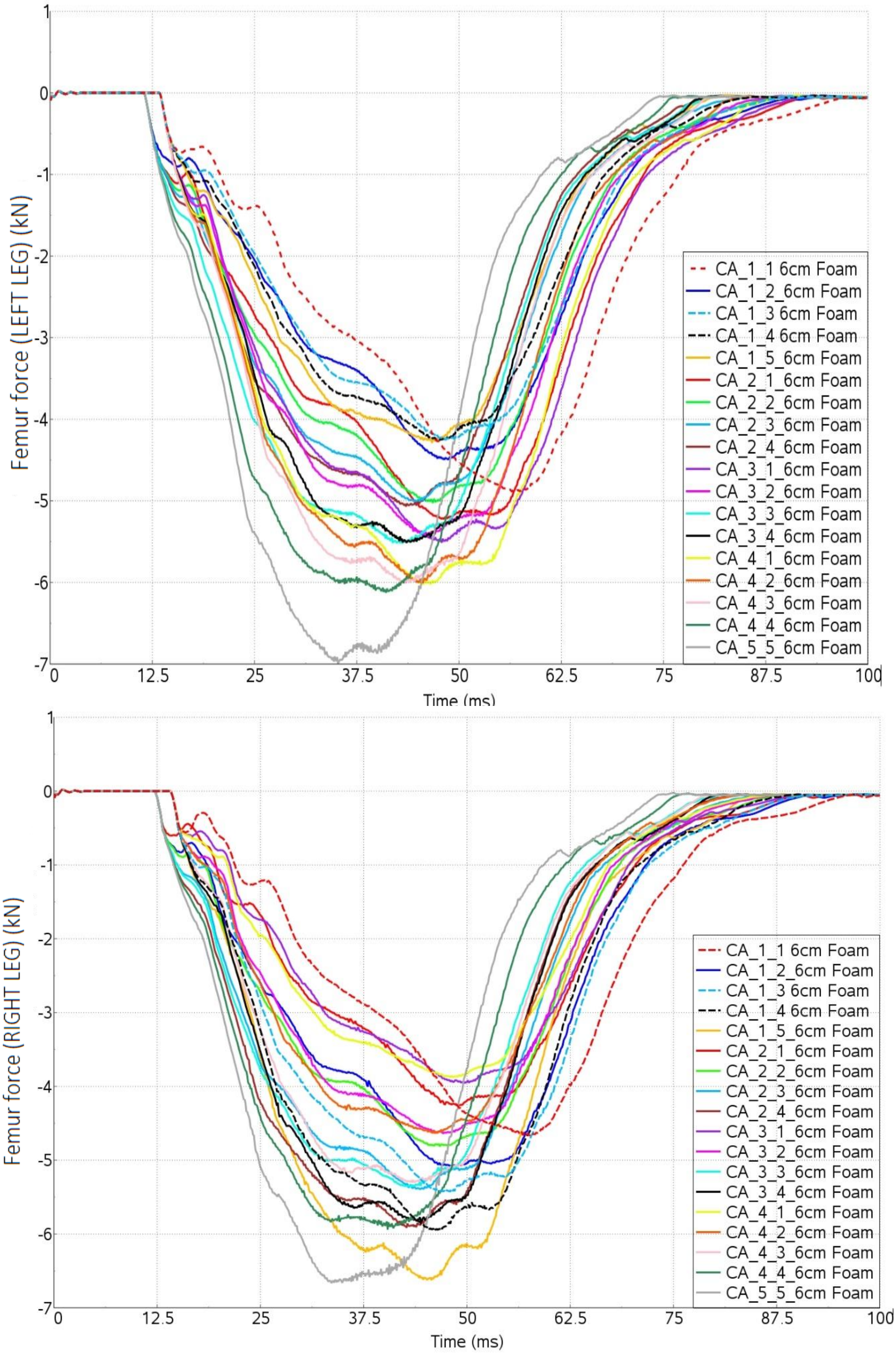


Figure 4.14, different forces obtained when variating the thickness of the left and right panels for concept CA.

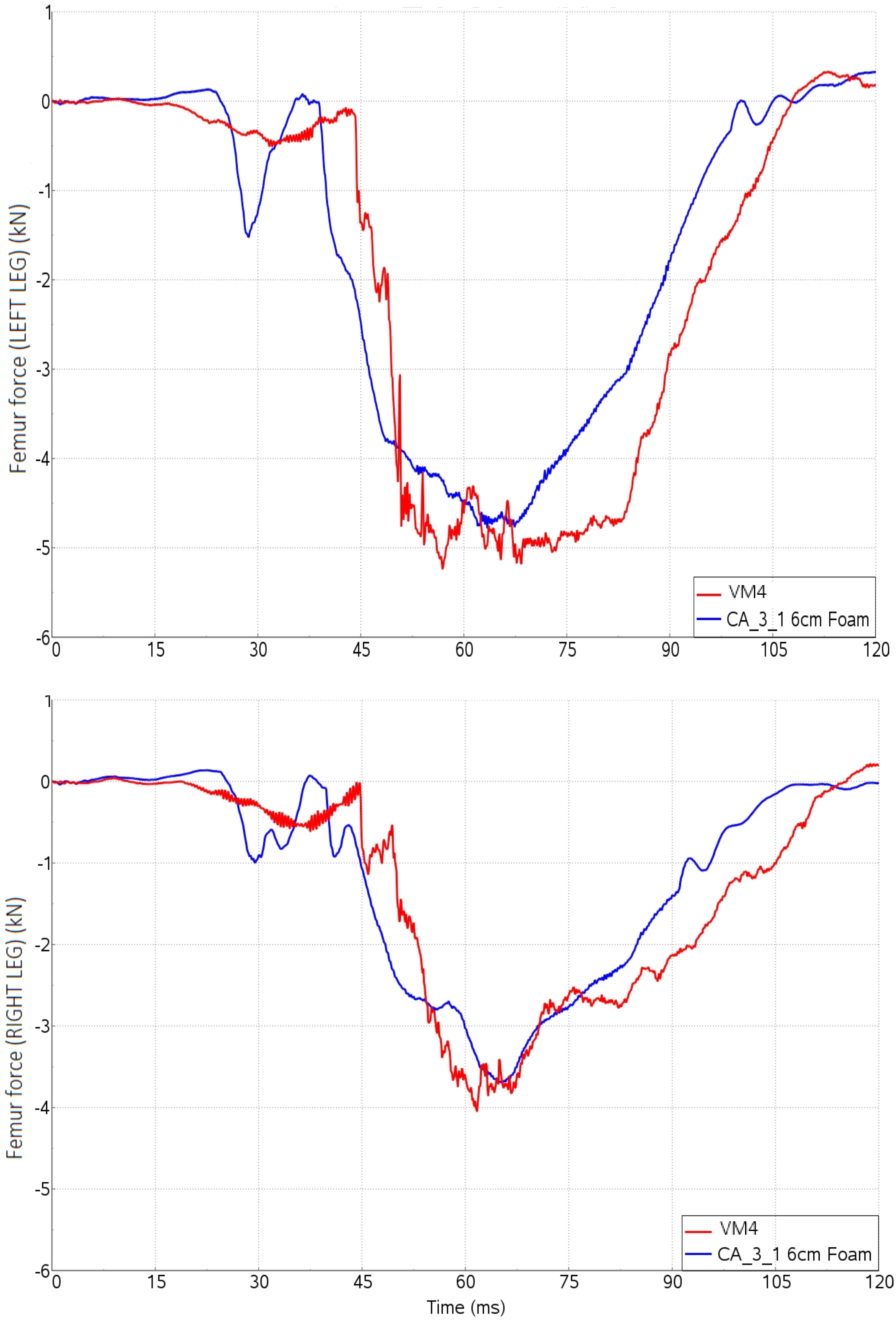


Figure 4.15, results from the functional generic rig simulation tests using the model CA_3_1_6cm Foam. The results are compared with the ones obtained in a frontal collision test of the car model VM4.

5. Conclusion

5.1. Conclusions

During this thesis project, the main objective was to redesign an IP module for being used in the functional generic rig during a frontal unbelted collision test. This model should replicate the behaviour of an IP module from a real car during a crash test (regarding legs response) and it should also be generic and able to adapt to different car models. Six different car models were selected to be the target models to be compared to our designed model.
Following Ullman´s mechanical design process theory and using CAE, we were able to design a model than can successfully adapt to the six target models variating only the thickness of the frontal left and right panels and adjusting the results adding a layer of foam to absorb the first knees impact. The model, called CA, is composed of a thin steel open-top box fastened in the back to a thick steel structure that embraces the thin steel box and connects with the rig in the laterals, as Figure 9 previously shown. The frontal panel of the box, is made of two panels, left and right, that have different thickness and that are covered by a layer of foam with adjustable thickness. Moreover, the lateral left and right inclination angles measured from the vertical are 35º and 33º respectively, to mimic the frontal shape of a car IP.
The first conclusion elicited from this analysis is that is more convenient if the model is as simple and as similar to a globe box as possible. The model CA was made to resemble a globe box and is made with few pieces and materials that can be found at any time in Volvo´s facilities; these characteristics make it simple, inexpensive and fast to manufacture. The total price for producing this model is, the first time, 10500 kr and then 5500 kr for every generic rig crash test and the model can be manufactured in less than 24 hours.
Secondly, in this case rigidity has been proved to be counterproductive increasing the force imprinted on the knees and for that reason, model CA is a thin structure attached to the back structure in the back with only two screws. This attachment allows the box to have a higher degree of deformation, showing better results. Simulation tests suggest that the optimal foam thickness is 6 cm, that can be adjusted if needed to 8cm to refine the results. Nevertheless, decreasing or increasing the foam layer thickness outside the stated values is not convenient and leads, in both cases, to an increased force on the dummy´s knees.
Finally, variating the thickness of left and right frontal panels on the model CA, we were able to cover a wide spectrum of force imprinted on the knees that goes approximately from 4kN to 7 kN in both knees. With these results, we could satisfactorily reproduce the force response of the six car target models and obtain knee displacements that have the same degree of magnitude that the ones obtained in the target models also.

5.2. Recommendation for future activities

For furtherly understand the behaviour and features of the model selected for being used in the generic rig, a deeper study variating the lateral inclination angles is first suggested. In this thesis, 4 different models were made with this purpose (CA, CB, CC and CD) but the results show that four models are not enough to find a behaviour tendency and elicit useful conclusions.
Second, in the study performed in this thesis, the thin supportive structure that holds the frontal panel of the selected model has a fixed thickness of 3mm and for further research it would be interesting to observe the effect of modifying this parameter also.
Third, the thickness of the left and right side of the frontal panel have been increased up to 5mm in the left side and 5 mm in the right side. In the future, exploring the thickness combinations around 5mm is recommended, for example: 1mm left and 5mm right, 2mm left and 5mm right, 5mm left and 1mm right, 5mm left and 2 mm right, etc.
Another thing that could not be done under the thesis period is an exhaustive study about the stresses and deformations that the functional generic rig suffers when implementing model CA. This study would help acknowledge the life cycle of the rig when using the design model.
Moreover, the reaction and interaction of the IP module with other components on the cockpit could be interesting to investigate, the same way as considering friction between the knees and the IP module.
Finally, building a prototype of the model would take this research to the next level to see how does the model behaves in a real set up and if the results are the same obtained during the simulations. This stage would be useful also so acknowledge the real production cost and the real time consumed for manufacture and setting the model on the generic rig.

6. Critical review

The project originated mainly from David Ullman's method Mechanical Design Process. The main facts in the theoretical frame (automotive industry terminology) mainly were done by interviewing of car engineering experts, because there is no such a book or information available in the public libraries. The project was to find the best solution for the functional generic rig, and according all simulation result, the task was done successfully.

From the begging of the project it was challenging to get know automotive industry without being familiar with it before. But this experience open new opportunities for getting familiar with the car industry and software's like ANSA, META, LS-DYNA, which were very stimulating and beneficial for the project.

From an ecological point of view, the designed construction is made from steal and foam. Both materials are recyclable and does not affect much on the environment.

According Volvo Cars manufacturing department the product fulfills economical requirements being as inexpensive as it is, bear in mind that the prices presented in this thesis were calculated considering materials and also working hours and services. To lower the prices even more, batches with 10 or more products can be made and for this situation it is convenient to plan ahead how many crash tests are going to be done.

Moreover, the design presented on this thesis makes possible to accurately use the functional generic rig to analyze a car collision test. Being able to analyze a collision test using a structure like the rig, makes the whole crash-test process extremely more inexpensive because crashing a full-scale car is evidently much more expensive than crashing a steel-beams structure.

From the ecological point of view, the designed construction can be considered to have low ecological impact. As already stated, the product is made mainly from steal but even if the production of steel has a considerable impact on the environment (carbon dioxide emissions mainly from coal) this material has the benefit of being able to be recycled and be also a long-lasting material (Steel_Institute, 2017).

Finally, even if the work on this thesis is not directly related with occupational health and safety aspects (because it is focused on the simplified IP module to be installed in the generic rig) this types of improvements on the rig pieces helps the whole Volvo structure to keep the focus in safety matters, and maintain the excellence that characterizes that company.

APPENDIX I - Gantt chart

The Gantt chart that is used to illustrate a plan, schedule for a project. It is one of the methods widely used for project planning. The diagram consists of bands oriented along the time axis. Each bar in the diagram represents a separate task as part of the project (type of work), its ends are the moments of beginning and completion of work, its length is the duration of the work. The vertical axis of the diagram is the list of tasks. In addition, the chart can indicate aggregate tasks, completion percentages, sequence and work dependency indicators, key moment marks (milestones), today's time stamp, etc (Wilson, 2002). The Gantt chart used to plan this thesis project is shown below in Figure A1.

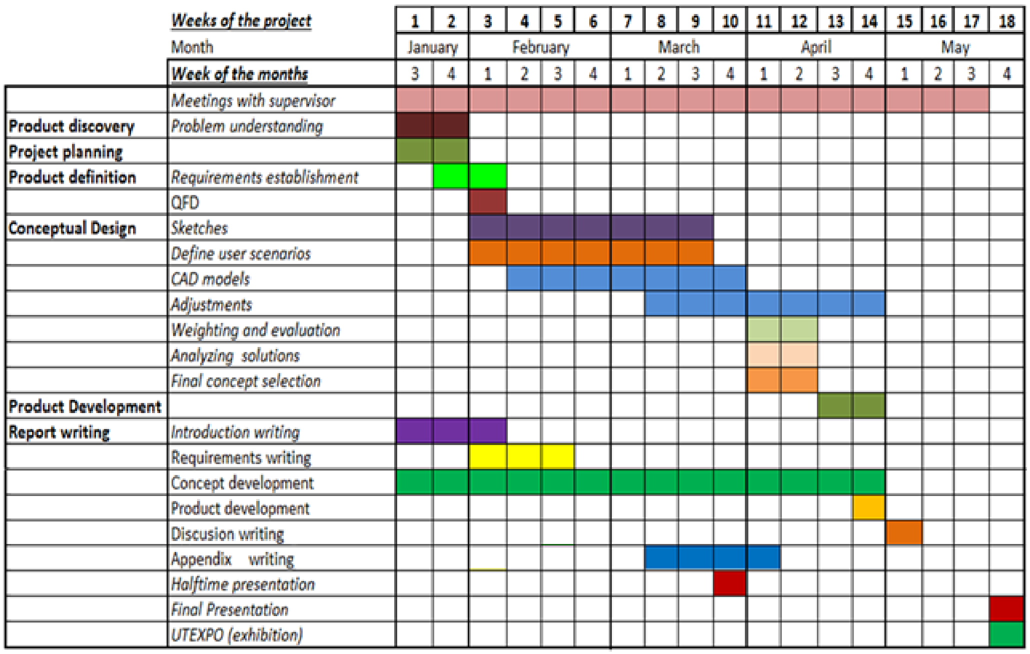


Figure A1, Gantt chart used for the development of this thesis project.

APPENDIX II – Product design and Ullman´s theory

History of product design

Product development is a process that combines people and their knowledge, tools and skills for the development of a new creation. This process contains economic expenses and time. The final product should satisfy the customers' requirements to be considered a quality product.
Earlier, one person could design and manufacture a whole product, even for a large project, such as design of the bridge or a ship. This person had enough knowledge of physics, materials and manufacturing processes to control all characteristics of the design and construction of the project. But by the mid-twentieth century, products and production processes became so complex that one person no longer had sufficient knowledge or the time to cope with the project. Therefore, the tasks were divided and there was a group of people who was responsible for different aspects of the. This evolution has led to the design process called "over-the-wall" (Ullman, The mechanical design process, 2010).

Figure A2, Testing of a bridge over the Ob River in Novosibirsk,1987.

Unfortunately, this method was not suited to customer requirements, since the design engineers were limited with communication with marketers, they could not understand a clear picture of customers´ needs.
Approximately hundred years ago, to test that a final manufactured product fulfilled all quality standards some tests were performed where engineers who were responsible could even die. A famous case is the first railway bridge across the Ob River, in 1897 Novosibirsk, Russia. The day of the first trials of the bridge, on the bridge were located four locomotives with 51.5 tons in total and under the bridge were the builders and engineers, that built the bridge, as shown in Figure A2 (RIANovosti, 2013).
Crash tests were implemented in Europe to test cars´ safety and Volvo was one of the companies who got first involved in them. The first crash test was done in 1959, where Volvo engineers were doing research of effectiveness of using a

three-point seat belts. This occasion lead to creation of a special research department in the company called Accident Research Team. Already in 1970, experts of this department had contact with the police and were doing research in every car accident analyzing each situation, they were looking for not only the causes of the accident, but also the technical possibilities to reduce its effects.
In the beginning, in addition to researching about car accidents, in Volvo's were also performed different impact tests: by dropping the classic model "240" from the height of the frontal part down and on the roof of the models "740", "850" and "940" were placed the tilted wagons. After many years of experiments with the pressure on the roof of all models in the US market were included in the standard procedures of US crash tests (SubaruCenter, 2016).

Case studies/Applications of Ullman´s theory

Ullman´s theory for mechanical design process has been applied several times since his book has been released in 1991.
During the manufacturing test development process at Cisco, students from the Master of engineering and Master of Business in the Massachusetts Institute of Technology (MIT) focused on the *Project Planning* phase and built a Design Structure Matrix used to first understand the new product development process and then to organize the tasks necessary to complete a project and also which tasks depend on which tasks (Go, 2007).
Intertal Polymer Group in 1997 implemented interviews and focus groups for gathering information about the voice of the customer and begun using the QFD during their *Product Definition* phase developing a heat activated tape product basing their target and threshold values in a technical competitive benchmark study (Rawlings-Quinn, 1997).
When BMW initiated the development of the drivetrain for the ActiveHybrid 5, during the *Conceptual Design* stage they used morphological matrices to help map the fundamental relationships among and between hybrid functions and components, the tool helped analysing the different possible architectures in a standardized way, in what already was a large field of design possibilities (Ullman, Designing a Hybrid car at BMW, 2014).
In manned space exploration is mandatory to have a reliable Portable Life Support System (PLSS) to provide to the astronauts all the functions needed to be alive and comfortable in a spacewalk. The primary challenges in designing the Advanced PLSS is to integrate evolving technologies that are not fully mature in a compact envelope to be used as a backpack. For accomplishing this purpose, during the *Conceptual Design* phase NASA uses a series of prototypes to refine the system and the sub systems simultaneously and uses a Technology Readiness Level scale to communicate technology maturity. It is a good example of the use of prototypes and of technology readiness (Carly Watts, 2012).
Ullman also states that the design process must consider the entire life cycle of the product focusing on the environmental impact of the process. Steelcase, which is leader in supplying workspace products has a history of doing the right thing for

customers, neighbours, and employees and developed a Life Cycle Assessment (LCA) technique to identify environmental impacts associated with the different stages of the product life. Using the LCA, they ended up using Ecovative as a provider of biodegradable packaging made with agri-waste and mushrooms (Bayer, 2010) (Harrington, 2011).
Like the cases stated above, Ullman´s theory have been also used at the Russian space program where engineers used TRIZ in the design of a lamp for the Luna 16 lunar lander (OxfordCreativity, 2016) or at Motorola Solutions that uses benchmarking and the Design for Assembly techniques for designing mobile radios, handheld RFID readers, multimedia micro kiosks and many other products (BoothroydCosting, 2017).

APPENDIX III - The QFD tool

Description of the QFD tool

The Quality Function Deployment (QFD) is a structured element used to define customer requirements (needs) and to translate them into specific plans to produce a product that would meet those needs (DRMAssociates, 2016).
According to Ullman, the eight steps to generate a QFD are:

- Identify the customers: Identify all the customers along the product life cycle, do not consider only the final consumer.
- Determine the customers 'requirements: Using methods like observation, surveys or focus groups the voice of the customer must be attended and from it, information about customers´ requirements can be gathered. With this information, must be elaborated a list, in positive terms, with all the requirements.
- Determine relative importance of the requirements: Sometimes, not all the requirements are possible or convenient to fulfil and in order to prioritize the most important ones the relative importance of every of them must be acknowledged. To accomplish this, a very effective method is a survey using a "fixed sum method" where each customer is asked to distribute 100 (or any other number) points among the requirements. From analysing all the surveys´ results, the relative weight of every requirement can be obtained. Basic requirements should not be weighted because they are considered mandatory.
- Identify and evaluate the competition: The competitors must be identified and it must be determined how well they fulfil the customers´ requirements and how satisfied customers are with them. For the QFD, the existing design of the competitors can be evaluated in scale (from 1 to 5, for example) considering how well (or not) their product meet the customers´ requirements.
- Generate engineering specifications: From the customers´ requirements, the engineering specifications list must be made in terms of parameters

that can be measured and that have target and threshold values. As many engineering specifications as possible, must be found. In the QFD they must be listed with their measurement units and the "direction" of improvement (whether more is better or less is better) or specific required value.

- Relate customers´ requirements to engineering specifications: It must be indicated for every engineering specification (using a convenient scale) the level of achievement of each customers´ requirement. Ideally, each engineering specification will be related to more than one customers´ requirement.
- Set engineering specification targets and importance: The importance of each engineering specification must be established to know where to put the efforts for improvements; to do this, for every engineering specification the weights assigned in step 3 (for each customers 'requirement) must be multiplied by the level of achievement of the specification from step 6. The results will be the terms (one term for each customers´ requirement) of the sum for determining the importance of a certain engineering specification. Then, the results of the importance of every specification must be normalized with the other specifications (This will be clarified in question 3 where a QFD is built). After determining relative importance, is measured how the competition meet the specifications. To do this the competitors' product should be measured and analysed but if this is not possible, simulations or research can be implemented. Finally, target and threshold values must be established for each engineering requirement, this information can be partially obtained from the previous step researching the competitors.
- Identify relationships between engineering specifications: Is important to identify the possible dependencies between engineering specifications, these dependencies are marked in the QFD with + and – signs (or green and red dots in question number 3). The + sign (or green dot) means that meeting one of the engineering specifications will improve the other; the – (or red dot) means that meeting one specification will harm or compromise the other (Ullman, The mechanical design process, 2010).

How the QFD was implemented in this thesis

1. **Customers and customers´ requirements**

Identifying customers

This design project needs to satisfy some different customers´ groups; the customers for the IP module of the functional generic sled were considered to be:

- Functional generic rig´s sled technicians, in charge of assembling the IP module on the functional generic sled and monitor the collision test.
- Functional generic rig´s IP module building technicians, in charge of building the IP module to be used on the generic sled.
- Restrains division, they are in charge of presenting a IP model that satisfies certain design needs with an inexpensive price.

Customers´ requirements

Using focus groups and interviews it was possible to gather customers´ requirements that would satisfy the demands of the different customers 'groups. Then, all the requirements were prioritized using focus groups and brainstorming sessions using the fixed sum method[10], the results are shown in the list below:

- Can fit on the sled´s IP passenger side (20)
- Robust design (20)
- Adaptable to different car models (15)
- Inexpensive to build (5)
- For building it, using materials present at Volvo Car´s facilities (5)
- Easy to install (5)
- Easy to build (5)
- Reproduce the response of an IP of a complete car crash test (20)
- As light as possible (5)

2. Engineering specifications

To fulfil the customers´ requirements a list of engineering specifications was created. As table A1 shows, for every specification, a target and threshold value were established, these values were obtained from interviews to experienced designer engineers and from benchmarking from the previous IP module of the functional generic sled:

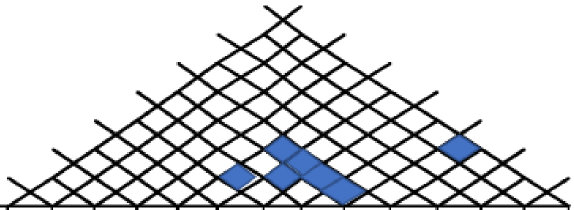
Engineering specifications	Target value	Threshold value
Length (mm)	200	>200
Depth (mm)	250	>640
Width (mm)	600	>600

Table A1, engineering specifications with its corresponding target and threshold values for designing the IP module to be used the generic rig during a frontal collision test.

[10] In the fixed sum method, the participants are asked to allocate a total of 100 points among all the options, the result is a, in this case, customers´ requirements list that is weighted and ordered showing the most and least important requirements (Ullman, The mechanical design process, 2010).

Inclination of the front surface (γ)	Model dependent	Model dependent
Weight (kg)	<80	90
Displacements of the dummies knees (cm)	Model dependent	Model dependent
Force imprinted on the dummies knees (kN)	4-6	<4 - >6
Number of steps to build it	<15	15
Time spent to build it (min)	120	300
Number of steps to install it	<10	10
Time spent to install it (min)	30	60
Number of pieces	<10	20
Materials cost (SEK)	<15000	15000

Whit this information, the relations between the requirements were established ("roof" of the QFD "house"), the customers´ requirements were related with the engineering specifications (showing the degree of relationship with numbers from 1 to 3) and the importance of every specification was calculated using the procedure previously explained. The QFD house used for this project can be seen in Figure A3.

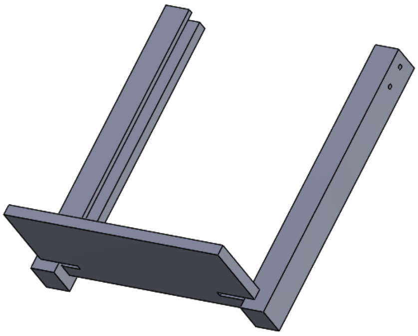


		Length	Depth	Width	Materials cost	Time spent to install it	Time spent to build it	Number of steps to install it	Number of steps to build it	Number of pieces	Displacements of the knees	Force imprinted on the knees	Inclination of the frontal surface	Weight	Previous model´s customers´ requirements fullfilment
					↓	↓	↓	↓	↓	↓					
		mm	mm	mm	sek	min	min	-	-		cm	N	θ	kg	
Should fit on the sled´s IP passenger place	20	3	3	3									3		▲▲▲
Robust design	20									2				2	▲▲▲
Adaptable to different models	15	3	3	3									3	2	▲▲▲
Inexpensive	5				3	1	1								▲▲
Using materials present at Volvo car´s offices	5				3		3		1						▲▲▲
Easy to install	5					3		3		1					▲▲
Easy to build	5						3		3	2					▲
Reproduce the response of a real car crash test	20	1	1	1							3	3	2		▲
As light as possible	5													3	▲
Importance		125	125	125	30	20	40	15	20	15	60	60	145	85	
Rel. Importance.		14	14	14	3,5	2,3	4,62	1,7	2,3	1,7	6,94	6,9	17	9,8	
Previous model		200	400	600							-	8	-	85	
Target		200	250	600	<15k	30	120	<10	<15	<10	-	6	-	<85	
Threshold		>200	>640	>600	15k	60	300	10	15	20	-	8	-	90	

Figure A3, QFD used for this master thesis.

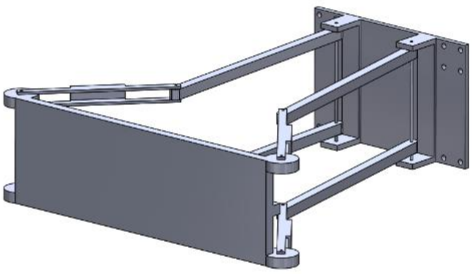
APPENDIX IV - Lists of concepts developed

Dynamic concept 1



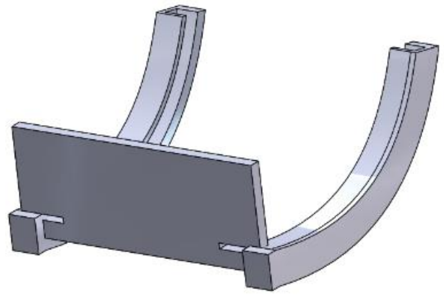
This concept is a sliding frontal plate. The front panel under the impact of the knees would slide upwards using a guide inclined at an angle of 45 degrees.

Dynamic concept 2



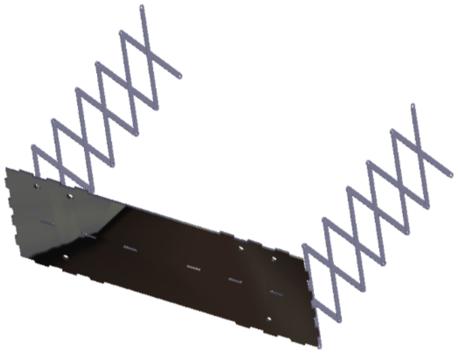
This model is a metal plate with 4 articulate arms attached to que back of the rig. Those arms bend and move back and forward to allow different load cases when knees intercepting in different angles.

Dynamic concept 3



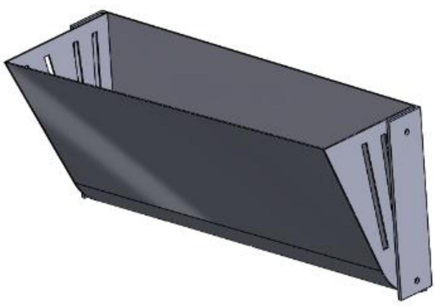
This concept is a sliding frontal plate that, under the impact of the knees would slide upwards on a curve guide.

Dynamic concept 4



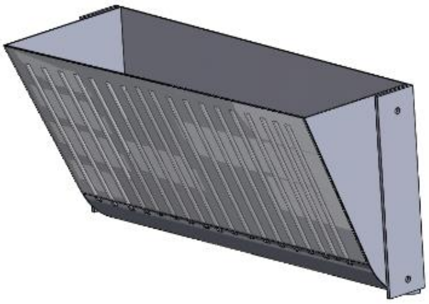
This model is made with a thin steel plate covered by a medium size foam layer. The plate is attached to two lateral mobile devises that work moving the frontal plate back and forward with a mechanism similar to that used on some old elevator doors.

Static concept 1



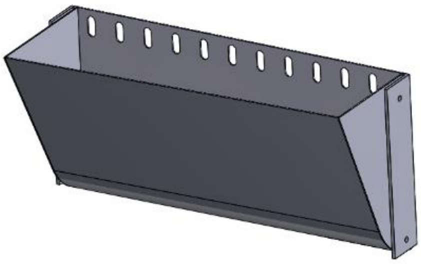
In this model, when knees collide with the IP, this should be deformed in the sides, but front and back plate should get closer (due to the deformation of the laterals) like a book. To guarantee the deformation on the sides and not on the frontal panel, the model is weakened with holes made in the sides.

Static concept 2



In this model, when knees collide with the IP this should be deformed in the frontal panel. In this case, the frontal plate is weakened to facilitate the deformation there, and cover with a layer of foam to don´t injure the dummy.

Static concept 3

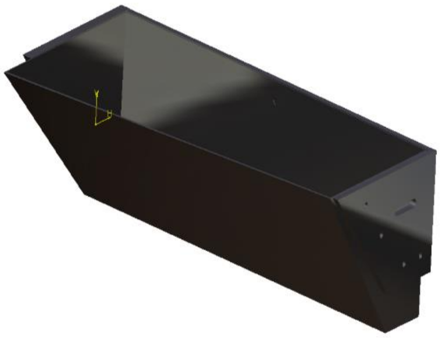


For this concept, it can be analysed the previous crash tests and identified when exactly the IPs were cracked. Where the cracks are identified, the material in this concept is going to be thinner in those exact places in order to force it to break there.

Static concept 4

This model is a made with a steel plate that imitates the shape of a globe box door. On the sides, it is attached to the rig but allowed to rotate (for doing the opening and closing globe box movement) and on the top it would be fastened to a steel support, to simulate the superior lock on a real globe box.

Static concept 5

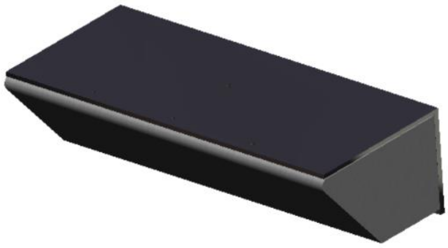


This model is a thin steel box structure with an open top. This structure is fastened in the back to a thick steel structure. This thick steel structure is fastened in the laterals to the generic rig.

Static concept 6

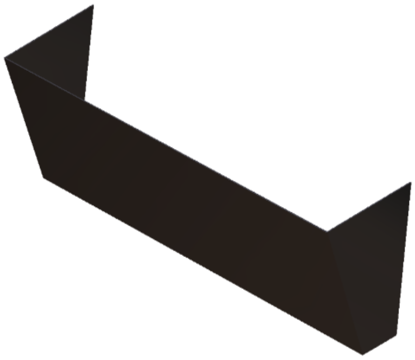
This concept is a complete box (6 walls) made of thin steel plates. The walls are intended to be cut separately and then welded together. This box would be fastened to a more rigid structure made with thick steel plates. Those steel plates would be placed on the top and back of the thin box, and fastened to the rig structure. The intention is to fasten the box with the rigid structure in the same places that a real IP module is fastened to its surroundings.

Static concept 7



This model is made just with a frontal thin steel plate and two laterals that would be fastened to the rig structure. This model is similar to Concept 1.1 but the absence of the bottom plate, gives the entire structure more possibilities to deform freely.

Static concept 8



This model is a deformable 4-walls (frontal, two laterals and bottom) box made with that would stand in the place of the IP.
The lateral of the box would be fastened to the lateral rig adapters and the 4 walls of the box would be cut separately but then welded together.
The material chosen was steel, but covering the frontal wall with a thick layer of rubber is a possibility.

APPENDIX V- LS-DYNA files

In this thesis it was implemented an LS-DYNA master-file structure (.key), in this file are included several other files with the extension .k that provide all the necessary information to perform a simulation.
The structure of the .key file for the LS-DYNA software can be characterized as a set of groups of input lines responsible for a particular function. Those input lines reference to the .k files and can be divided into three groups:

- The first group contains information about the coordinates of the nodes of the model objects, the way they are combined into the final elements and the property of the materials of the objects. This group helps describing the construction.
- The second group determines the conditions for constraining the workpiece and the laws of motion of the simulation.
- The third group controls the calculation method and its parameters.

After LS-Dyna processed the master file, it is necessary to read the simulation results in Meta post-processor.

APPENDIX V- Model CA compared with the targeted cars

Figures A4 to A9 show the femur response of the model CA compared with the six targeted car models and Figure A10.

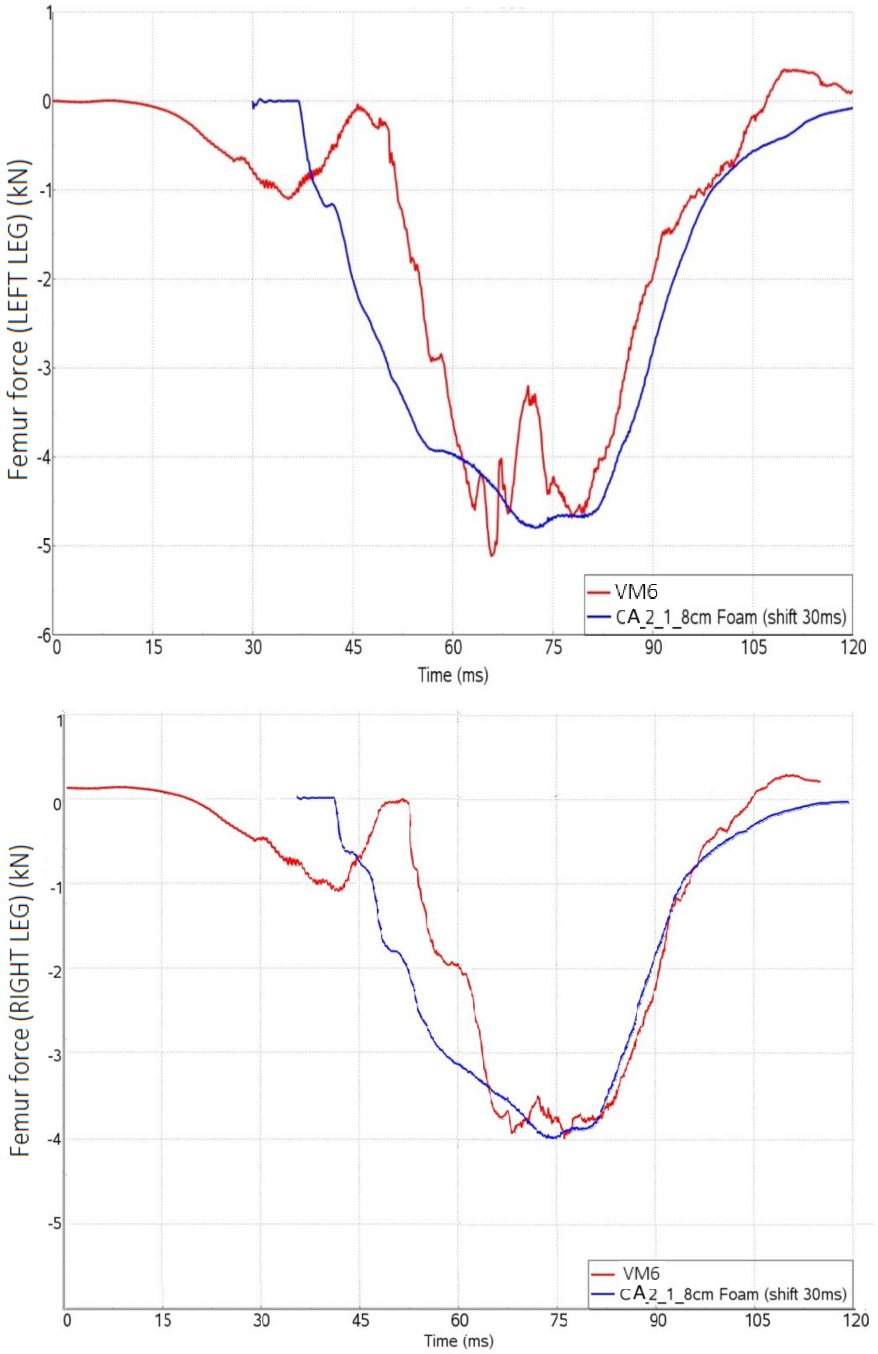


Figure A4, knee drop test for the model CA_2_1 8 cm Foam compared with the results of a frontal collision test with VM6. The model results have been shift 30ms to make easier the comparison between the two results.

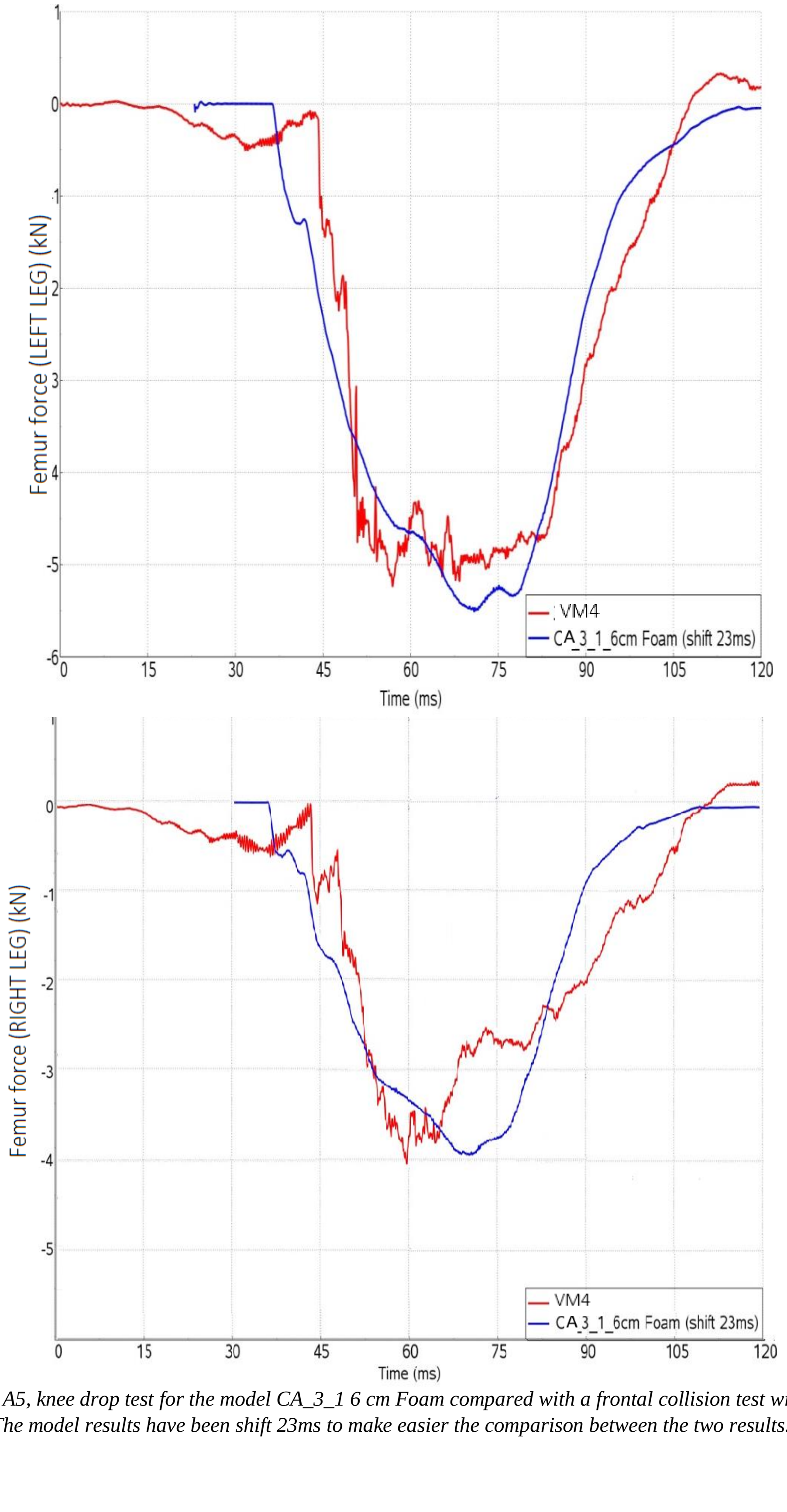


Figure A5, knee drop test for the model CA_3_1 6 cm Foam compared with a frontal collision test with VM4. The model results have been shift 23ms to make easier the comparison between the two results.

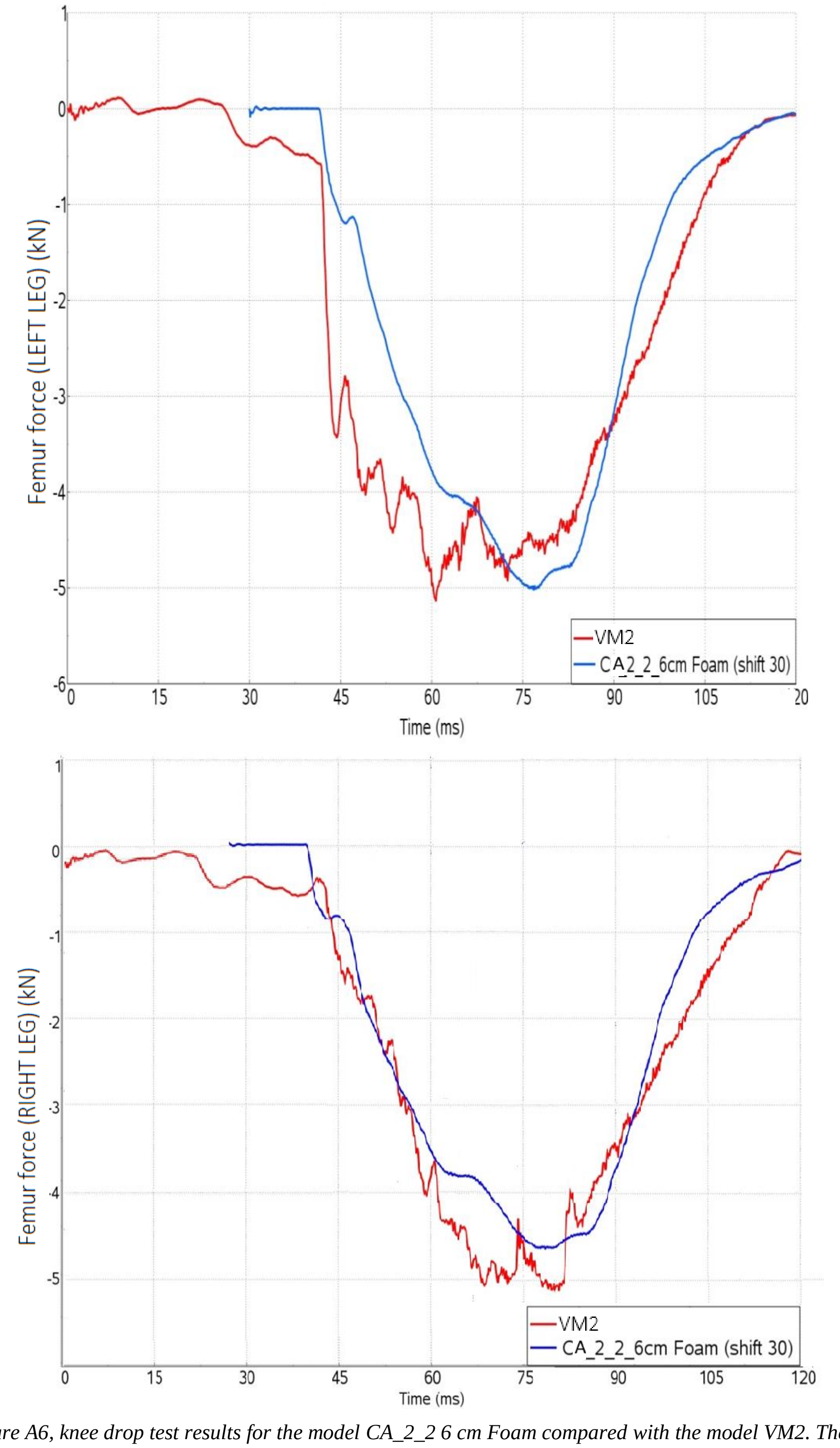
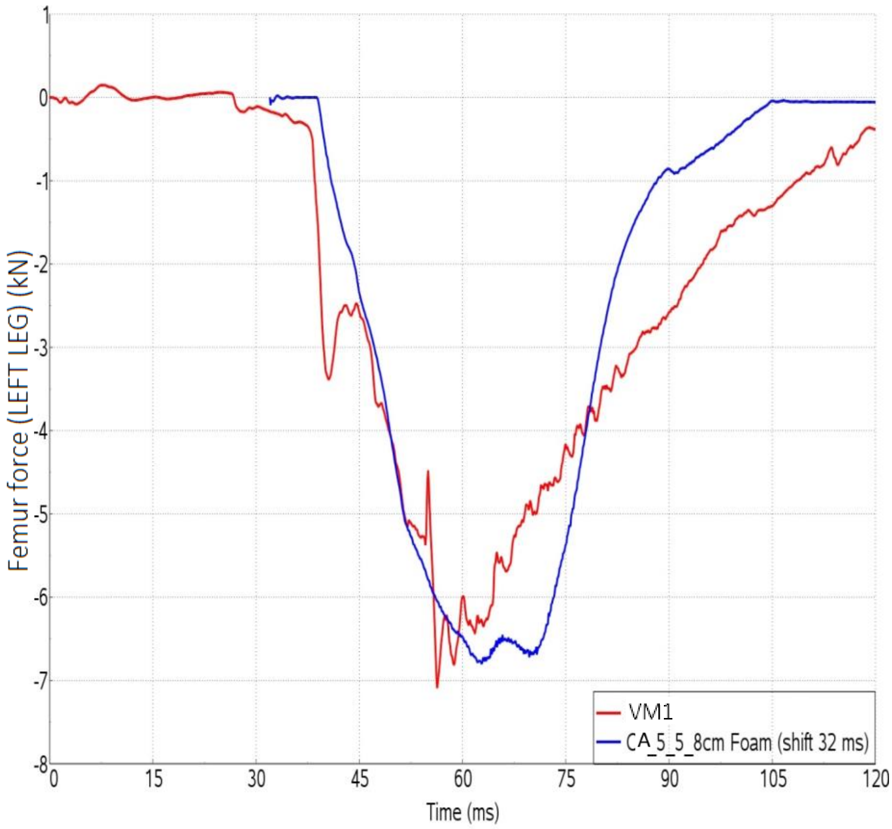


Figure A6, knee drop test results for the model CA_2_2 6 cm Foam compared with the model VM2. The model results have been shift 30ms to make easier the comparison between the two results.



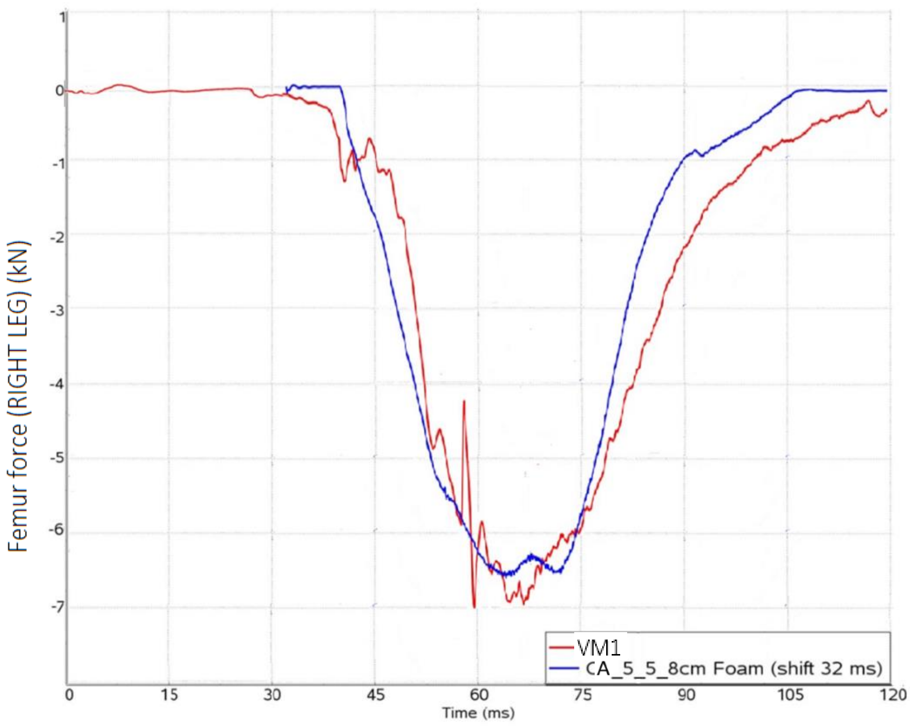


Figure A7, knee drop test results for the model CA_5_5 8 cm Foam compared with the results obtained in a frontal collision test with the model VM1. The model results have been shift 32ms in order to make easier the comparison between the two results.

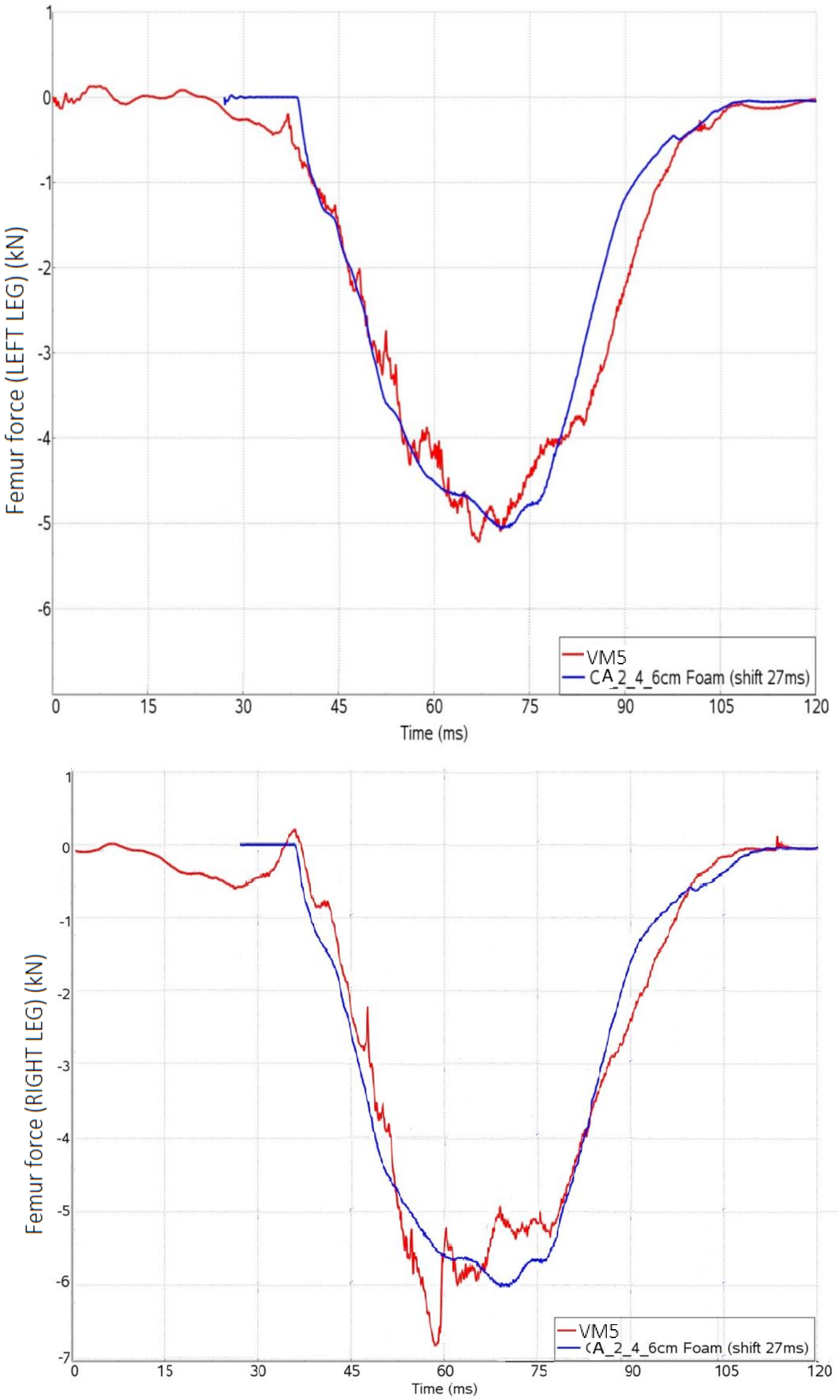
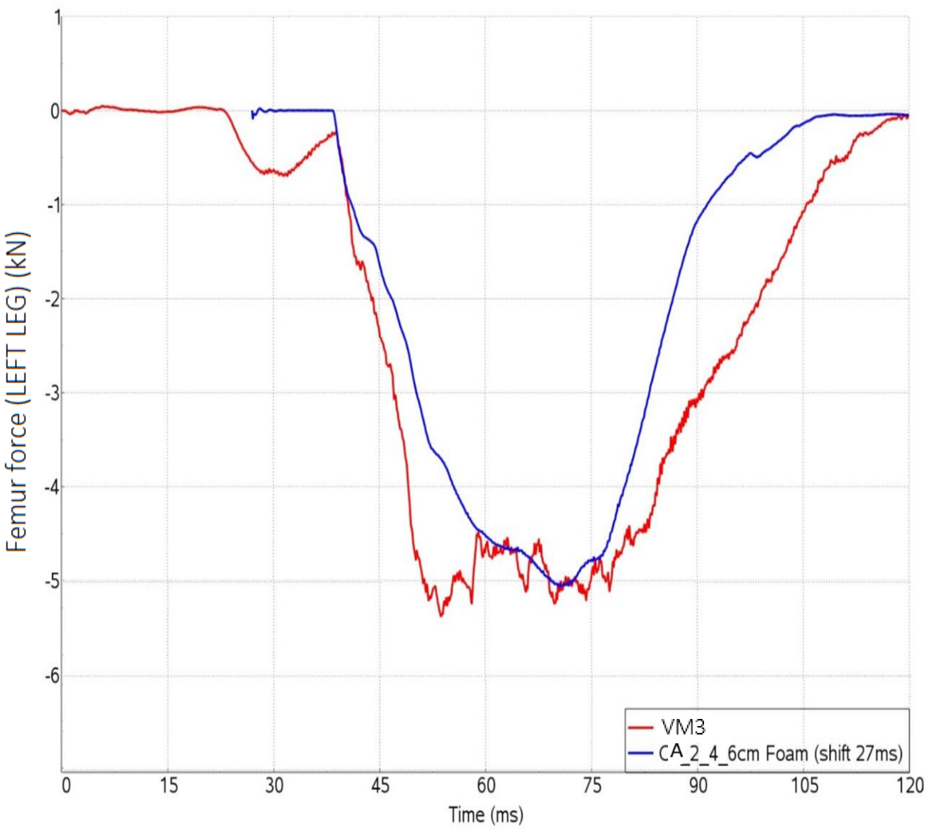


Figure A8, knee drop test results for the model CA_2_4 6 cm Foam compared with the results obtained in a frontal collision test with the model VM5. The model results have been shift 27ms in order to make easier the comparison between the two results.



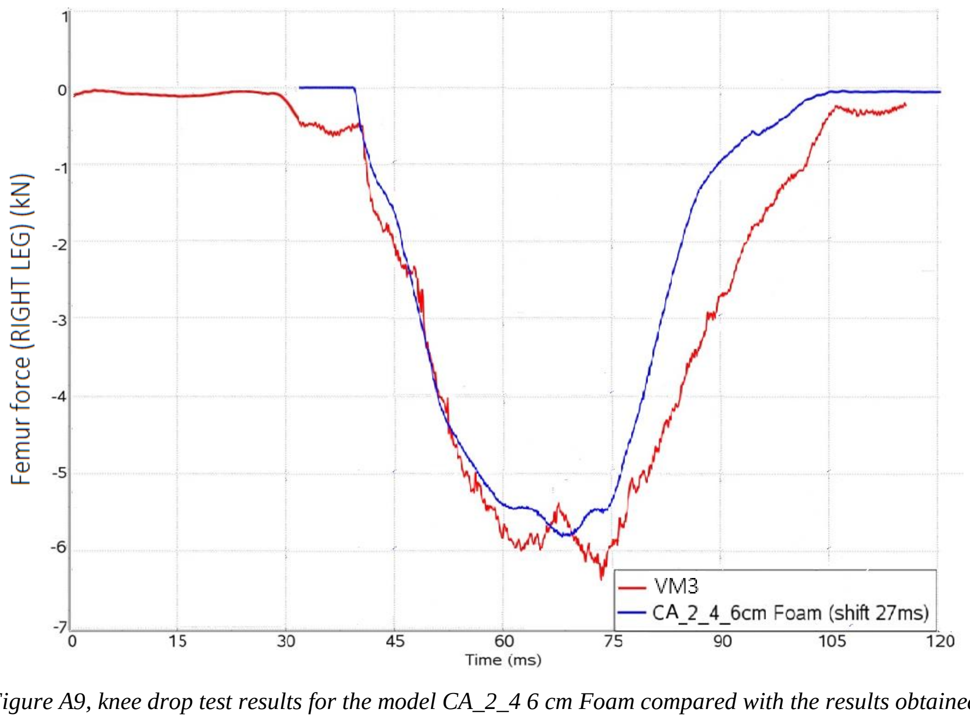
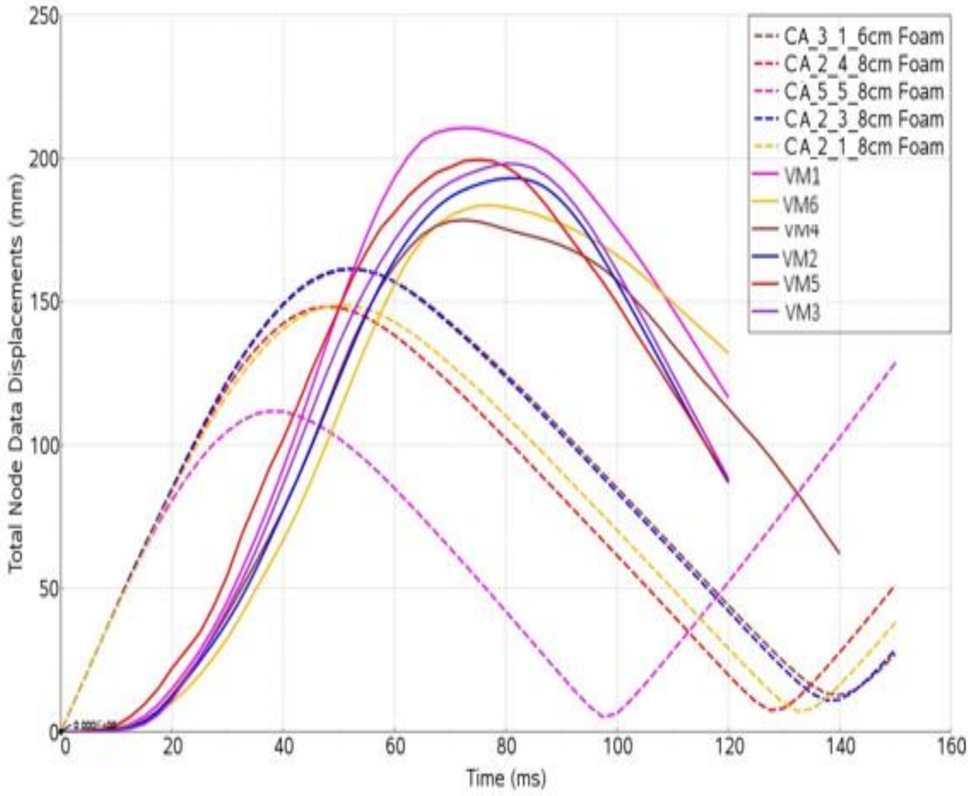
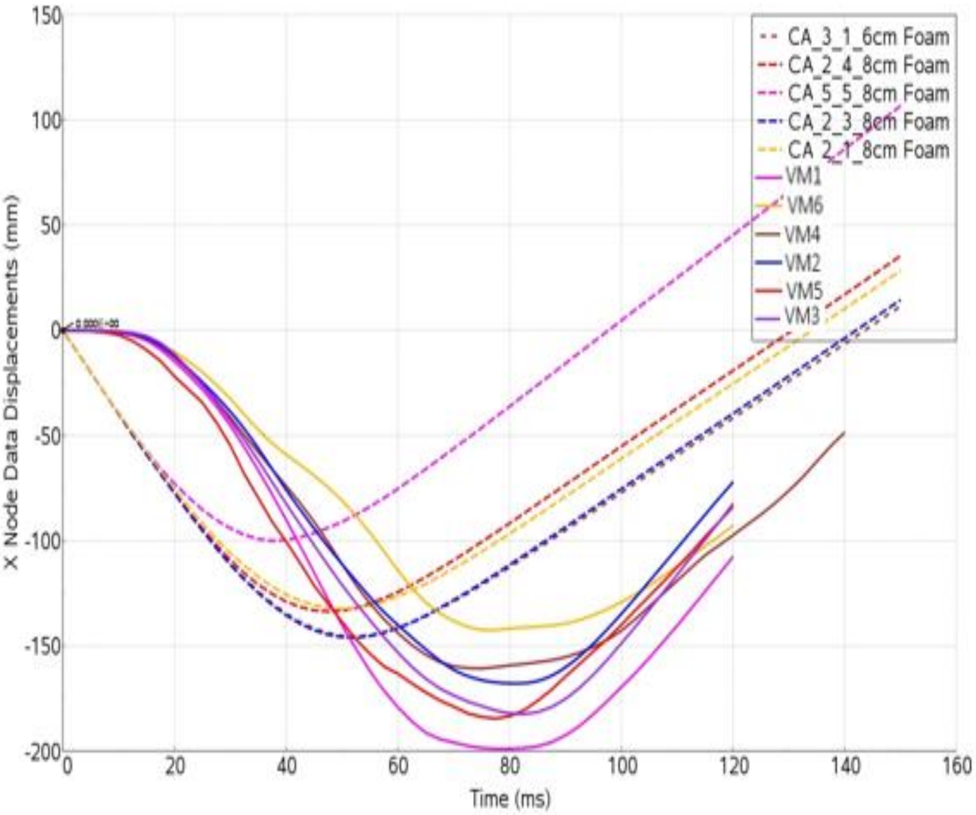


Figure A9, knee drop test results for the model CA_2_4 6 cm Foam compared with the results obtained in a frontal collision test with the model VM3. The model results have been shift 27ms in order to make easier the comparison between the two results.



Total Node Data Displacements (mm)
Time (ms)
CA_3_1_6cm Foam
CA_2_4_8cm Foam
CA_5_5_8cm Foam
CA_2_3_8cm Foam
CA_2_1_8cm Foam
VM1
VM6
VM4
VM2
VM5
VM3



X Node Data Displacements (mm)
Time (ms)
CA_3_1_6cm Foam
CA_2_4_8cm Foam
CA_5_5_8cm Foam
CA_2_3_8cm Foam
CA_2_1_8cm Foam
VM1
VM6
VM4
VM2
VM5
VM3

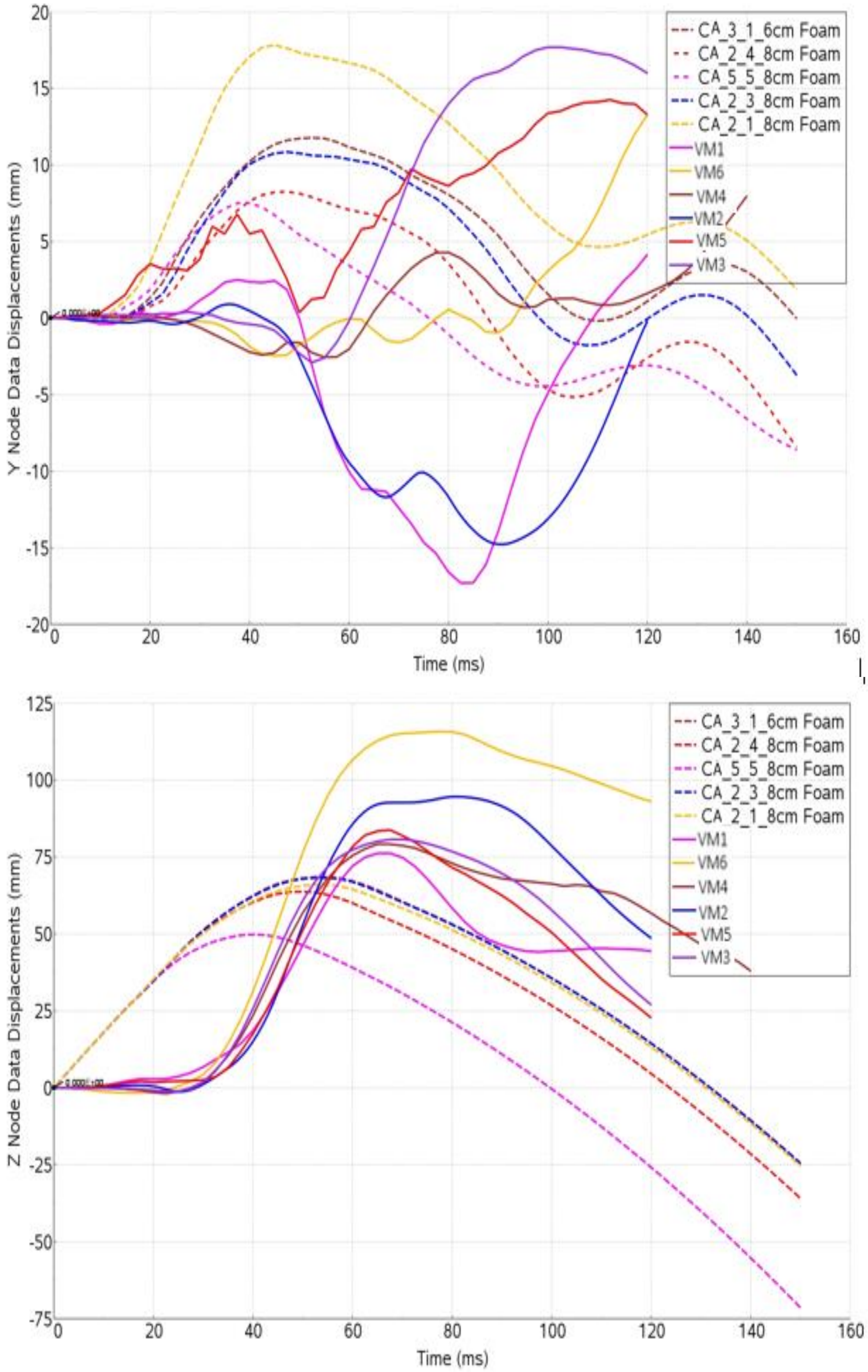


Figure A10, knee displacements comparison between the proposed thickness variations for model CA and the 6 cars target models. a) Total displacements vs. time, b) Displacements on the x coordinate vs. time, c) Displacements on the y coordinate vs. time, d) Displacements on the z coordinate vs. time,

APPENDIX VII – Inclination angle influence on femur force

From Figure A11 to A18 is shown the different femur force response in kN when the lateral left and right inclination angles variate

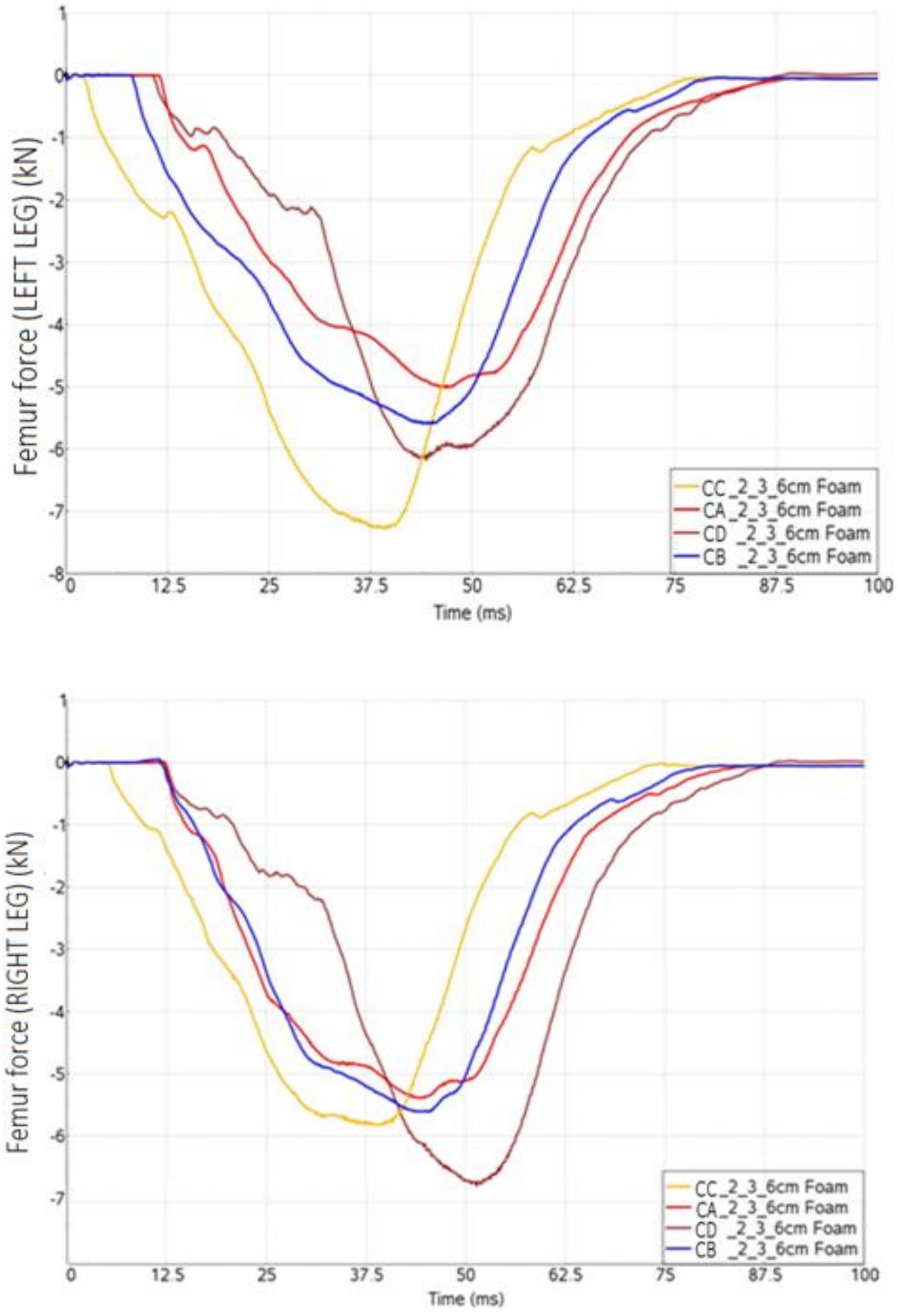
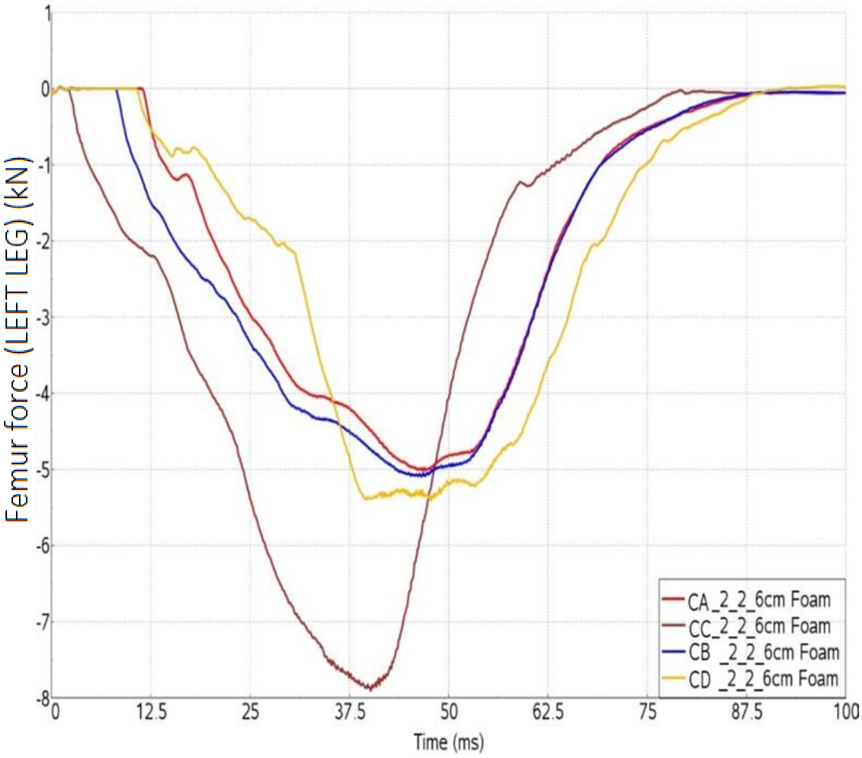


Figure A11, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left side thickness of 2mm and a right side thickness of 3mm.



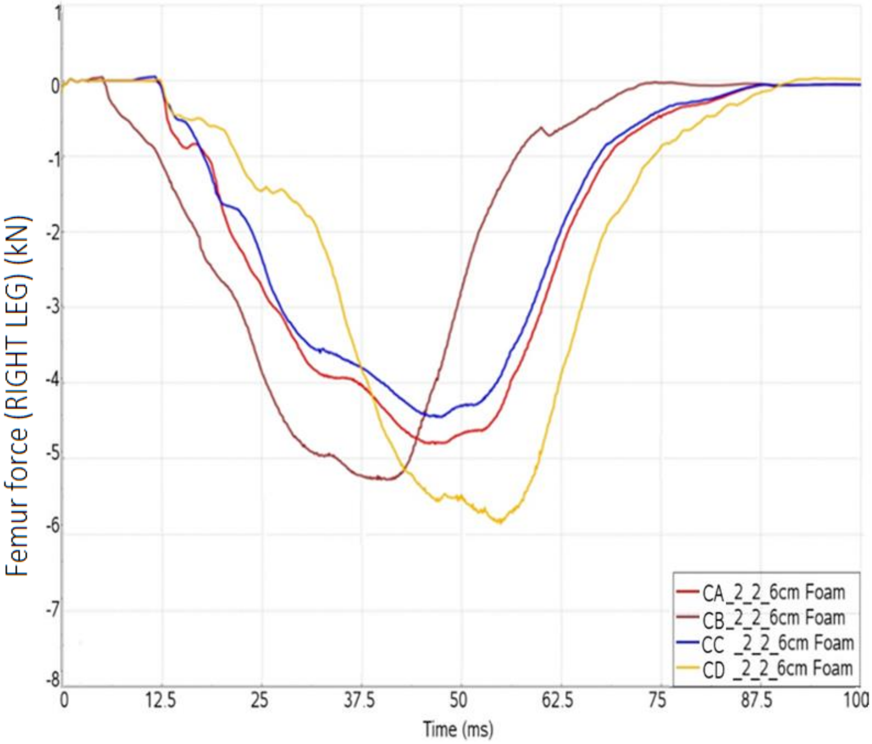


Figure A12, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left and right side thickness of 2mm.

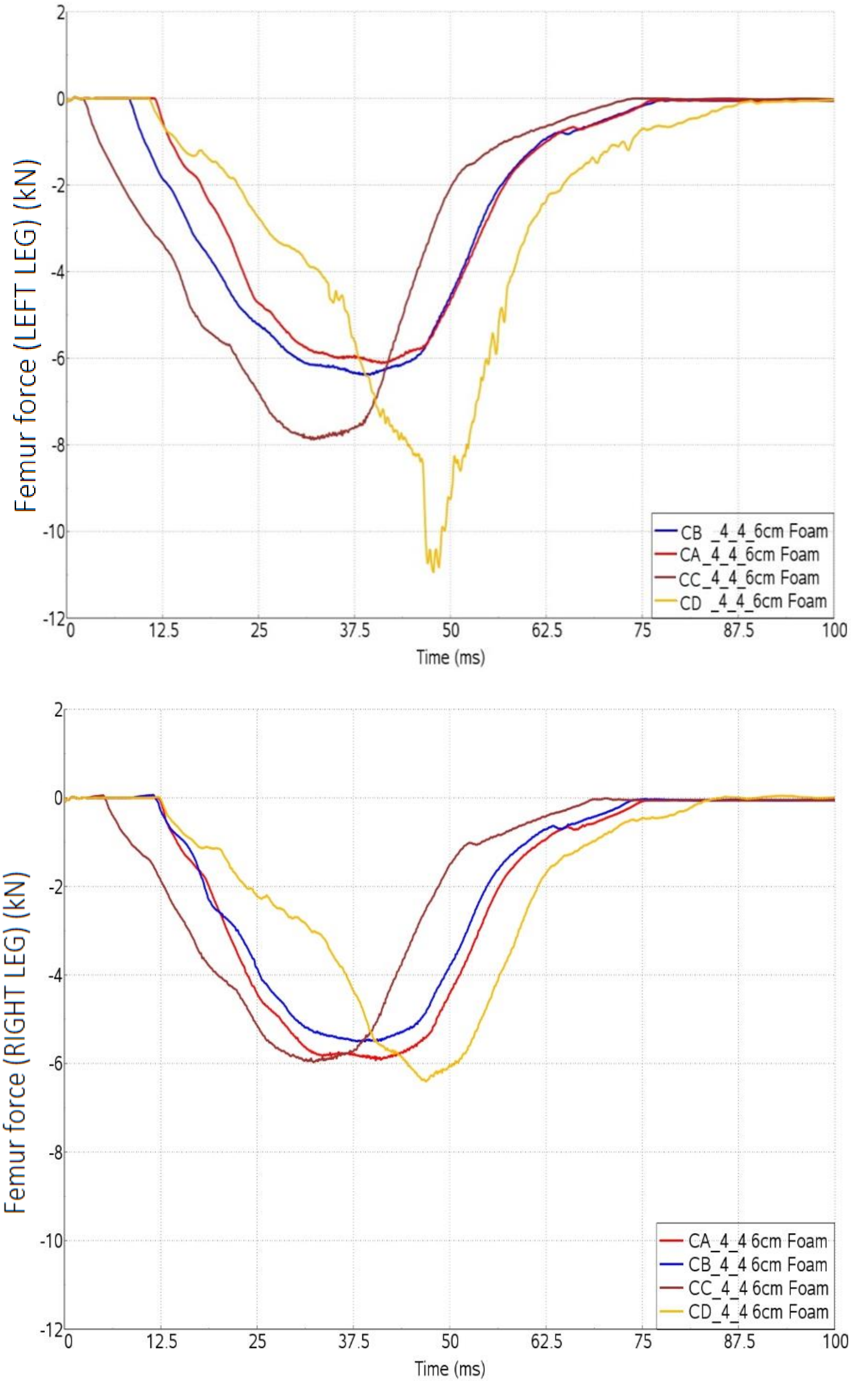


Figure A13, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left and right side thickness of 4mm.

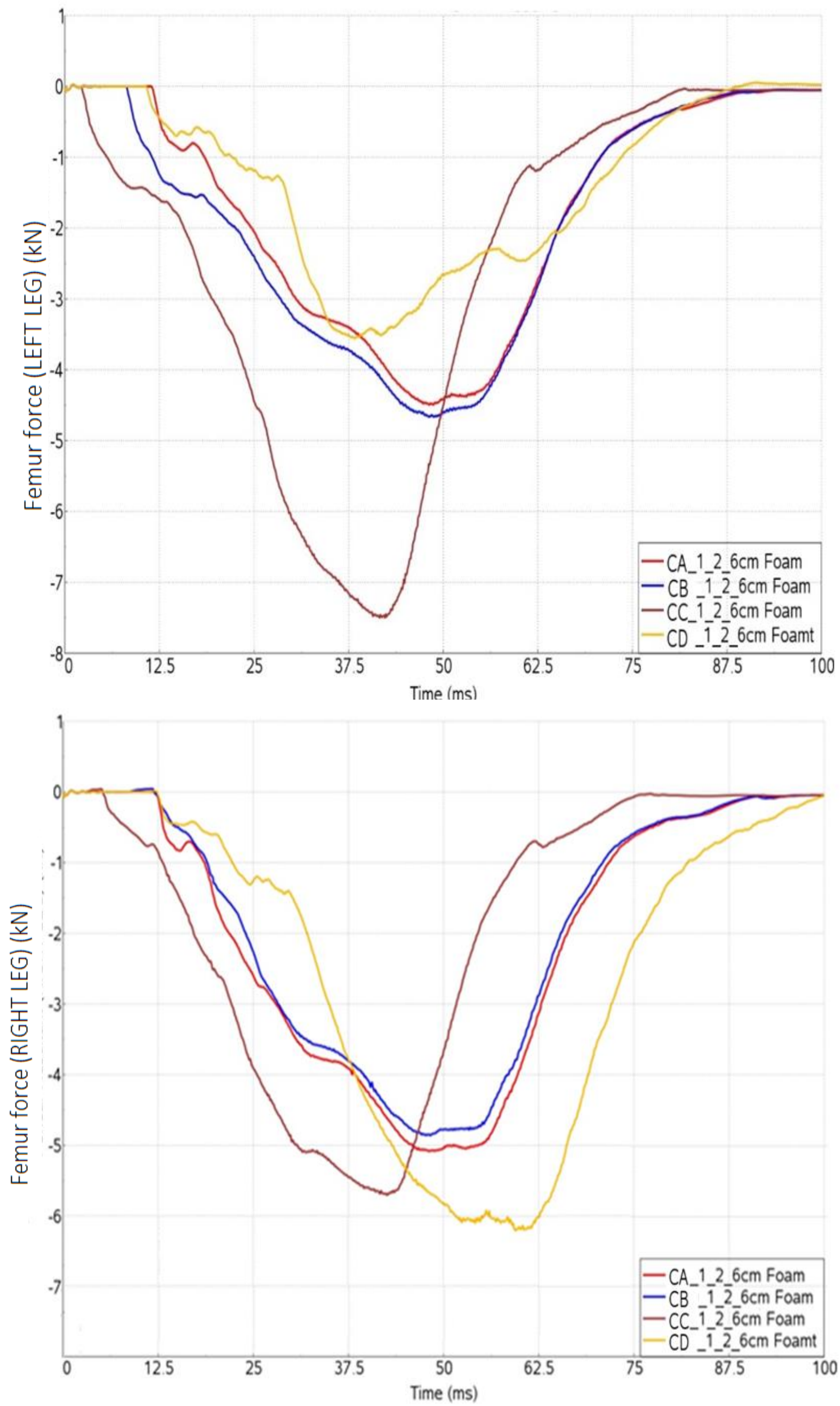


Figure A14, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left side thickness of 1mm and a right side thickness of 2mm.

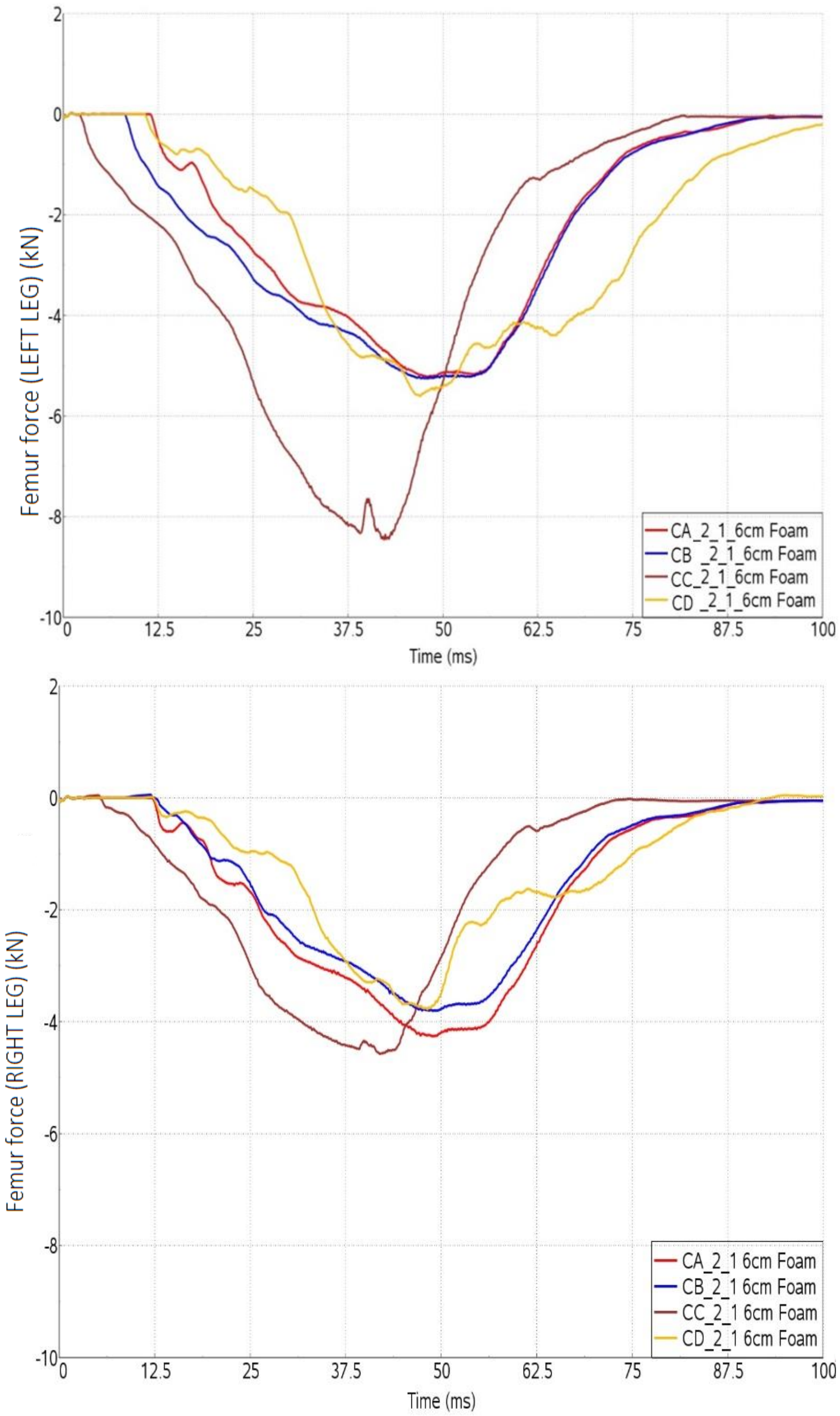


Figure A15, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left side thickness of 2mm and a right side thickness of 1mm.

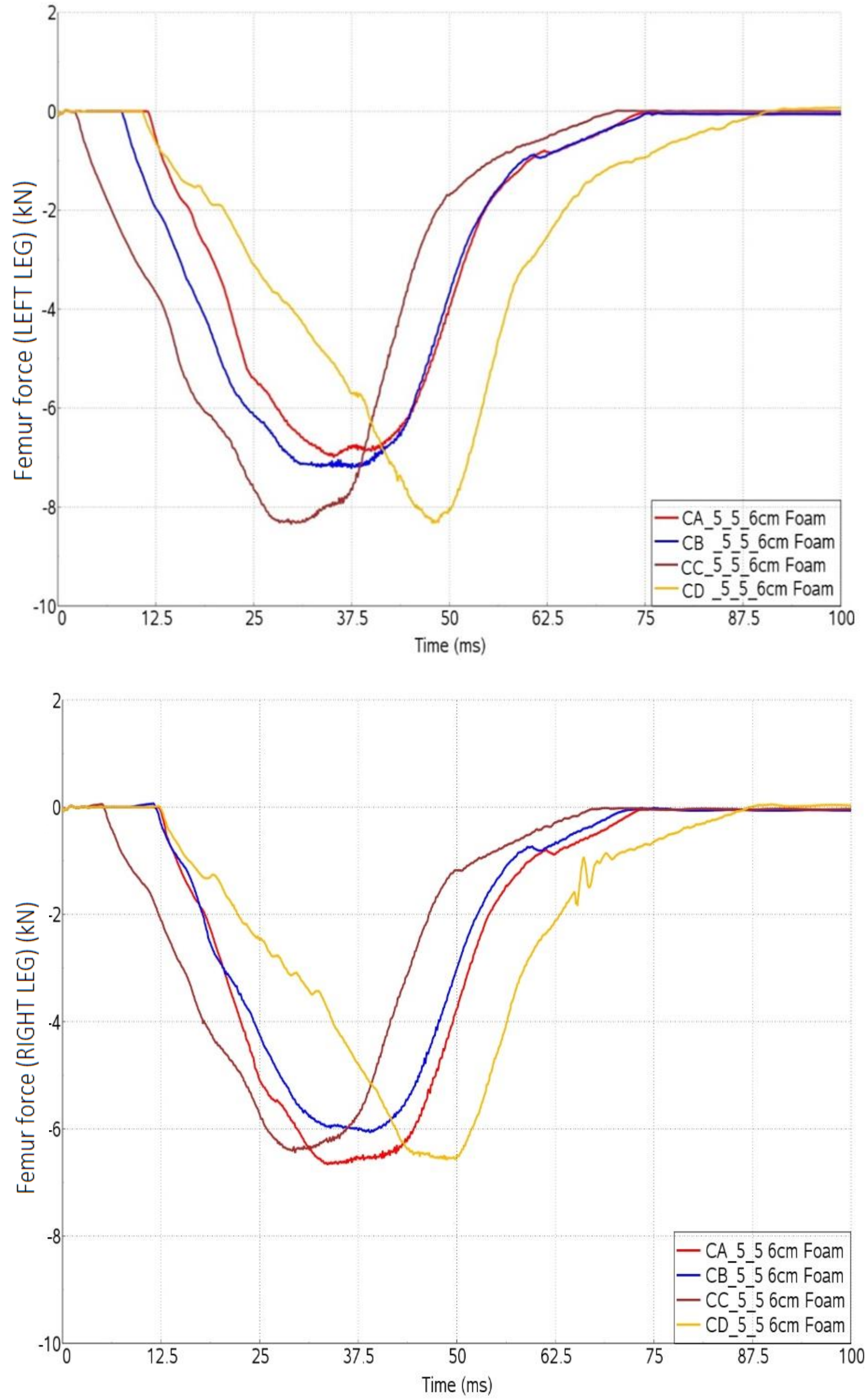


Figure A16, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left and right side thickness of 5mm.

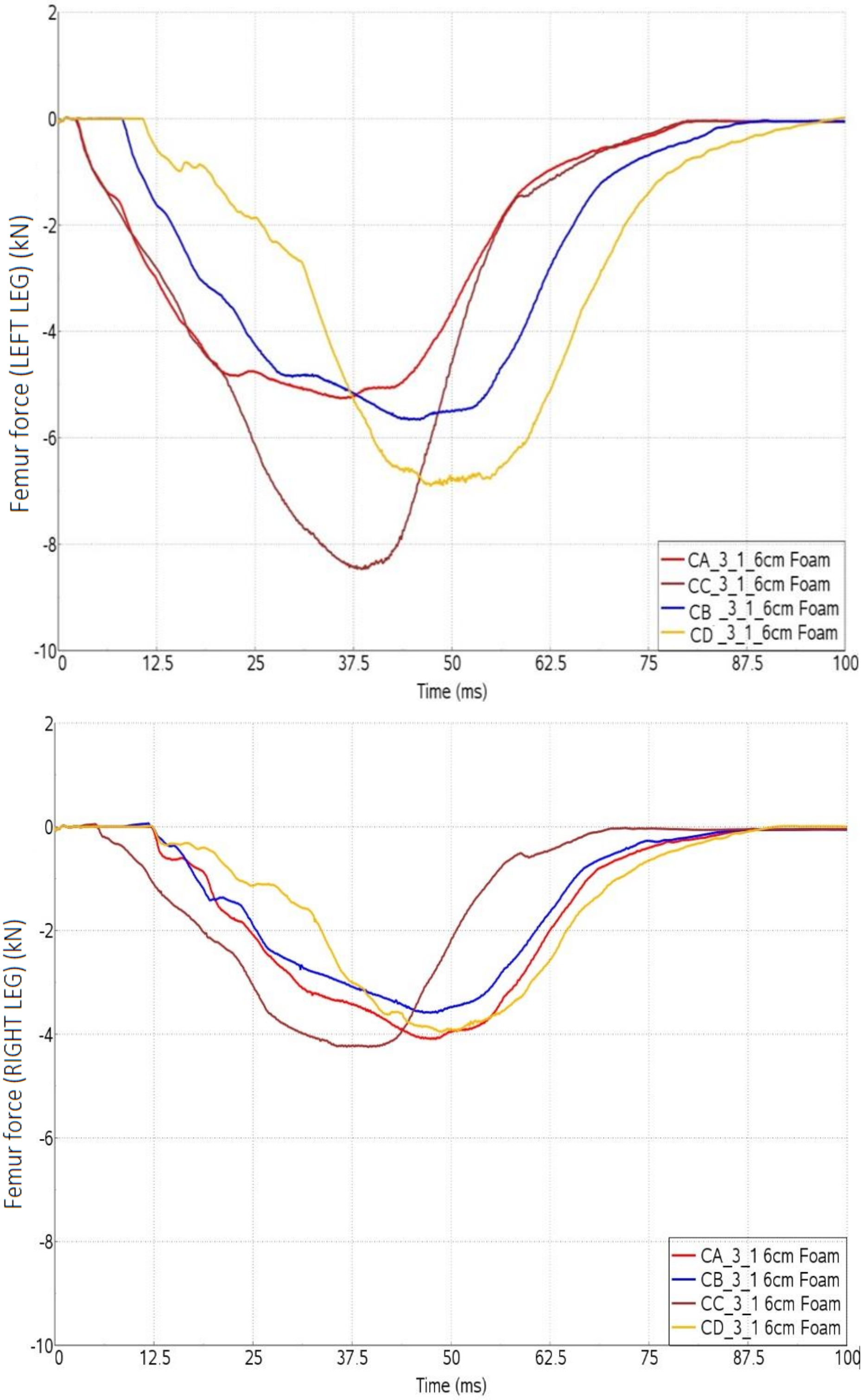


Figure A17, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left side thickness of 3mm and a right side thickness of 1mm.

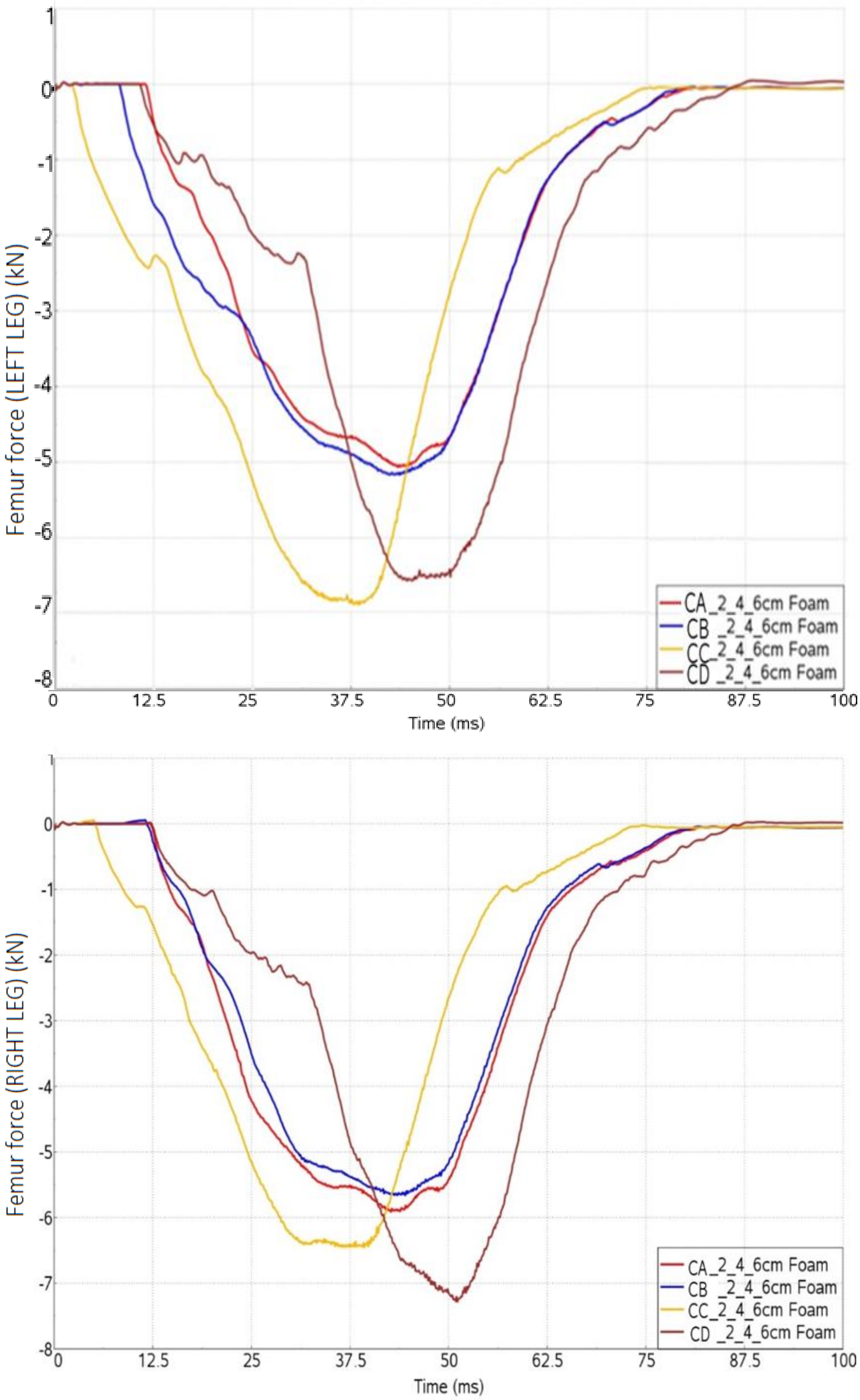


Figure A18, knee force vs. time for models CA, CB, CC and CD with a 6cm foam layer and a frontal panel with a left side thickness of 2mm and a right-side thickness of 4mm.

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